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BEFORE THE WATER QUALITY CONTROL COMMISSION

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PROPOSED AMENDMENT TO 20.6.2 NMAC (Copper Rule)	)	**No. WQCC 12-01(R)**

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Physical Aspects of Waste Storage From a Hypothetical Open Pit Porphyry Copper Operation

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U.S. Department of the Interior

U.S. Geological Survey

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Introduction

Copper porphyry deposits are most often mined as open pit operations. The deposits' relatively low ore grade and high-tonnage production generate significant amounts of solid waste compared with the units of copper recovered. Approximately 98 percent of the material extracted from the mine reports to waste storage. These wastes can be subdivided into three major categories—leach rock, mill tailings, and waste rock. This report describes the physical attributes that compose the "footprint" (the space occupied) generated by a model open pit copper porphyry mining and milling operation. This model represents only one possible scenario for accommodating waste from an open pit copper mine. Other options include waste and tailings storage that uses different geometry and design, placing waste back into the pit (backfilling) following the mine's production life, or using waste material as an aggregate (road base or concrete). Selection of engineering and other criteria presented in this study is based on accepted industry standards. A base model is provided in the main text. In Appendix A, figures and tables are provided with a range of values for various engineering parameters.

Mine Model

The analyses are based on the extraction of copper ore from a porphyry deposit by an open pit mine operator. The data were analyzed by using numerous criteria that affect the generation of mine waste and mill tailings. Several parameters with respect to the hypothetical open pit mining operation that affect mine and mill waste generation were selected (table 1).

They include waste-to-ore ratios, mine ore reserves, ore dilution,[1] ore grade, ore recovery, specific gravity of in situ rock, and percentage of expansion (percent swell) of the broken rock. Some of these criteria were projected over a range of values to reflect the impact on hypothetical waste generation for a typical open pit porphyry copper mine (figure 1).

Table 1. Mine criteria—Base model.
[Mt, million metric tons; %, percent; t/m^3, metric ton per cubic meter]

Rock type = Granite porphyry
Mine type = Open pit
Total in situ reserve (Mt) = 210
Total ore production (Mt) = 200
Waste to ore ratio = 2:1
Coppe ore in situ grade (%) = 0.75
Ore dilution (%) = 1.07
Diluted ore grade (%) = 0.70
Primary ore mineral = Chalcopyrite
Mine ore recovery (%) = 95
In situ rock specific gravity (t/m^3) = 2.24
Blasted rock specific gravity (t/m^3) = 1.82

Figure 1. Phelps Dodge Mining Company's Sierrita open pit copper mine in Sierrita, Arizona. (Arizona State Mine Inspector's Office, 202)

[1] Dilution is the contamination of ore with barren (zero-grade) wall rock.

Mine Waste

Mine Waste Rock Production

Waste rock derived from copper porphyry operations is removed during development and production as a means to gain access to ore. Waste rock is generally coarse material but includes a wide range of sizes from very large boulders that weigh several metric tons to dust-sized particles. The size and shape of the material depends on the characteristics of the rock, extraction methods (ripping, drilling, and blasting), loading equipment (front-end loaders and mechanized shovels), and transport method, which includes mostly trucks, as shown in figure 2, as well as conveyor belts or rail cars. Generally, waste rock contains residual levels of copper and its coproducts or byproducts, if any, that are not economically recoverable during the time of extraction. Copper is recovered by circulating acid through the low-grade waste rock; the waste rock storage site may require additional design engineering that is not addressed in this study. The amount of waste rock generated at the mine depends largely on the shape of the ore body, the mining plan, and the total ore and waste production during the mine's life. For this estimate, the total amount of waste generated during mining was assumed to have been placed in waste storage. The hypothetical waste storage site is based on engineering standards that are used in actual mining operations.

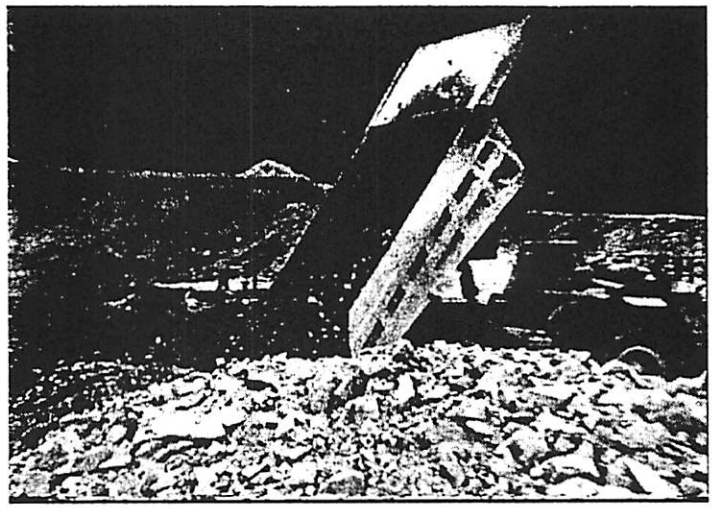


Figure 2. Truck depositing mine waste from an open pit copper mine in Papua New Guinea (Forderkreis >> Rettet die Elbe < < eV, 2001).

Mine Waste Storage Engineering Criteria

Numerous criteria must be considered when estimating the amount of mine waste generated and waste storage site geometry—the amount of development tonnage (preproduction stripping), variations in the waste-to-ore ratio, production and mine life, and waste rock volume and compaction, which is determined by the size distribution of the waste; the angle of repose, or slope angle; and the moisture content (table 2). The diversion of a portion of the waste rock for uses at the mine facilities for embankments, fill construction, impoundments, and road base and off-site sales for such uses as aggregate for concrete, rail ballast, and road base would reduce the waste storage requirements. The use of waste rock to fill open pit mines also as part of a reclamation plan is not included. Local climate and geologic characteristics, which include seismicity of the site, are also design criteria. Federal, State, and local regulations; responses to concerns by the public (social perceptions can be critical to the design and placement of the mill waste tailings because of the belief that tailings impoundments are inherently unsafe); and non-

Government organizations and others can also have a major impact on the intial and ultimate design of the waste rock storage facility (Verburg, 2002, p. 15). These are not specifically addressed in the

Table 2. Mine waste dump criteria—Base model.
[Mt, million metric tons; t/m³, metric tons per cubic meter;
%, percent; m, meter; ha, hectare; 106 m3, million cubic meters]

Rock type = Granite porphyry (copper ore)
Total waste tonnage (Mt) = 400
In-situ rock specific gravity or density (t/m3) = 2.24
Blasted rock specific gravity or density (t/m3) = 1.84
Swell factor = 0.74 (35% expansion)
Compaction factor (%) = 1.11 (10% reduction factor)
Geology of dump site = Acceptable
Dump site topography = Flat
Active dump angle of repose (degrees) = 34 (1.5:1)
Remediated dump angle of repose (degrees) = 27 (2:1)
Height (m) = 100
Total unremediated basal area (ha) = 252
Total volume (106 m3) = 212
Total weight (Mt) = 400
Total remediated basal area (ha) = 267

analyses. The material characteristics and engineering criteria that formed the basis for developing the models are discussed on the following pages, listed in the tables, and discussed in Appendix A.

Topography

Topography can greatly influence waste storage. Waste can be disposed of on many types of areas—from nearly flat topography to valley or canyon deposition. Filling in a topgraphic low can provide side support that allows greater efficiency (and lower cost) in waste

storage and allows higher and steeper slope angles. In some situations, excavated portions of the open pit can be backfilled with waste rock, thus reducing the area needed for waste storage. Because topography is a site-specific crtieria, an area of flat topography was selected to model. Hydrology (primarily runoff and flood control) as influenced by topography must also be considered.

Geology

Siting of a waste rock storage site must be evaluated for geologic considerations. Criteria that relate to the competency of the foundation (underlying support) include depth, permeability, shear strength, strength, thickness, and type of rock. No special conditions are considered in this evaluation.

Mine Waste Rock Characteristics

Although waste rock is generally coarse material, it includes a wide range of sizes from very large boulders that weigh several metric tons to dust (figure 2). The size and shape of the material depends on the chemical and physical characteristics of the ore and waste rock, extraction methods, loading equipment, and transport. The size distribution, the amount of the material, and the composition of the material determine, to a great extent, the volume occupied by the waste rock.

Swell and Compaction Factors

When waste rock is excavated, its volume expands because the spaces between the fragments increase. This expansion, which is called the percent swell, is measured as a percentage increase above the undisturbed in situ volume. The swell factor is the undisturbed in

situ volume of the rock divided by the expanded volume of the blasted rock. For this analysis, a swell factor of 35 percent, which is a widely accepted average for waste derived from a blasted open pit copper mine in the mining industry, was selected. Loose material will compact to some degree after placement on the dump. Compaction results from mechanical compaction by equipment, decomposition, and natural compaction over time. The degree of compaction depends on the disposal method, elapsed time, the height of the dump, the moisture content, the size distribution, and the type of material. The compaction factor is the expanded volume of the rock divided by the compacted volume of the rock. Common total compaction estimates range from 5 to 15 percent. For this study, 10 percent was selected.

Specific Gravity (Density)

For this analysis, an in situ specific gravity of 2.24 metric tons per cubic meter (t/m^3) for the waste rock was selected on the basis of the mineralogical components that compose most altered granitic porphyries. Following blasting, swelling, and compaction, the material was estimated to have a specific gravity of 1.84 t/m^3.

Active Dump Angle of Repose

The stability of the slope of the waste storage facility is critical to determining the area of the site. The high shear strength (the maximum stress that a material can withstand before failure in shear) of dry waste rock contributes to high bearing stability and a high angle of repose that ranges from 34 degrees (°) to 37 ° (figure 3A). A conservative angle of repose of 34 ° (a run to rise of 1.5 horizontal to 1 vertical) was selected for the hypothetical model. The remediated angle of repose used in this study is 27 ° (a run to rise of 2 horizontal to 1 vertical). The lower angle of repose is attained by using earth-moving equipment to push material down along the

margins of the waste dump, which results in essentially no change in overall height (figure 3B). Keeping the height constant, the material removed from the margins at the top of the waste dump to lower the slope angle will result in a decrease in the area of the top and an increase in the basal area of the site. The lower angle generally ensures long-term stability, minimizes erosion, and provides surfaces suitable for revegetation for use as wildlife habitat and other purposes.

Height

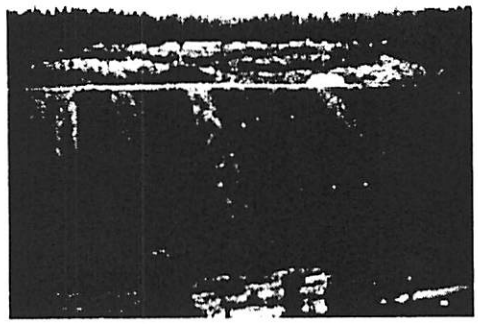
For the base model, a final height of 100 meters (m) for the mine waste storage facility was selected. Some waste rock storage sites can signifcantly exceed this height, but they are usually favored by topography.

Geometry

A frustum, or truncated cone, at selected radii was used to model the shape of the mine waste pile. The use of a frustum for model development is an acceptable engineering method (figure 3C).

Mine Waste Rock Storage Facility—Shape, Basal Area, Volume, and Weight

The preceding engineering criteria, as incorporated into the base model, were used to determine the basal area, the top area, and the volume of the unremediated and remediated mine waste rock site. On the basis of those factors, the basal area for the unremediated storage site was calculated to be 252 hectares (ha) at a volume of 212 million cubic meters (10^6 m^3). The remediated storage site would have a larger basal area because of the reduction in slope angle to provide greater long-term slope stability at the site. The basal area would be approximately 264



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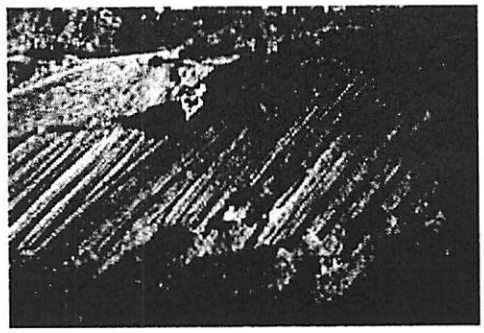

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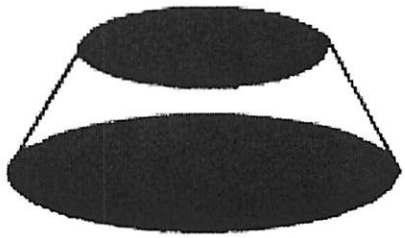

C.

Figure 3. Waste dumps. A, Mine waste dump; B, mine waste dump in process of remediation; C, frustum, or truncated cone (Mining Association of British Columbia, undated).

ha, and the volume and the maximum height would be essentially the same because only material along the margins of the waste dump is used to lower the angle of repose. The dry weight of the material would be approximately 400 million metric tons (Mt). The detailed calculations are in Appendix A.

Mill Tailings

Mill tailings from the treatment of copper ores are the solid (suspended in liquid that consists mostly of water) residue of the milling or beneficiation process. During this process, ores are first crushed and finely ground and then treated in flotation cells with chemicals to recover copper concentrates. Mill tailings, which consist predominantly of fine particles that are rejected from the flotation process, are generally uniform in character and size and consist of mostly hard angular siliceous particles with a high percentage of fines. Tailings can also contain variable amounts of sulfide minerals, such as pyrite. Mill tailings are usually sent to the tailings impoundment area as a slurry, which contains about 50 percent solids, through a pipleline. Water is either recovered, especially in arid areas, and returned to the mill for ore processing or treated and released to the environment. The design of a mill tailings storage site is dependent on many of the same factors as mine waste storage site.

Mill Tailings Disposal Storage Criteria

Disposal of mill tailings on the surface, especially those that contain sulfide minerals, must be designed to minimize interaction with the environment through dust generation, leakage of fluids, which can be acidic and contain dissolved metals and other harmful or potentially harmful constituents; and from failure of the containment structure. The embankment, stored residues, and ancillary structures at the tailings impoundment must retain their integrity as long as possible because the impoundment will need to function for many years after mining operations cease. Disposal of mill tailings depends on tailings and site-specific characteristics. Those methods include placement of dry or thickened tailings in impoundments or freestanding piles, backfilling underground mines or open pits, and subaqueous disposal. The most common

method and the one selected for this evaluation is disposal of tailings as slurry in an impoundment area. Impounded mill tailings are generally stored behind restraining dams to form a retention area, which permits containment of the tails and recovery of excess water; this is especially important in arid areas. Most types of impoundment dams are built sequentially. An upstream tailings dam, which is the most common type of tailings retention dam, was selected for this study (figures 4, 5).

The construction of an upstream tailings dam requires that new parts of the embankment be built on top of the tailings impounded during the previous stage. Embankment material, which consists of the coarser material, forms a beach as it drops out of the tailings slurry shortly after it enters the impoundment by means of spigots. Coarse material is deposited on top on the upstream side of the active dam and is used to construct the subsequent dam with the use of light equipment. Less coarse material is carried further in the slurry and is deposited on the distal portion of the beach. Fine material forms a low density mass as it settles in the pond (United Nations Environmental Program, 1996). This method causes the dam crest to move "upstream" as a series of overlapping deltas. Numerous design criteria for mill tailings storage must be considered; for example, the amount of mill feed over the life of the operation, recovery of commodities, grain size and size distribution of material, concentrate grade, angle of repose, moisture content and permeability, topography, and area available for disposal. Except for use in the construction of the dikes that compose the tailings dams, any diversion of tailings for use on site or from sales are not included in the calclations for the weight and size dimensions of the modeled tailings storage site.

As with waste rock, local climate, environmental considerations, geologic characteristics (which include seismicity), and hydrologic characteristics also contribute to its design. Federal, State, and local regulations and responses to concerns by the public, non-Government

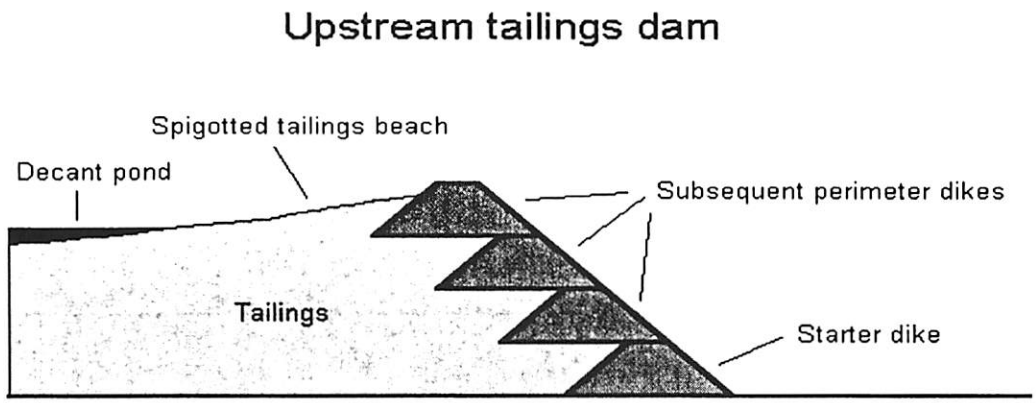

Figure 4. Upstream-type tailings dam, which is the most popular type of embankment for tailings dams. New parts of the embankment are built on top of the tailings impounded during the previous stage. This method causes the dam crest to "move upstream" (World Information Service on Energy, 2002).

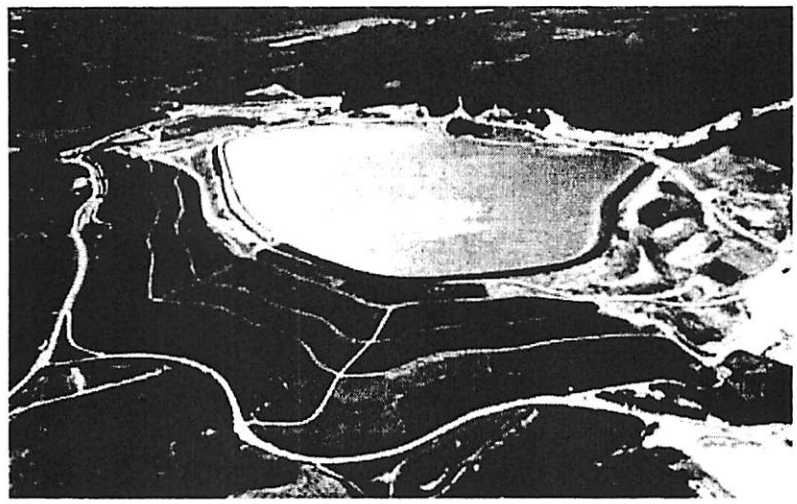

Figure 5. Tailings storage facility at the Martha Mine near Waihi, New Zealand, nearing its final height. This aerial photograph, which was taken in early 2000, shows the embankment structure. The lower slopes have been rehabilitated. The impoundment where tailings are deposited as a slurry can be clearly seen as can the light-colored tailings beach at the far left end of the pond (Waihi Gold Mining Company Limited, undated).

organizations, and others can also have a major effect on the initial and ultimate design of the waste rock storage facility. The generalized model does not address all these criteria. The selection criteria used in developing the base model and variations in its design are discussed in the following section and are listed in table 3. Effects of the selection of different values, such as mill recovery, on the production of tailings are provided in the Appendix.

Table 3. Tailings impoundment calculation criteria—
Base model.[%, percent; Mt, million metric tons; t, metric ton; t/m^3, metric ton per cubic meter; m, meter; ha, hectare; 10^6 m^3, million cubic meters]

Ore feed grade (%) = 0.7
Mill feed tonnage (Mt) = 200
Mill recovery (%) = 88
Concentrate grade (% Cu) = 30
Moisture content (%) = 15
Tailings/ton ore (t) = 0.979
Tailings specific gravity or density:
Dry (t/m^3) = 1.16
Wet (t/m^3) = 1.36
Topography = Flat
Geology of tailing impoundment site = Acceptable
Tailings dam slope (degrees) = 22 (2.5:1)
Height (m) = 50
Total basal area (ha) = 376
Total top area (ha) = 296
Total dry and wet volume (10^6 m^3) = 169
Total dry weight (Mt) = 196
Total weight at 15% moisture (Mt) = 231

Topography

Topography can greatly influence tailings waste storage. Like mine waste, tailings disposal on land can take place on areas that range from nearly flat topography to valley or canyon. Filling a topgraphic low can provide side support, which allows greater efficiency in

waste storage, primarily in the form of higher and steeper slope angles. Hydrology (primarily runoff and flood control) as influenced by topography must also be considered. Because topography is a site-specific crtieria, an area of flat topography was selected.

Geology

As in designing the mine waste storage site, the mill tailings impoundment site needs to be evaluated for geologic considerations. Criteria that relate to the determination of the competency of the foundation (underlying support) include depth, ground-water conditions, permeability, shear strength, strength, thickness, and type of rock. Frequency, probability, and severity of seismic events must also be evaluated. No special conditions were considered in this evaluation.

Mill Recovery and Copper Concentrate Grade

Mill recovery of copper from typical copper ores ranges from 80 to 90 percent. The model assumes a copper ore feed grade of 0.7 percent and a mill recovery of 88 percent of the copper contained in the ore following crushing, grinding, and the flotation process. The mill concentrate, which consists mostly of chalcopyrite, has a copper grade of 30 percent. Therefore, the vast majority of material entering the mill (approximately 98 percent) reports to the tailings impoundment as a fine slurry that comprises about 50 percent solids. Water is almost always recovered and is eventually recycled for use in the beneficiation plant, especially in arid regions. The tailings contain all constituents of the original ore except for the extracted minerals and the addition of water and some chemicals used in the separation process.

Particle Size and Distribution

Typically, mill tailing particles from the flotation process range in size from sand to clay [40-90 percent passing a 0.075-millimeter (mm) (No. 200) sieve] depending on the degree of processing needed to recover the desired mineral(s) (U.S. Federal Highway Administration, 2002). In general, the lower the concentration of mineralization in the parent rock, the greater the amount of processing needed and the finer the particle size of the resultant tailings. Some ores, such as iron ore, are found in relatively high percentages and are fairly easy to separate. The resultant tailings are coarser than those from other ores, such as copper, which is found in very low percentages in the host rock and requires very fine grinding for separation. Copper tailings are usually quite fine grained with a large percentage passing through a 0.075-mm (No. 200) sieve (North Carolina Division of Pollution Prevention and Environmental Assistance, 2003).

Volume and Specific Gravity

The density per metric ton of tailings depends primarily on the size and shape of the grains and the mass of the materials. The determining factors are based on the physical and mineralogical (chemical) characteristics of the material processed and the method of processing. The moisture content does not significantly effect the final volume of placed tailings because over time, moisture is often reduced to 10 to 20 percent and occupies the interstices between the solid particles. Moisture is lost to tailings through collection for process water, compaction, and evaporation. One cubic meter of mill tailings weighs approximately 1.16 metric tons dry (Mt dry) and 1.36 metric tons wet (at 15 percent moisture). Each metric ton of tailings, dry or wet (15 percent), occupies 0.85 cubic meter. Total volume of tailings, dry or wet (15 percent), occupies 169 10^6 m^3 and weighs 196 Mt dry or 231 Mt at 15 percent moisture.

Height and Angle of Repose

An ultimate height of 50 m was selected for the frustum-shaped upstream tailings embankment model. Actual heights vary depending on the nature and amount of tailings and site-specific criteria. Upstream tailings dams can be thick, approaching heights of 125 m. The tailings impoundment at the Sierrita copper mine in Arizona is a rare exception. The height of the tailings impoundment exceeds 300 m in height (Arizona State Mine Inspector, 2002). The angle of repose of the tailings impoundment used in the model was 22 ° or a run to rise of 2.5:1.

Geometry

The geometry of a tailings impoundment facility is dependent on such numerous factors as topography, moisture content, climate, geology, seimicity, the type of dam selected, and regulations. A flat depositional surface was selected for the base model, and the shape was assumed to be a frustum at selected radii at the base (1,094 m) and top (970 m). Using a frustum for model development is an acceptable engineering method (figures 3C, 5).

Tailings Impoundment Facility-Basal Area, Volume, and Weight

Most of the preceding engineering criteria defined in the base model were used to determine the mill tailings impoundment basal area, volume, and weight. On the basis of those factors, the basal area for the site was calculated to be approximately 376 ha with a volume of about 169 10^6 m^3 and a weight, which includes moisture, of approximately 231 Mt. Please see the Appendix for detailed calculations.

Conclusions

Most porphyry copper deposits are relatively low grade. They are generally mined by using high-tonnage open pit methods. Through the course of mining and processing ore and removing waste, large amounts of material with little or no market value must be placed, perhaps in perpetuity, by responsible miners in physically competent and environmentally sound storage sites. The physical aspects that establish the "footprint" generated by this material are determined by on-site engineering and environmental criteria that include climate; hydrology; geology; seismicity; topography; Federal, State, and local regulations; and social acceptance. Physical criteria that affect the volume of material generated include mine production and waste-to-ore ratio, rock type and specific gravity of ore and waste, swell factor, and the method and effectiveness of ore beneficiation.

Parameters, such as rock type, in situ density, and swell factor, were assumed on the basis of typical values for the type of material to be mined and industry practices. Total ore production of 200 Mt and a stripping ratio of 2 t of waste generated per metric ton of ore mined were selected as the base case. A range of values for total ore production from 100 million tons (Mt) to 1 billion metric tons (Gt) and stripping ratios from 0.5 to 1 to 3 to 1 were also investigated. By using a frustum for the shape of the waste storage facility, the aerial extent for waste disposal assumed an angle of repose of 34° (1.5 run to 1 rise) for active waste dumps and 27° (2 run to 1 rise) for remediated waste dumps. The lower slope for the remediated waste allows for a greater degree of stability in the long term. The height of the waste dump has great impact on the area occupied by mine waste. On the basis of the factors selected for the base model, the basal area for the unremediated storage site was calculated to be 252 ha at a volume of 212 10^6 m^3 and a height of 100 m. The remediated storage site would have a larger basal area because of the reduction in slope angle to provide greater long-term slope stability of the site.

The basal area would be approximately 267 ha, and the volume and height would be essentially the same as before remediation. The dry weight of the material would be approximately 400 Mt.

An upstream tailings impoundment, also in the shape of a frustum, was used to estimate the aerial extent and volume of mill tailings. By using a slope angle of 22 ° (2.5 run to 1 rise) and other selected engineering criteria defined in the base model, the hypothetical site was calculated to be approximately 376 ha at a volume of about 169 10^6 m^3 and a height of 50 m.

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