An Assessment of Potential Mining Impacts on Salmon Ecosystems of Bristol Bay, Alaska

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Appendix I: Conventional Water Quality Mitigation Practices for Mine Design, Construction, Operation, and Closure

Appendix I

Conventional Water Quality Mitigation Practices for Mine Design, Construction, Operation, and Closure

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Mitigation includes the steps needed to avoid, minimize, or compensate for any potential adverse impacts on the environment from a given activity (Hough and Robertson, 2009). Hardrock metal mining is an activity that provides metals for numerous purposes, but it has the potential to have adverse effects on nearby aquatic environments. Many mitigation measures developed to avoid or minimize impacts to water quality and aquatic ecosystems have become current industry practice and several of these are presented in this document for selected waste streams associated with mining, along with discussions of accidents and failures associated with storage of waste rock and tailings. Compensatory mitigation, which may be required under Section 404 of the Clean Water Act (CWA) when there are unavoidable impacts anticipated to lead to the loss of wetland, stream, or other aquatic resource, is not included in this Appendix.

The most important aspects of mitigation for any mining site are proper planning, design, construction, operation, management, and closure of waste and water containment and treatment facilities, and monitoring and maintenance over all mine-life phases, including following closure. A failure in any aspect of mitigation may result in environmental and/or human health impacts. Planning for design and construction must consider site-specific factors such as climate, topography, hydrology, geology, seismicity, and waste material specific factors such as geochemistry, mineralogy, particle size, and presence of process chemicals. These factors should be based upon accurate characterization and conservative estimates of future conditions to minimize potential for failure over time. In addition, the planning and design should incorporate considerations for the land's use following closure of mining operations.

1. WASTE ROCK

Overburden is unconsolidated surface material that would be removed to expose the ore/waste rock zone and often comprises alluvium, colluvium, glacial tills, or other soils; overburden may be stockpiled separately for later use in reclamation. Waste rock includes rock that is removed above the ore and rock that is removed along with the ore, but cannot be mined economically at the time of mining (sub-economic ore). The particle size distribution of waste rock may vary from sand-sized fines to large boulders, with the quantity in a given particle size class dependent upon the site geology and the specifics of the method(s) in which it was extracted (e.g., blasting strength). The sources of potential environmental influence to surface water from waste rock piles include sediment loading due to erosion and deposition of fugitive dusts, and contaminant loading due to leaching of acidity and inorganic contaminants, such as metals and metalloids, contained in the waste rock. Precipitation and surface water run-on can lead to weathering and erosion of materials into runoff (dissolved and particulate) transported to surface water. Percolation and infiltration that lead to leaching and transport of ions through seepage of the leachate to groundwater may occur also, as may seepage through sloped pervious material to a surface water body. Additional routes of environmental exposure include movement of material mass (e.g., through rockslides due to physical instability) into a water body and wind erosion carrying finer particles (dust) through the air.

Waste rock, and other mining materials may be classified as potentially acid-generating (PAG) or non-acid generating (NAG, also called non-PAG); this distinction is determined through geochemical characterization, acid-base accounting (ABA) static tests, and kinetic leachate testing [e.g., see (American Society for Testing and Materials (ASTM) 2000, Hornberger and Brady 1998, Lapakko 2002)]. ABA tests are rapid methods to determine the acid-generation potential (AP) and neutralization potential (NP) of a rock or mining waste material, independent of reaction rates (i.e., in contrast to kinetic tests). These potentials are then compared to one another by either their differences (net neutralization potential, NNP) or their ratios (neutralization potential ratio, NPR).

Although methods used for ABA have limitations, it is common industry practice to consider materials that have an NPR of 1 or less as potentially acid generating (PAG) (e.g., Brodie et al., 1991; Price, 2009; Price and Errington, 1998) and materials with a ratio greater than 3 (Brodie et al., 1991) or 4 (Price and Errington, 1998) as having no acid generation potential (non-PAG or NAG). Materials having ratios between 1 and 4 require further testing via kinetic tests and geochemical assessment for classification (Brodie et al., 1991; Price, 2009; Price and Errington, 1998). This further testing and assessment are necessary because if neutralizing minerals react before acid generating minerals, the neutralizing effect may not be realized and acid might be generated in the future. Additionally, some toxic elements (e.g., selenium and arsenic) may be released from mining materials under neutral or higher pH conditions, which would be observed during kinetic leaching tests conducted at variable pH values.

Waste rock is susceptible to acid generation and leaching of ions due to the open pore network allowing for easy advection of air (Mining Minerals and Sustainable Development (MMSD) 2002) to oxidize minerals, which subsequently are dissolved in water that encounters the rocks.

1.1 CONVENTIONAL PRACTICES

There are numerous mitigation measures available for waste rock piles. The selection of mitigation measures are site-specific and depend on the sizes and amounts of the material to be placed in the pile, the methods employed during mining, the mineralogy of the material, the site's specific hydrology, climate, seismicity, and topography, and plans for future land-use.

1.1.1 Operational Phase

Non-reactive (i.e., NAG) waste rock might be used in creation of mining roadways or transported off-site for use in roadways or another purpose requiring rockfill, with unused waste rock stored in piles. Waste rock piles generally are disposed in locations close to the mine site to reduce handling costs and are placed in locations that provide physical stability. Waste rock and overburden piles typically are not placed on lined foundations because of the cost and stability risk (Mining Minerals and Sustainable Development (MMSD) 2002), but rather are constructed on natural terrain; although the decision for lined or unlined piles is site-specific. Prior to placement of a waste rock pile, the topsoil is removed and stockpiled for later use in reclamation. The angle of repose (where the outer slope is just stable under static loading conditions) is typically 37-40° (Mining Minerals and Sustainable Development (MMSD) 2002), but will depend on site-specific and material-specific factors. Piles constructed in lifts or by using benches typically have lower slope angles and concurrent increased stability (U.S. Environmental Protection Agency (U.S.EPA) 1995b, Mining Minerals and Sustainable Development (MMSD) 2002).

When waste rock contains materials that have the potential to generate acid or release metals, metalloids, or other ions of concern that would have environmental or human health impacts, management of the materials must include practices to minimize potential for any environmental impacts. Mitigation/management measures used during the operational phase can include a variety of methods either used independently or in combination; these include diversion systems to route water away from the pile, use of liners underneath the waste rock pile, selective handling / segregation, blending and layering, minimization of infiltration potential, leachate collection systems and seepage drains and routing systems to divert leachate to treatment facilities, addition of bactericides to slow oxidation of PAG, encapsulation, and/or adding low permeability materials to slow infiltration rates (Boak and Beale 2008, Mining Minerals and Sustainable Development (MMSD) 2002, U.S. Environmental Protection Agency (U.S.EPA) 1995b, U.S. Environmental Protection Agency (Region 10) 2003a, U.S. Environmental Protection Agency (Region 10) 2003b, Perry et al. 1998). Additionally, the amount of waste rock exposed to the environment can be reduced by disposing the rock into depleted pits or underground mine tunnels, or through reclamation activities conducted concurrent with active mining (called progressive reclamation).

Selective handling involves placement of materials combined with management strategies to avoid or minimize release of acidic drainage. Physical separation of PAG and NAG materials will not prevent acid-rock drainage formation, but may be necessary to control the amount and location of potential drainage and to manage the PAG material. PAG material can be kept completely saturated to minimize air exposure (e.g., placed into the open pit post active mining), disposed in a separate lined or unlined engineered containment system, or blended with NAG material and stored in an aboveground pile, coupled with minimizing exposure to water.

Blending involves mixing waste rock types of varying acid-producing potential (AP) and neutralization potential (NP) to create a mixture that has acceptable quality (i.e., no net acid-generation potential). The viability of blending as a mitigation measure depends on the materials available and the mine plan, the stoichiometric balance between acid generating and neutralizing materials, geochemical properties, reactivity of waste rock types, flow pathways created within the waste rock pile, and extent of mixing and blending. If a site does not have sufficient neutralizing material with which to blend the PAG material, limestone or other neutralizing rock might be used, if available from another location on-site, or trucked into the site. The geochemical characteristics of the materials being blended and mixed must be well-characterized in order to attain a resultant mix that has no net acid production potential.

PAG materials may be kept isolated from direct exposure to precipitation and oxygen transfer by layering NAG materials on top of them in the waste pile. This would involve layering of PAG with a mix of PAG-NAG material, with a top layer of NAG only material, or another combination.

Encapsulation of a waste rock pile with an impermeable layer serves to limit infiltration and oxygen transfer. Progressive reclamation with multiple impermeable layers within a waste rock pile can minimize infiltration, seepage, and oxygen transfer. Compaction is used also, if it can be done safely (physically). Once a pile is covered, overburden or other non-reactive material can be placed on top and the site vegetated to provide stability against erosion and to meet regulatory requirements for restoration.

Some microorganisms are able to facilitate rapid oxidation of PAG sulfidic minerals; thus, a bactericide could be added to eliminate their presence and slow the oxidation rate. Such an amendment must be mixed thoroughly into the PAG material as the pile is constructed to ensure effectiveness.

Sub-economic ore removed during the active mining phase might be segregated from the primary waste rock pile to be mined if/when it becomes economically feasible. These piles may be mined with their resultant waste disposed into a tailings impoundment or placed directly in the completed pit, if mined at closure.

Building an under-drain system to collect seepage/leachate water potentially containing leached ions/acidity allows this water to be directed toward collection systems for either use in processing or treatment and discharge to a surface water body. Diversion structures collect and direct runoff and seepage to treatment and/or settling ponds. Groundwater monitoring wells are used downstream of these structures to evaluate their performance.

1.1.2 Closure and Post-Closure

During the closure phase of mining, a dry cover (or encapsulation) can be placed over the waste rock pile to isolate it from water and oxygen, or the pile can placed into the completed open pit to be kept below the water line (subaqueous disposal if PAG material), with choices dependent upon site specifics (O'Kane and Wels 2003). Additionally, in some settings, it is beneficial to fill the pit with waste rock and other waste material and then construct a dry cover over the filled pit area. When stored above ground, the stockpiled overburden may be used to cover the pile and then it is vegetated to provide stability against erosion. Blight and Fourie (Blight and Fourie 2003) recommend that outer slopes reclaimed with vegetation not exceed 15 degrees. Post-closure monitoring, maintenance, and inspection are conducted indefinitely when a pile requires long-term collection and treatment of leachate through use of the drainage collection and monitoring structures in place during the operational phase of mining. A number of different types of covers could be used, with each having their benefits and limitations. Factors affecting the long-term performance of covers include physical stability, volume change, vegetation, soil evolution, and ecological stability (Wilson, Williams and Rykaart 2003).

1.2 ACCIDENTS AND FAILURES

If waste rock piles are designed properly with appropriate mitigation measures, monitored and maintained, release of contaminants is possible, but unlikely; however, accidents and failures causing contaminants to be transported may still occur. Seven major factors affecting the physical stability of a waste rock pile against failure are: 1) configuration; 2) foundation conditions; 3) waste material properties; 4) method of construction; 5) dumping rate; 6) piezometric and climatic conditions; and 7) seismic and blasting activities ((Piteau Associates Engineering Ltd. 1991), as referenced in (U.S. Environmental Protection Agency (U.S.EPA) 1995b). An additional factor to consider is monitoring and maintenance for early detection of conditions that indicate inadequate stability. Although it depends on a number of site-specific factors, data indicate that most waste dump failures occur on foundations with slopes in excess of 20 degrees (U.S. Environmental Protection Agency (U.S.EPA) 1995b).

Physical failures of waste rock piles may occur through slope failures. These result from changes in the effective stresses of the rock material, variations in material properties (including particle size and gravity sorting), or changes in the rock pile's geometry (Pastor et al. 2002, Tesarik and McKibbin 1999). Changes in effective stress can result from earthquakes, human actions, changes in underlying soil properties, or through changing pore pressures resulting from rainfall, snowmelt, or changes in drainage conditions. Properties of the rock will change over time due to weathering and from the influence of acid dissolution, if any nearby PAG materials are oxidized and dissolved. Changes in a waste rock pile's geometry can result from erosion or from actions such as excavation, construction, or rebuilding/reshaping of the pile.

Waste rock piles typically have heterogeneous particle size distribution and varied permeability throughout the depth and breadth of the pile. In a field test using tracers, Eriksson et al. (Eriksson, Gupta and Destouni 1997), found that 55-70% of the total water followed preferential flow pathways. The authors also found that chemical tracers behaved differently in weathered waste rock piles versus newer piles. Results from Eriksson et al. (Eriksson et al. 1997), support the need for understanding longer-term behavior of the materials and their distribution within a waste rock pile through leaching tests, modeling, and field measurements. Blending waste rock with limestone is a standard practice to minimize the production of acidic leachate; however, the mixing method used during construction of the pile construction may influence the method's success. For example, Miller et al. (Miller et al. 2006), reported blending during waste rock pile construction to have only limited success when using haul trucks, due to insufficient blending of the limestone with the finer size fraction of waste rock, but that better mixing was achieved using a conveyer and stacker. Morin and Hutt (Morin and Hutt 2004), as presented in Price (Price 2009), found that variability in acidity from seeps of a single waste rock dump ranged from zero to approximately 90 g $CaCO_3$/L (standard unit for acidity, where 50 grams of $CaCO_3$ neutralizes 1 mol H^+) in one year, which further supports the need for homogenous blending of neutralizing materials and complete characterization of waste rock materials.

Isolation covers have the highest probability of success against geochemical failure (i.e., leaching of acidic and/or contaminant-laden water), with their purpose being to limit infiltration and oxygen transfer. In a study of a waste rock pile at a mine site in Papau Province, Indonesia, however, Andrina et al. (Andrina et al. 2006), found aspects of a waste rock pile, including the type of waste rock, particle size distribution, and dumping methods, each influenced variations in oxygen and temperature profiles. At that site, they found that an impermeable surface cover had only a limited effect on oxygen concentrations within the profile of the waste rock pile and concluded that advection of airflow through the coarse rock / rubble zone at the foundation of the dump was the primary pathway for oxygen transport.

Monitoring and maintenance activities must continue beyond construction of a waste rock pile. Although the pile may have been constructed based on sound slope stability studies, and have appropriate covers and means to divert water, the properties of the pile may change over time and breaches to covers may occur. Additionally, freeze/thaw cycling in colder climates may cause cracks, channeling, and exposure of surfaces below the cover (Sartz et al. 2011) and should be considered when designing piles and mitigation measures in these climates. Such cycling could result in accelerated weathering and leaching of materials (Dawson and Morin 1996, SRK Consulting 2009). With careful monitoring and early remedy of observed defects, some catastrophic consequences can be avoided.

2. TAILINGS

Tailings are a solid-liquid slurry material comprising fine-grained waste particles remaining after ore processing (e.g., milling, flotation, separation, leaching) and typically in the silt size-fraction ranging from 0.001 to 0.6 mm, along with water and residual chemicals (Mining Minerals and Sustainable Development (MMSD) 2002, U.S. Environmental Protection Agency (U.S.EPA) 1994). Similar to waste rock, tailings materials may be potentially acid-generating (PAG) or non-acid generating (NAG) and testing is conducted to assess their characteristics. The majority of ore mined and processed ends up as tailings. Tailings slurries have a solids content from 15 to 55 percent weight (U.S. EPA 1994). The liquid portion of tailings comprises water and chemicals used in processing of the ore (e.g., sodium ethyl xanthate, methyl isobutyl ketone, hydroxy oxime, acids, alcohols). Cyanide and metals may be present if the process includes cyanidation or pyrite suppression, with disposal of waste solution and tailings in the tailings impoundment. Logsdon et al (Logsdon, Hagelstein and Mudder 1999) present concentrations of cyanide and various metals that might be expected (if present in the ore) in solutions following gold extraction: total cyanide (50-2000 mg/l), arsenic (0-115 mg/l), copper (0.1-300 mg/l), iron (0.1-100 mg/l), lead (0-0.1 mg/l), molybdenum (0-4.7 mg/l), nickel (0.3-35 mg/l) and zinc (13-740 mg/l).

The sources of potential environmental impacts to water from tailings storage facilities (TSF) are sediment loading and leaching of acidity and inorganic contaminants, such as metals and metalloids, and other chemicals used that may be present in the processing waste tailings. The main environmental influences originate from seepage of contaminants into groundwater, leakage through containment walls, and exposure of waterfowl (if a tailings pond is present) to chemical contaminants. Additional routes of environmental exposure include movement of material mass from structural failure of a tailings impoundment (e.g., through breach of embankments) into a water body, and wind erosion carrying finer particles through the air during construction.

2.1 CONVENTIONAL PRACTICES

The selection and design of a tailings disposal site is site specific and depend on factors such as climate, topography, geology, hydrology, seismicity, economics, and environmental and human safety (e.g., see (Commonwealth of Australia 2007, U.S. Environmental Protection Agency (Region 10) 2003a, U.S. Environmental Protection Agency (Region 10) 2003b). The most basic requirements of any tailings storage facility (TSF), also called a tailings disposal facility, are that it is safe, stable, and economical, and that it presents negligible public health and safety risks and acceptably low social and environmental impacts during operation and post-closure. Effective construction must be based on a correct geotechnical assessment.

2.1.1 Operational Phase

Disposal options for tailings include 1) land-based placement into an impoundment; 2) disposal into underground workings or open pits; and 3) underwater (sub-aqueous) disposal into an existing water body or a constructed water body. The most common method of disposal is into a tailings slurry impoundment. Tailings impoundments are constructed as water-holding structures. This generally is accomplished by constructing a tailings dam in a valley. As tailings are placed behind the dam, a basin is formed. The solid portion of the tailings settles and the liquid portion creates a tailings pond. Construction of a tailings impoundment is done in lifts over the life of the mine. Tailings deposited against the embankment in creation of beaches leads to water draining away from the embankment, which reduces seepage and increases dam stability. Water levels in the tailings pond are controlled through removal of excess water for use in the mining process or for treatment and discharge to the local surface water; this minimizes water storage to enhance stability.

Special care must be taken during operations and post-closure to isolate acid-producing/metal leaching tailings from oxidation. A common method is for disposal of such tailings underwater (either into an existing water body or into a tailings pond). Sub-aqueous disposal is common in Canada and is considered a BMP for long-term isolation of tailings from oxidation; loss of any existing water body through this method must be replaced (O'Kane and Wels 2003). Sub-aqueous disposal has the potential for problems with physical stability, seepage, and water quality; however, if properly designed, constructed, and maintained, this type of storage provides good long-term isolation post-closure. At least a 30-cm barrier of stagnant water should overly the tailings (wave action would re-suspend particles closer to the surface if not stagnant); in Canada, a minimum recommended depth is 100-cm (SRK Consulting 2005). Sub-aqueous disposal is not applicable in all environments (e.g., arid regions), and disposal into an existing water body is not supported at all in Australia (Witt et al. 2004).

Tailings impoundments can be constructed using upstream, downstream, and centerline methods. The upstream method involves construction of walls on top of consolidated and desiccated tailings in an upstream direction, using waste rock or tailings for construction material; the downstream method involves construction with waste rock or borrow materials in a downstream direction; and the centerline method involves construction of the walls above a fixed crest alignment, using waste rock, borrow materials, or tailings (Commonwealth of Australia 2007). According to the International Commission on Large Dams (ICOLD), from a seismic standpoint, tailings dams built by the upstream method are less stable than dams built by either the downstream or the centerline method (International Commission on Large Dams (ICOLD) 2001). The state of Idaho considers upstream construction unsuitable for impoundments intended to be very high and/or to contain large volumes of water or solids (http://www.idl.idaho.gov/Bureau/Minerals/bmp_manual1992/p16-ch4.pdf). The downstream method is considered more stable from a seismic standpoint, but it also is the most expensive option; centerline construction is a hybrid of upstream and downstream construction types and has risks and costs lying between them (Chambers and Higman 2011, Martin et al. 2002).

When tailings impoundments are constructed in earthquake-prone locations, a critical design criterion is magnitude of earthquake that could be expected to occur. The most conservative design would consider the maximum credible earthquake (MCE), which would be the largest quake that could occur reasonably at any location at the mine site, based on seismological and geological evidence and interpretation (Chambers and Higman 2011).

Dewatering (thickening) of tailings prior to disposal enables more process water to be directly recycled back to mineral processing plant to reduce losses and operational demand, while reducing the amount of water stored in the TSF. Reduction of water quantity will reduce risks of overtopping, seepage, and evaporative losses of water that could be used in the mining process (rather than fresh water). Depositional beach angles also are steeper, which aids in containment.

Paste tailings technology requires thickening (water content ~ 20%) the tailings and placing them onto a lined disposal site. Dry stack tailings require filtering the tailings and placing the tailings onto a lined pad. Tailings thickened to a paste and filtered tailings can be ‘stacked’ for long-term storage. This method is relatively new, but has the advantages of reduced potential for liquefaction during an earthquake and tailings release from a breach in containment would be localized instead of flowing long distances (Witt et al. 2004). Filtered (e.g., moisture content ~ < 20%) and stacked tailings require a smaller footprint for storage, are easier to reclaim both at closure and by progressive reclamation, and have lower potential for structural failure and environmental impacts (Martin et al. 2002). Additionally, in cold climates, dry stacking prevents pipes from freezing, prevents frosting problems associated with conventional impoundments, and assists in retention and recycling of process water during cold weather operations (Access Consulting Group 2007). Disadvantages include that dry stacking is not appropriate for acid-generating tailings and pumping to the storage facility is difficult due to high viscosity and resistance to flow (filtered tailings for stacking are transported to storage via truck). There also is potential for generation of dusts (Witt et al. 2004). Thickened and paste tailings disposal is becoming more widespread; past limitations were high costs and lack of suitable thickener technology (Commonwealth of Australia 2007). This type of storage has less application at larger operations where tailings ponds may serve a dual role of process and excess water storage as well as tailings storage. Dry stacked tailings disposal is most applicable in arid regions or in cold regions where water handling is difficult (Martin et al. 2002).

Mitigation measures for a TSF may include any combination of a liner, under-drains, and decant systems when there is expectation of seepage or the presence of groundwater, and prevention of the formation of low permeability lenses or layers on tailings beaches that could cause future seepage or stability concerns (Commonwealth of Australia 2007). Liners can include a high-density polyethylene (HDPE) or other type of geosynthetic material, a clay cover over an area of high hydraulic conductivity, or a combination. A properly constructed clay liner could be expected to have a saturated hydraulic conductivity of 10^{-8} m/s and a geomembrane to have a hydraulic conductivity of ~ 10^{-10} m/s; however, the lifetime of a geomembrane may vary widely, depending on a number of factors, including composition and site temperature. For example, Koerner et al. (2011) presents that a nonexposed HDPE liner could have a predicted lifetime ("as measured by its halflife") of 69 years at 40 °C to 446 years at 20 °C. Where geomembranes are used, a drainage layer atop the membrane is commonly included to reduce the water pressure on the liner and minimize leakage. Liners may cover the entire impoundment area, or only the pervious bedrock or porous soils. Full liners beneath TSFs are not always used; however, there is a growing requirement to use liners to minimize risks of groundwater contamination, with new mines in Australia being required to justify why one wouldn't be required (Commonwealth of Australia 2007). Under-drains serve a dual purpose of reducing water saturation of the tailings sediments to improve geotechnical strength and safety of the facility as well as for directing drainage toward a storage area for subsequent treatment. If seepage from the TSF is expected (or if observed during monitoring), mitigation or remedial measures include interception trenches and/or seepage recovery wells to be installed around the perimeter and downstream to capture the water for redirection to a treatment facility. A spillway diversion commonly is constructed to provide a catchment for precipitation runoff.

The flotation process used to produce metal sulfide concentrates from porphyry deposits results in two tailings waste streams: one from the rougher circuit (to remove gangue material comprising silicates and oxides) and one from the cleaner circuit (pyrite-rich). It is possible to use a technique called "selective flotation" to separate most of the pyrite into the cleaner circuit tailings (PAG) with the rougher tailings comprising mostly NAG. Traditionally, these tailings streams were combined, but they could be separated selectively, with the PAG being discharged deeper into the TSF and the NAG discharged and used as a cover for the PAG. Success is dependent upon the ore and the efficiency of a clean separation (Martin et al. 2002).

In leaching of gold ore, mitigation practices include not locating leaching operations in or near a water body, detoxification of materials prior to disposal or closure, and ensuring that the solution can be contained in the presence of increased flows, up to the maximum reasonable storm event (U.S. Environmental Protection Agency (U.S.EPA) 1995a). When tank leached, the tailings and spent solution are stored in the TSF. The conventional method for recovery of gold from ore typically involves tank leaching with dilute (100-500 ppm) sodium cyanide (Logsdon et al. 1999). Following leaching, either zinc metal or activated carbon is added to the solution to recover the gold. The residual solution either is treated in a water treatment plant or stored with the process tailings in the TSF pond. When stored in the TSF pond, the cyanide concentrations should be such that there would be no adverse effects to wildlife, such as birds landing on the pond. Although rates could depend on the climate and other site specifics, cyanide concentrations are known to decrease through natural attenuation, including volatilization and subsequent interactions with UV, biological oxidation, and precipitation (Logsdon et al. 1999).

Monitoring groundwater quality for contaminant transport includes piezometers for groundwater mounding assessment. Regular inspections/monitoring for TSF stability include evaluation of seepage discharges through the dams, foundations, abutments, and liners; phreatic surface in ponds and dams; pore pressures; horizontal and vertical movement; and the status of leak detection systems, secondary containment, auto flow measurement and fault alarms, condition of pump and pipelines. Azam and Li (Azam and Li 2010) point out the importance of monitoring pore water pressures and embankment deformation based on correlation with several types of failure, and provides a basis to rectify the situation before failure ensues.

2.1.2 Closure and Post-Closure

Closure requires the TSF to have either a continuous water cover or an engineered cover to prevent oxidation of tailings. Sufficient capital is required to finance inspections, maintenance, and repairs in post-closure for as long as the tailings exist.

Closure of a TSF includes containment/encapsulation, minimization of seepage, stabilization with a surface cover to prevent erosion and infiltration, diversions and collection of precipitation, and design of final landform to minimize post-closure maintenance (the final landform desired should be considered during the planning phase). There are a number of cover types and depths that can be chosen; the choice is site specific and depends on climate, type and volume of tailings, size and geometry of the TSF, available cover material, and the end-use for the property (e.g., (O'Kane and Wels 2003, Wilson et al. 2003). A conventional cover is typically a low hydraulic conductivity layer of clay (and/or a geosynthetic membrane) overlain with protective soil layers and generally 1.2 to 1.5 meters thick (O'Kane and Wels 2003). The soil layers minimize deterioration due to desiccation, frost action, erosion, animal burrowing, and infiltration of plant roots [(Caldwell and Reith 1993) as reported in (O'Kane and Wels 2003)]. Covers are not used for submerged tailings, and placing covers on tailings that have not been dewatered can cause future stability problems (http://www.idl.idaho.gov/Bureau/Minerals/bmp_manual1992/p16-ch4.pdf).

Diversions and spillway structures are constructed to minimize potential erosion of the cover from surface water. Traditionally, water in TSF ponds has been drained as completely as possible prior to closure to reduce potential for overtopping and erosion of the embankments; raising water levels in large dams could cause considerable long-term risk. However, water covers might be used when feasible to maintain a submerged condition, such as in regions where the hydrology is well-understood and the terrain is flat, such as has been used and encouraged in Canada (Martin et al. 2002).

Regardless of the type of reclamation used for closure, the reclaimed facility must be monitored and maintained to ensure stability over time. Post-closure monitoring for contaminant transport is the same as during the operational phase, with piezometers for assessment of ground water mounding and monitoring wells for groundwater quality. The reclaimed facility should be monitored for any deformations, structural changes, or weaknesses, and the surfaces should be inspected for intrusion by animals, humans, or vegetation, any of which could compromise long-term stability.

2.2 ACCIDENTS AND FAILURES

The main causes of physical failures of tailings storage facilities are related to 1) a lack of control on the water balance; 2) lack of control on construction; and 3) a general lack of understanding of the features that control safe operating conditions (International Commission on Large Dams (ICOLD) 2001). Additionally, the upstream method for dam construction was found to be more prone to failure as compared to those constructed via the downstream method most likely due to embankment material generally having a low relative density and high water saturation (U.S. EPA, 1994).

In order of prevalence, failure mechanisms observed for TSFs are slope instability, earthquakes, overtopping, inadequate foundations, seepage, and structural problems (Blight and Fourie 2003, Commonwealth of Australia 2007). Failure during operation could occur from any of the following: 1) rupture of delivery pipeline or decant water return pipeline; 2) rainfall induced erosion or piping of outer tailings face; 3) geotechnical failure or excessive deformation of containment dyke; 4) overfilling of the tailings storage facility leading to overtopping by water; 5) seepage through containment dyke; and/or 6) seepage into the foundation. In addition to the above (aside from deliver and return pipelines), failures post-closure could result from failure of the spillway (if present), or failure of the cover through internal or external forces, including weathering of materials, erosion, extreme weather events, or intrusion by vegetation or wildlife (Commonwealth of Australia 2007, Witt et al. 2004).

Earthquakes can cause liquefaction, which is a process in which a soil mass loses shear resistance through increased water pressure. Liquefaction in the absence of an earthquake is called static liquefaction. Static liquefaction can result from slope instability or another mechanism. As reported in Davies (Davies 2001), upstream constructed dams are "more susceptible to liquefaction flow events and are solely responsible for all major static liquefaction events"; the author also states that earthquakes are of little concern for non-upstream dams. Liquefaction of a large volume of tailings causes them to flow out of a breach as a viscous liquid which is capable of moving long distances before coming to rest. For example, 3 million cubic meters of tailings escaped at Bafokeng, South Africa, and travelled 42 km before the remaining 2 million cubic meters was stopped by flowing into a water retention dam (Blight and Fourie 2003). Conventional TSF materials can have very low shear strength and are susceptible to liquefaction. Therefore, earthquake-induced liquefaction is a key design consideration to minimize risks of failure resulting from an earthquake event (Martin et al. 2002). Earthquake risks also are reduced when tailings have a higher density or are dry tailings.

Overtopping is caused by excessive water inflow, such as through precipitation or rapid snowmelt, and is cited as being the primary failure mode for almost half of all reported incidents occurring at inactive dams (Davies 2001). Overtopping can result in erosion and breaching of the embankment to release tailings and contaminated water downstream. Internal erosion by water (called piping) is a slow process and related to seepage/infiltration causing internal water pressures to exceed the critical hydraulic gradient and result in a pathway through which particles are carried. Guidelines exist for TSF design to minimize this risk; however, Jantzer and Knutsson (Jantzer and Knutsson 2010) believe that, at least in Sweden, critical gradient guidelines are insufficient to yield long-term stability. Unstable materials experience particle migration at much lower hydraulic gradients than do more stable or compacted materials.

Structural failure could result in the release of large amounts of tailings solids and water; for example, a failure at Church Rock, New Mexico released 357,000 cubic meters of tailings water and ~990 tons of solids into an adjacent stream in 1979 (Witt et al. 2004). Closed facilities are more prone to failures caused by external erosion, primarily because of a lack of frequent monitoring, which occurs more easily when the site is occupied daily during active mining. Diversion ditches help prevent erosion by redirecting surface flow away from the TSF. Usually, failures result from a combination of factors, with climate, tailings properties, and geometry influencing which of these processes is likely to be the most prominent cause. Seepage-related failures are the main failure mode for tailings dams constructed using downstream or centerline methods (Davies 2001). Increases in seepage rates or turbidity can be key indicators of a developing failure situation (Alaska Department of Natural Resources (AK DNR) 2005). Thus, adequate planning, suitable design, and monitoring and control of operation and post closure may prevent deteriorative actions.

The failure rate of tailings dams depends directly on the engineering methods used in design and the monitoring and inspection programs in the other mine-life stages. According to Witt et al. (Witt et al. 2004), with an assumption of 3500 worldwide tailings dams and failure rates of 2-5 dams per year, the annual probability of a TSF failure is between 1 in 700 to 1 in 1750, in contrast to < 1 in 10,000 apparent for conventional water dams. Using data obtained from the World Information Service of Energy (WISE, www.wise-uranium.org/mdaf.html) for the 10 years prior to March 22, 2011, Chambers and Higman (Chambers and Higman 2011) report that the worldwide failure rate of tailings dams has remained at 1 failure every 8 months (i.e. two failures every 3 years). Azam and Li (Azam and Li 2010), using databases from the United Nations Environmental Protection (UNEP), the International Commission on Large Dams (ICOLD), the World Information Service of Energy (WISE), the United States Commission on Large Dams (USCOLD), and the United States Environmental Protection Agency (U.S. EPA), found that causes of observed failures occurring in the years of 2000-2009, regardless of country (e.g., North American, South American, European, Asian, African, and Australian), were unusual weather, management, seepage, instability, and defect, in order of decreasing percentage contribution. Weather causes were observed to have increased by 15% from pre-2000 failures and management issues by 20%. Azam and Li (Azam and Li 2010) report that failures in all but Europe and Asia have decreased since 2000; this is attributed to improved engineering practices, with none from 2000-2009 being due to subsidence of the foundation or to overtopping. Additionally, seismic liquefaction was not a causal mechanism in failures between 2000 and 2009, but accounted for 14% of failures prior to 2000. Data presented indicate that failures peaked to about 50 per decade in the 1960's through the 1980's and has dropped to about 20 per decade over the last 20 years, with the frequency of failure occurrences shifting to developing countries. The authors also estimate that, on average, one fifth of the stored tailings are released resulting from tailings dam failure. Dalpatram (Dalpatram 2011) presented a slide at a recent Workshop on Dam Break Analysis that indicated volumes released range from 20-40% of the stored tailings.

Reports of failures generally discuss physical failures causing a large release of tailings and/or water, but failure in design, construction, monitoring, and/or maintenance of the entire TSF system could result in slow release of contaminants into surface water or groundwater. Additionally, releases could result from compromise to the cover over PAG material or from inaccurate prediction of acid-generation potential for storage of PAG versus NAG tailings.

3. PIT

Following open-pit mining, a wide and deep hole remains that typically is filled in (or fills naturally) with water to form a pit lake. The source of environmental influence from pits and resultant lakes includes their size and the potential for acid-rock drainage (ARD) from dissolution of sulfidic minerals exposed on pit walls. Contaminated water may seep into groundwater, overflow into surface water, or adversely affect waterfowl landing in the formed pit lake. Additionally, the steep pit slopes generally remain after closure and continue to pose a risk to wildlife from falling into the pit and not being able to get out. Mitigation methods chosen will depend on site-specific considerations, as well as the future use envisioned for the pit (McCullough 2011).

3.1 CONVENTIONAL PRACTICES

3.1.1 Operational Phase

During the operational phase, pit walls are monitored closely for signs of weakness that might lead to a failure. Suggested means for reducing operational hazards from a slope failure in a pit include "1) safe geotechnical designs; 2) secondary supports or rock fall catchment systems; 3) monitoring devices for adequate advance warning of impending failures; and 4) proper and sufficient scaling of loose/dangerous material from highwalls" (Girard 2001). Typically, water is pumped or drained out of the pit to allow safe access as well as to expose material being mined.

3.1.2 Closure and Post-Closure

At closure, pits may be used as a repository for waste rock, followed by sealing of the area against air and water exposure, such as by an isolation cover, to minimize the potential for generation of acidity. Partial backfilling and regrading of upper levels with subsequent vegetation and/or creation of wetlands provides for passive water treatment. Most commonly, pits naturally fill with water over time, from groundwater, surface water, and precipitation inflows. Filling may be accelerated by pumping water from the TSF or other storage ponds both to minimize exposure of any PAG rock wall materials and PAG waste rock and/or tailings disposed into the pit at closure to oxygen, and to balance high pore water pressures to help prevent slope failures. Once the desired water level is achieved to retain the pit lake as a sink, water can be directed away from entering the pit through diversions that were used during the operational phase, or pit water can be pumped and treated prior to discharge to a surface water body.

Because the pit walls contain mineralized rock that has been exposed during the mining period, and during the period over which the pit lake forms, pit lake water can become acidic and/or contain metals and metalloids from natural geochemical processes. If acidity is anticipated from pit walls, mitigation measures to control for acid generation (e.g., sealing the rock against oxidation) and/or for ensuring that any such acidic or metal/metalloid-laden water would not migrate to surface or groundwater must be considered.

Water quality modeling can assist in identifying if a pit lake will become acidic and/or accumulate metals and metalloids. The three basic processes of importance and considered in modeling include the chemical loading by water sources flowing into the pit; loading from the rock walls, benches, and fractures behind the walls, and the geochemistry of the water during the time it has been in the pit (Morin and Hutt, 2001). Factors important in these processes include the time of exposure of a surface to both oxygen and water, and the surface area of reactive materials exposed. During mining, oxidized pit wall surfaces are washed with precipitation and that water is pumped out of the pit, but not all surfaces are reached by precipitation (e.g., fractures behind walls) and may have years of accumulation of oxidized minerals that will release acid and/or metals/metalloids into the pit lake once exposed to water. Although not the only issue, one inherent difficulty in prediction is that it is difficult to measure or estimate percentages of surface areas that are flushed regularly, intermittently, or never during the operational phase of mining for use in modeling anticipated pit water chemistry (Morin, 1994). Nonetheless, modeling is useful in planning for closure and post-closure of the pit.

If production of acidity and contaminant ions are anticipated, and exposed surfaces cannot be covered or sealed against oxidation, chemicals may be added to the pit lake to neutralize acidity and precipitate metals. Organic material and microorganisms may be added and conditions optimized for sulfate-reducing bacteria (SRB) to allow for formation of insoluble metal sulfides in the anaerobic regions of the lake. If pit water becomes contaminated, treatment of any water leaving the pit would be necessary to meet applicable water quality standards prior to any discharge.

Barriers, such as fences, berms, or other structures, are constructed to mitigate unauthorized access by humans and access by wildlife and should be monitored and maintained regularly for stability.

4. UNDERGROUND MINE WORKINGS

The sources of potential environmental influences from underground mining are similar to those for open pit mining, i.e., waste rock piles, tailings, dust, and wastewater. An additional source of potential impact to both groundwater and surface water is from acid rock drainage from tunnels and adits created during mining. Depending on many factors, including the depth of the underground mine to the surface and the strength of the overburden rock, mine workings have the potential to subside and may create a depression in the landscape and alterations in surface and ground water flows.

4.1 CONVENTIONAL PRACTICES

The mitigation measures to prevent potential significant environmental impacts from wastes originating from underground mining are similar to those for open pit mining. In addition, waste rock and or tailings may be disposed in mined out tunnels, which may assist in minimizing impacts from subsidence. Additionally, void-filling grout may be used to mitigate subsidence. In regions where there is potential for ground water interaction with mine workings, cracks may be sealed with grouting or other material. Additionally, groundwater flow paths may be intercepted (such as by grouting of faults and sheer zones, or by a grout curtain) and thus redirected to avoid the mined out area, minimizing contact of the water with potentially acid-generating rock surfaces (e.g., (Wireman and Stover 2011)). In some cases, the mine workings are flooded, which, if done prior to oxidation occurring on PAG surfaces and kept anaerobic, will minimize the formation of acidic drainage.

5.0 DUST

Mining activities can generate dust during multiple stages in the operational phase, including those generated during construction of roads, trucking of materials, and heavy equipment exhaust. Fugitive dusts are diffuse and generated through wind erosion of large areas, including waste rock piles, tailings, the pit, and other disturbed areas. Other dusts originate at locations where processes are occurring, such as blasting, crushing, grinding, and milling. Dusts containing metals from mining activity pose human health concerns through inhalation. The particles are carried by the wind and may cause environmental concerns through sedimentation in water bodies and/or by being transported further downstream.

5.1 CONVENTIONAL PRACTICES

Mitigation of dust from processing points within mining operations can include collection by dry collectors, wet scrubbers, enclosures at the source, and/or wetting of surfaces (Commonwealth of Australia 1998). A cover on a truck bed can minimize dusts originating from materials being hauled. Wetting of surfaces is most useful for active blasting, haul roads, and material movement and placement activities, and may involve the use of water or water mixed with a chemical dust suppressant. Typically, dust from waste rock piles is controlled by wetting during the operational phase. During closure, waste rock piles are covered and vegetated; this can be done as piles are completed during the operational phase to minimize potential for dust production. Although wet slurry tailings do not pose a dust issue, dust from large dry beaches of tailings facilities is a concern, and wetting or using special products to stabilize the surfaces is used for temporary wind erosion and dust control. Tailings beaches are covered with gravel (or other material) and may be vegetated during closure.

6. STORM AND WASTEWATER

Storm and wastewater have the potential to contain suspended sediment and particulate and dissolved contaminants that could contaminant water bodies if they were to leave the site untreated. The main environmental influences originate from seepage of contaminants into groundwater, leakage through barriers (e.g., tailings embankment), and flooding or washout into nearby surface water bodies.

6.1 CONVENTIONAL PRACTICES

Mitigation of stormwater begins with designing components using an accurate site water balance to assure adequate storage and treatment capacity. Conventionally, runoff and seepage are diverted through ditches and diversion channels to a treatment pond, or to a settling pond if the water source is solely from precipitation. Water from settling ponds can be decanted and discharged (if it meets required water quality criteria), or used in the mining process if of sufficient quality. Spillway diversions commonly are constructed around waste rock and tailings facilities to provide catchments for precipitation runoff. Excess water in tailings ponds is controlled through removal and treatment for use in the mining processes or discharge to the surface water. Traditionally, water in TSF ponds is drained as completely as possible prior to closure to minimize potential for overtopping due to precipitation. For TSF ponds containing sub-aqueously disposed PAG tailings, sufficient water would remain in the pond post-closure to ensure they remain isolated from oxygen.

Stormwater from undisturbed areas may require treatment only for sediment, which is accomplished through simple settling in a sedimentation pond. Stormwater from disturbed areas and mining wastewater is treated via either active or passive methods prior to being used in the mining process or released into a water body. Active treatment of wastewater generally involves a chemical addition (e.g., lime, alum, iron oxides) to precipitate and/or adsorb metals and metalloids followed by dewatering of the precipitated solid and disposal; and/or a physical process (e.g., reverse osmosis, filtration, microfiltration). Operating mines generally have high volumes of water needing treatment prior to discharge to a surface water body and thus rely on active treatment methods. Active treatments also include microbial methods, such as the use of contained bioreactors, but these generally require lower flows and are options for post-closure or co-treatment during operations. Passive treatments are those that capitalize on natural processes and do not require constant reagent addition for operation. Wetlands are an example of a commonly used passive treatment system for water contaminants, as are anaerobic biochemical reactors (also called sulfate-reducing bioreactors). Passive treatment options are most commonly used post-closure, although they can be used during the operational phase for other purposes. For example, a biochemical reactor could be used to treat contaminants present in brine from reverse osmosis treatment. Passive treatment technologies generally require large land areas and low flows to allow sufficient time for biological processes to convert them to non-toxic forms. Additional passive and active treatment options for potential use post-closure can be found in U.S. EPA (2006).

7. CHEMICALS

Chemicals used at mining sites have the potential to enter into the environment through accidental spills during transport, storage, and/or use, or from excess usage in processes to recover metals being mined (e.g., during flotation/frothing, cyanidation, or smelting).

7.1 CONVENTIONAL PRACTICES

Conventional practices include having a chemical hygiene plan and training of all personnel in the proper handling of chemicals, including how to deal with cleanup of spills, provision of spill kits and personal protective equipment, and availability of MSDS for consultation (e.g., see (Logsdon et al. 1999)). Secondary containment (dikes or collection basins) must be used and incompatible chemicals must be isolated from one another during storage and use. Storage containers are commonly equipped with indicators and instrumentation to monitor levels in tanks to ensure that a spill does not occur, or that any spill/leak is captures quickly when it begins.

8. PIPELINES

A slurry-concentrate pipeline break or spill has potential to affect aquatic life adversely, if into a nearby stream. Additionally, placement of pipelines results in land disturbance and can cause soil/sediment to enter streams through runoff.

8.1 CONVENTIONAL PRACTICES

Pipelines that might be necessary for mining operations include those for transport of slurry, return water, and fuel for the mining site. Standard practices for construction, operation, and monitoring of slurry pipelines are available from the American Society of Mechanical Engineers (American Society of Mechanical Engineers (ASME) 2003).

Mitigation measures for pipelines include using the proper pipe material, protection against leaks, breaks, and corrosion, containment drains or sumps along the corridor, and secondary containment of the pipeline where crossing a river or transportation route. Protection includes increased wall thickness, corrosion inhibitors, and internal linings or coatings. Joints, welds, valves, etc. are designed to accommodate expected stress, as based on flows desired for the pipeline. Pipelines may be equipped with monitoring systems to detect flow, temperature, or pressure changes, along with alarms and automatic shutoffs. Pipelines are stress-tested for leaks and weaknesses prior to being placed into operation; and they require routine inspections over the course of their use. Mitigation of construction impacts, such as soil erosion and turbid storm water runoff caused by pipe installation (e.g., excavation and boring), can include silt fences, ditches, or other temporary diversions. Pipelines that are constructed near water bodies require containment and may or may not be placed above ground on bridge structures.

9. NON-MINING MATERIAL AND DOMESTIC WASTE

Mining operations produce a number of wastes in addition to waste mineral materials. Additionally, there is domestic waste produced from persons employed. These wastes have the potential to attract wildlife (food wastes), or to contaminate water bodies (e.g., sewage waste) and thus must be managed.

9.1 NON-MINING MATERIAL AND DOMESTIC WASTE

At remote mining sites, non-hazardous wastes generally are managed on site. Non-hazardous solid wastes typically would be disposed in engineered solid waste landfills that meet regulatory requirements. For some types of wastes, and in some locations, incineration may be an acceptable alternative. Recycling of segregated wastes such as paper and plastic may be preferable, but high transportation costs could make this option economically unattractive.

Sanitary waste often is treated via a decentralized system (e.g., septic tank) or in a packaged sewage treatment plant, with the effluent discharged after verification that it meets the permitted discharge standards. Sewage sludge may be land-farmed, hauled to a licensed treatment facility, or land filled on site depending on local requirements.

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