# Estimated Water Requirements for the Conventional Flotation of Copper Ores

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Front cover: A photograph of the tailings storage facility for the Sierrita copper porphyry mine in Arizona. The facility is about 4.5 kilometers across at its widest point. Photograph courtesy of Freeport-McMoRan Copper & Gold Inc.

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# Conversion Factors

SI to Inch/Pound

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| kilometer (km) | 0.6214 | mile (mi) |
| | Volume | |
| liter (L) | 0.2642 | gallon (gal) |
| cubic meter ($m^3$) | 264.2 | gallon (gal) |
| | Mass | |
| metric ton | 1.102 | ton, short (2,000 lb) |
| metric ton per day | 1.102 | ton per day (t/d) |

# Estimated Water Requirements for the Conventional Flotation of Copper Ores

By Donald I. Bleiwas

## Introduction

This report provides a perspective on the amount of water used by a conventional copper flotation plant, including the makeup water required to compensate for water losses. Much of the global supply of copper originates from mines that also produce byproduct molybdenum, but for simplicity, a single copper concentrate has been modeled for this study. In 2011, approximately 13 million metric tons (Mt), or about 80 percent of the world's primary copper supply, originated from concentrate produced by flotation (International Copper Study Group, 2012). In 2011, about 60 percent of primary copper produced in the United States originated from flotation (Daniel E. Edelstein, Copper Commodity Specialist, U.S. Geological Survey, written commun., March 20, 2012).

Copper sulfide ores must be concentrated before they can be economically transported to a smelter. Froth flotation is part of a copper beneficiation process in which finely ground ore is placed in aerated tanks that contain a water-based solution from which a copper-sulfide-rich froth is recovered through the use of a combination of physical and chemical interactions. The remaining non-ore minerals (tailings) are disposed of (Herbst and Pate, 1999; Rosenqvist, 2004). Flotation circuits are custom designed to accommodate the chemical and physical nature of the ore, the climate where the plant is located, and the intended production capacity; nonetheless, the great majority of circuits have common methods of processing the ore, which include (1) ore-size reduction; (2) the use of a water-based solution with recirculation; (3) the production of one or more concentrates; and (4) the production of tailings. The tailings is the finely ground waste product (which generally represents more than 98 percent of the original copper ore) suspended in a water-based slurry that is emplaced in a tailings storage facility (TSF).

Water is required for many activities at a mine-mill site, including ore production and beneficiation, dust and fire suppression, drinking and sanitation, and minesite reclamation. Assessing the availability of a sufficient and reliable supply of water for an operation to function effectively is essential, especially in areas where water may be difficult or expensive to acquire because of an unfavorable climate [arid and (or) high evaporation rate]; competition with other end uses, such as by agriculture, industry, or municipalities; and (or) compliance with regulatory requirements.

The availability of water is a long-term concern for most mine planners, especially for most low-grade copper mines that usually have a lifespan that exceeds two decades. The water required to operate a flotation plant may outweigh all of the other uses of water at a mine site, and the need to maintain a water balance is critical for the plant to operate efficiently. Process water may be irretrievably lost or not immediately available for reuse in the beneficiation plant because it has been used in the production of backfill slurry from tailings to provide underground mine support; because it has been entrapped in the tailings, evaporated from the TSF, or leaked from pipes and (or) the TSF; and because it has been retained as moisture in the concentrate. Water retained in the interstices of the tailings and the evaporation of water from the surface of the TSF are the two most significant contributors to water loss at a conventional flotation circuit facility.

When the amount of water reclaimed from the TSF is insufficient to meet the plant's requirements, the lost water must be replaced from sources of "fresh water," which include lakes, reservoirs, rivers, and wells; precipitation and runoff collected in the TSF may also be sources of makeup water. The amount of makeup water needed can be very significant, especially in arid regions where the availability of water is problematic. The need to conserve water, especially in arid regions and areas where there is competition for limited water resources, motivates plant managers to minimize water use whenever possible.

## General Description of Ore Processing in a Conventional Copper Flotation Plant

Figure 1 is a generalized diagram of a conventional copper flotation plant from the point where ore first enters the circuit to the production of concentrate and tailings. To prepare ore for the flotation process, run-of-mine ore, which may contain from about 2 to 5 percent water, by weight, when mined, is delivered to the crusher(s) to be reduced in size. At this stage, much of the moisture with the ore may be lost to evaporation and drainage because of climatic conditions, residence time in stockpiles, and the heat generated in the crusher. At most operations, water is sprayed into a crusher and onto conveyor belts to suppress dust in the plant, but this usage represents only a small fraction of the plant's total water usage. The crushed ore is transferred to a semiautogenous (SAG) mill or ball mill where the ore is further reduced in size. Water is added to the ball mill, in which a slurry that usually contains from about 20 to 55 percent solids is produced (Singh, 2010; International Mining, 2011) (see fig. 2). The mill operates in a closed circuit with screens that size the ore and cyclones that sort the ore by size and density. The underflow from the cyclones is sent back to the mill to be reduced further in size, generally from 75 to 200 microns, with further regrinding in some cases to improve the liberation of desirable components of the ore from unwanted waste (Huss, 2009; International Mining, 2011; Cameron Wolf, Senior Process Engineer, Tetra Tech MMI, written commun., March 21, 2012). The overflow (in the form of water-based slurry) is transported to the flotation circuit where the copper sulfide ore minerals are concentrated and separated from the nonmineralized material by a series of rougher (see fig. 3) and cleaner flotation cells, which produce successively higher grade concentrates. This flotation slurry, also referred to as pulp, contains from 25 to 40 percent solids. After the series of concentration steps, the final copper concentrate is sent to thickeners and pressure filters where the moisture content is reduced from about 40 percent to about 8 to 10 percent, by weight (Singh, 2010). The water removed from the concentrate is usually reused in the circuit. At this point, the concentrate, which contains from 25 to 35 percent copper, is ready to be shipped to a smelter.

The tailings produced from the flotation process are most often transported by pipeline to the TSF as slurry that contains roughly 40 to 60 percent solids (see fig. 4). The higher solids content is achieved when the slurry is thickened or clarified to recover water for recycling back to the plant. By doing so, the operation reduces the cost of pumping reclaimed water from the TSF and lessens the loss of water that occurs in the TSF. Tailings are discharged into the TSF by several methods, including subaerial slurry, subaqueous slurry, and less commonly, dry deposition. Tailings that contain a high sulfidic content (pyrite) may be deposited in the TSF subaqueously to prevent oxidation of wastes (Wardell Armstrong International Ltd., 2007).

Water is reclaimed from the tailings impoundment for reuse in the process after the solids contained in the slurry are allowed to decant. Makeup water is added to most beneficiation plants to compensate primarily for the loss of water entrained in tailings and evaporation. Makeup water is also required when mill tailing slurry is thickened to about 70 to 80 percent solids and used as hydraulic and (or) paste backfill for ground support in underground mines (Grice, 1998). Most of the water contained in the backfill is not available for reuse.

## Estimated Requirements for Process Water

It was estimated, based on discussions with industry specialists and the examination of numerous site-specific reports for operating and proposed operations and other published literature, that the amount of water required to process copper sulfide ore through a conventional crush-grind-flotation-concentrate circuit ranges from roughly 1.5 metric tons (t) to about 3.5 t of water to process 1 t of ore [Wels and Robertson, 2003, 2004; Misra and others, 2005; Wills and Napier-Munn, 2006; Chilean Copper Commission, 2008; Gault Group, Inc., 2008; Mongolyn Alt (MAK) Group, 2008; MWH, 2008; SRK Consulting, 2009; Tetra Tech, 2009; Keane and others, 2010; Singh, 2010; Gunson and others, 2012; Cameron Wolf, Senior Process Engineer, Tetra Tech MMI, written commun., March 21, 2012]. In the southwestern United States, approximately 2.5 to 3 t of water are required to process 1 t of copper porphyry ore that contains roughly 0.5 percent copper (Gault Group, Inc., 2008; Vargas, 2008; Mining Engineering, 2010; Singh, 2010). The highest ratio of water to ore feed discovered in the literature was KHGM Polska Miedzs S.A.'s Lubin Mine in Poland, which uses about 4 to 5 t of water to process 1 t of copper ore (KGHM Polska Miedzs S.A., 2011). The chemical and physical nature of the ore are the primary determinants of water requirements and include such factors as the size and shape of the mineral grains; the distribution and density of the mineral assemblage (including the ore grade); the settling rate; the clay content; and the hydrophobic characteristics of the ore, including its behavior in a water-based solution containing a mix of chemicals.

## Makeup Water Requirement for Conventional Copper Flotation

Makeup water is defined in this report as the amount of water required to compensate for water losses from the process of flotation and losses that occur in the tailings storage facility (TSF). Losses at the grinding and flotation portion of the facility are relatively minor. They include evaporation from flotation cells, water used in thickeners, and water contained in the concentrate. Water from leaks, spills, and overspray in a beneficiation plant is generally recovered from sumps and reused.

The most significant factors that contribute to makeup water requirements result from the loss of water in the TSF caused by evaporation and water retained in tailings. Makeup water requirements range from roughly 10 percent (where dry-paste tailings are produced because water is scarce and conservation is a high priority) to 100 percent in cases where water is abundant, mostly from precipitation and runoff into impoundments and reservoirs, or where it is not possible to recirculate water from tailing impoundments (U.S. Bureau of Mines, 1993; U.S. Environmental Protection Agency, Office of Solid Waste, 1994; Chilean Copper Commission, 2008). Based on the reviews of literature and discussions with industry specialists, it is estimated that for most operations makeup water accounts for 10 to 50 percent of the plant's total water requirement [U.S. Environmental Protection Agency, Office of Solid Waste, 1994; Yukon Zinc Corporation Ltd., 2007; Chilean Copper Commission, 2008; Vargas, 2008; Mongolyn Alt (MAK) Group, 2008; SRK Consulting, 2009; Tetra Tech, 2009; Keane and others, 2010; Singh, 2010; Gunson and others, 2012; Cameron Wolf, Senior Process Engineer, Tetra Tech MMI, written commun., March 21, 2012]. There are also unusual cases, such as at the Fort Knox operation in Alaska, where the availability of makeup water from the TSF is affected by the freezing of the tailings pond (Gillespie and others, 2004).

## The Tailings Storage Facility

The tailings storage facility (TSF) is an important source of makeup water for processing ore in the flotation facility and is also the major contributor to water loss. Most TSFs associated with flotation have four major components: (1) dams and (or) embankments that contain the tailings; (2) a beach, over which the slurry traverses; (3) a pond overlying saturated tailings; and (4) a dry beach of accumulated tailings that may be occasionally rewetted by slurry. The water losses in the TSF result from (1) entrainment of water in the tailings; (2) active beach evaporation; (3) rewetting; (4) pond evaporation; and (5) seepage [Wels and Robertson, 2004; Mongolyn Alt (MAK) Group, 2008; Keane and others, 2010; Gunson and others, 2012; Cameron Wolf, Senior Process Engineer, Tetra Tech MMI, written commun., March 21, 2012]. Wels and Robertson (2003) estimated water losses from tailings impoundments of three large copper operations in Chile that produced from 66,500 metric tons per day (t/d) to 161,000 t/d of tailings in a slurry of about 53 percent solids. They estimated that the percentage of water recovered from the TSF for reuse ranged from a low of 20 percent for the Chuquicamata facility located in the Atacama Desert in Chile to a high of nearly 58 percent for the TSW used for the tailings generated from the Candelaria operation located in the central region of Chile. Nearly all the losses were attributable to evaporation and entrainment of water. The losses at these two sites represent 32 percent and 20 percent, respectively, of the flotation facilities' total water requirement based on the assumption that 2 t of water are required to process 1 t of ore and the stated makeup water requirements. Approximately 70 to 80 percent of the water contained in the tailings slurry discharged to the Morenci and Sierrita, Arizona, TSFs is not recovered because of evaporation, entrainment in tailings, and seepage, which leaves about 25 percent of the water available for reuse (University of Arizona, Water Resources Research Center, 2002; Gault Group, Inc., 2008; MWH, 2008). Figure 1 shows the major sources of water loss from the circuit and the TSF. A detailed list of the components that pertain to the availability of water for reuse in a TSF is presented by Goñi (2011).

## Entrainment of Water in the Tailings Storage Facility

Water entrained in the TSF may range from 30 percent to more than 50 percent of the water contained in the slurry [Wels and Robertson, 2003, 2004; Mongolyn Alt (MAK) Group, 2008; Siepka, 2009; Keane and others, 2010; Wardrop Engineering Inc., 2010; Gunson and others, 2012; Singh, 2010; Cameron Wolf, Senior Process Engineer, Tetra Tech MMI, written commun., March 21, 2012]. The range is mostly a function of grain size, mineralogy, permeability, and thickness of the accumulation of tailings. In general, less water is retained in thicker tailing deposits because of overlying pressure and in those that contain heavy minerals, such as magnetite, because of the material's greater density. Through compression, the two factors result in displacement of the water from the tailings. An estimated 52 percent of the water placed in the Tranque de Talabre—a TSF for the Chuquicamata porphyry copper mine, which is located in Chile's Atacama Desert—is retained in tailings and is therefore unavailable for reuse (Wels and Robertson, 2003). Entrainment of water at the Mission Complex copper porphyry operation near Tucson, Ariz., was estimated to be nearly 30 percent of the water discharged to the TSF (Singh, 2010) and is probably representative of other TSFs in the southwestern United States that receive slurried tailings generated from porphyry copper ores.

## Evaporation of Water From the Tailings Storage Facility

Evaporation is primarily a function of the geometry of the impoundments, especially its areal extent and water depth, and climatic factors, which include the combined effects of solar radiation, air temperature, humidity, precipitation, wind duration, fetch, and intensity (Wels and Robertson, 2003, 2004; Singh, 2010; Goñi, 2011; Gunson and others, 2012). The amount of evaporation of water from the TSF may range from about 5 percent to more than 60 percent of the total water loss for the entire flotation-tailings storage impoundment facility and may exceed 15 percent of total plant requirements [Wels and Robertson, 2003, 2004; Reid and Derek, 2004; Reid, 2005; Mongolyn Alt (MAK) Group, 2008; BHP Billiton, 2009; Keane and others, 2010; Singh, 2010; Wardrop Engineering Inc., 2010; SNC-Lavalin Group Inc., 2011; Gunson and others, 2012; Cameron Wolf, Senior Process Engineer, Tetra Tech MMI, written commun., March 21, 2012]. An estimated 28 percent of the water placed in the Tranque de Talabre at the Chuquicamata porphyry copper mine is lost to evaporation and is therefore unavailable for reuse (Wels and Robertson, 2003). The combination of high altitude, low humidity, clear skies, and high temperature results in the loss to evaporation of approximately 30 percent of the water contained in the tailings slurry placed in Arizona's Mission Complex's TSF and more than 40 percent of the water in tailings slurry discharged to the TSF for the Sierrita Mine, which is also located in Arizona (Gault Group, Inc., 2008; MWH, 2008).

## Seepage From the Tailings Storage Facility

Additional losses may also result from seepage from embankments that border the tailings holding area or dam and possibly from percolation to the subsoil or groundwater underlying the tailings impoundment because liner systems are not always used. Collection systems bordering the tailings impoundment are designed to recover the water and minimize losses (Tailings.info, 2012). Water lost through seepage is relatively minor at lined impoundments and those constructed on clays or other materials with low water conductivity but can be significant if the underlying material is permeable. In general, water loss attributable to seepage for most TSFs is small relative to losses from entrainment and evaporation because of the low permeability values of the fine-grained tailings (Wels and Robertson, 2003). Data that pertain to losses through seepage from TSFs are limited, but such losses probably account for less than 10 percent of the makeup water requirements and less than 5 percent of total water requirements for most operations.

## Water Contained in the Final Copper Concentrate

Copper concentrate is shipped from the plant with a moisture content of approximately 8 to 10 percent, by weight. For most properties that employ conventional flotation, this represents less than 2 percent of the total water loss at the facility (Siepka, 2009; Singh, 2010; Gunson and others, 2012). The relatively low moisture content is achieved through the use of thickeners and pressure filters.

## Model of a Water Balance for a Conventional Flotation Copper Circuit Facility

A simplistic model was developed for a conventional flotation plant and TSF located in a semiarid region to provide a perspective on the amount of water that is required to (1) process the ore and (2) compensate for losses for water contained in the concentrate, the TSF, and other losses. The largest difference between this model and one developed for a more temperate region is that it is based on somewhat higher evaporative losses. The loss of water attributed to evaporation in an arid region, such as the southwest region of the United States and the high-desert regions of Chile, would be appreciably higher. The factors used in the calculations and estimates of water requirements and losses are shown in tables 1 and 2. Based on the broad assumptions described in tables 1 and 2, it was calculated (using figures rounded to two significant digits) that a conventional copper flotation facility that processes 17.5 Mt of ore per year containing 0.50 percent copper would produce about 290,000 t of concentrate containing 27 percent copper and would require about 44 Mt of process water based on a circuit designed to process copper porphyry ore that uses 2.5 t of water per metric ton of ore. Of this amount, about 17 Mt of water would be sent to the TSF as a slurry consisting of 50 percent solids. Approximately 11 Mt of water, or nearly 60 percent of the water sent to the TSF, would be lost to entrainment in the tailings and evaporation and seepage from the TSF, which leaves about 6 Mt for reclaim water (supernatant) for the plant. For simplicity, it was assumed that there were no additions of water to the TSF from precipitation or runoff. About 200,000 t, or less than 1 percent of the total annual amount of water required at the modeled facility, is lost as moisture contained in the shipped concentrate and as the result of evaporation in various parts of the plant facility. To compensate for these losses, the balance of the plant's water requirement (about 11 Mt of water) would need to be acquired from sources other than the TSF. If the modeled flotation plant were to operate at the parameters described in tables 1 and 2 for a period of 20 years, approximately 340 Mt of water would be required to compensate for moisture contained in concentrate and losses that occur in the plant and the TSF. About 35 percent of the required amount of water would be available from the TSF, and 65 percent would need to be acquired from other sources.

## Summary

This brief study of the water requirements to process copper sulfide ores by conventional flotation circuits illustrates that the requirement for makeup water is a significant factor for the successful operation of a plant. The two leading factors in the loss of process water are its entrainment in the interstices of the tailings deposited in the TSF and evaporation of water from the TSF. The availability of a reliable supply of makeup water for the concentration plant and water required for other components of the mining operation, such as dust control, is a major concern to companies when they contend with factors that affect the demand for water beyond the requirements of the mine and mill. These factors may include competition with other industrial or municipal demands, high net evaporation rates, absence of infrastructure, limited water resources, regulations, and social pressures. These types of concerns could be relevant for several decades, considering the relatively long lifespan of most mines that process ore from low-grade copper porphyry deposits.

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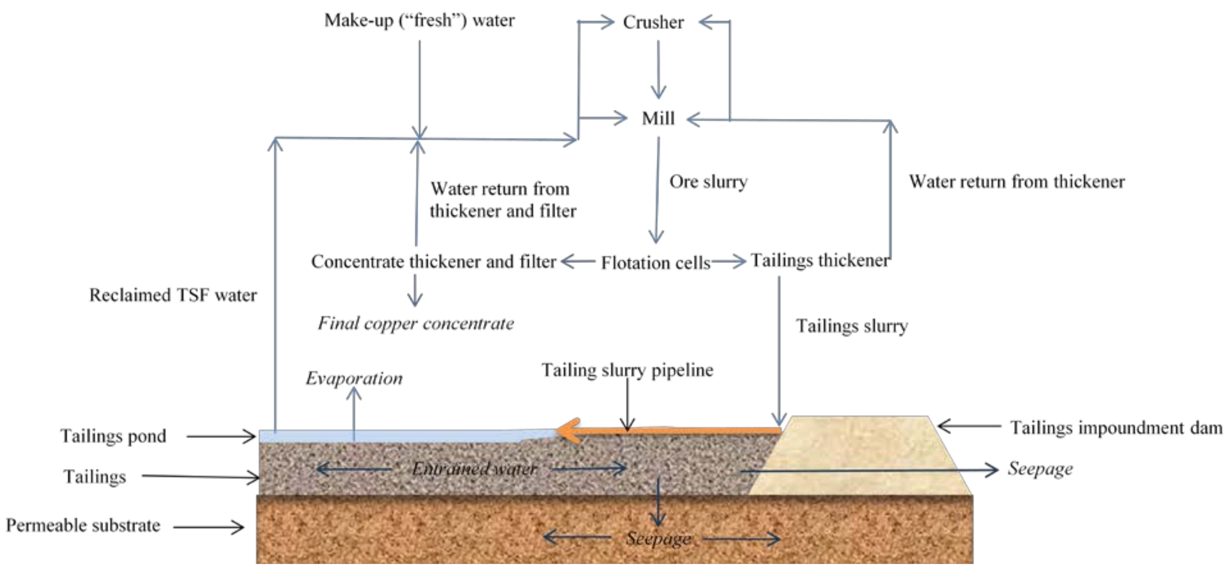


Figure 1. Simplified flow of water through a conventional flotation plant and unlined tailings storage facility illustrating water losses (labeled in italics), reclamation of process water, and addition of makeup water. In addition to the sources of water loss noted, minor amounts are also lost by evaporation and overspray in the plant.

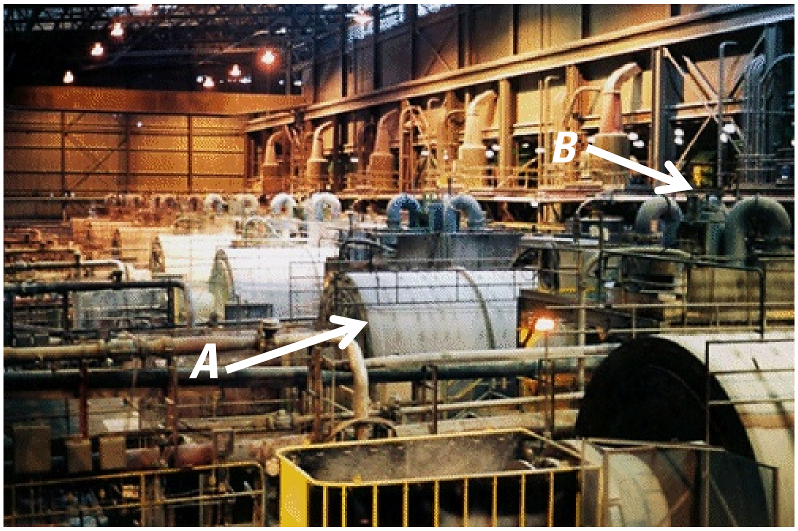


Figure 2. Ball mills (A) and cyclones (B) in the mill house at the Sierrita beneficiation plant in Arizona. Photograph courtesy of Freeport-McMoRan Copper & Gold Inc.; used with permission.

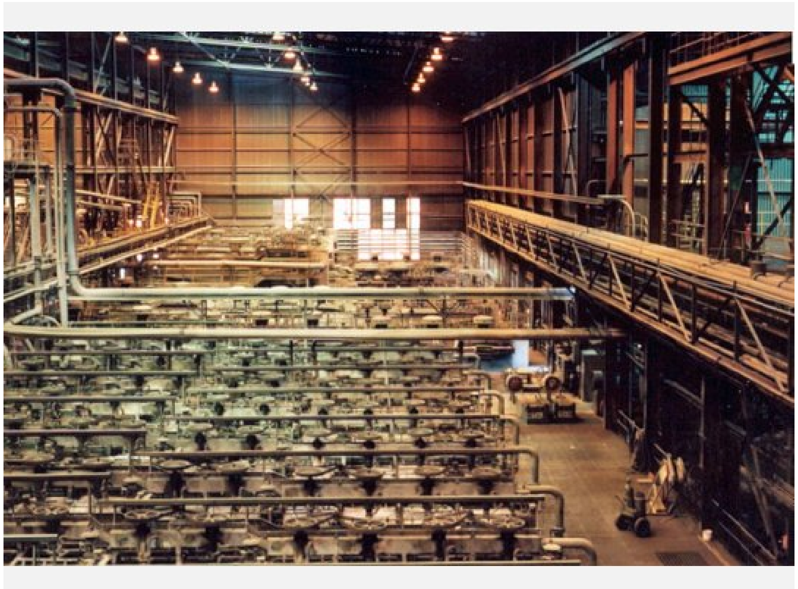

Figure 3. Banks of rougher cells in the flotation circuit of the Sierrita copper porphyry mine, Arizona. Photograph courtesy of Freeport-McMoRan Copper & Gold Inc.; used with permission.

Figure 4. Photograph of the tailings storage facility for the Sierrita copper porphyry mine in Arizona. Note the slurry pipeline in the foreground and where it traverses the tailings as indicated by the white arrow. The sun's reflection can be seen on the tailings pond in the right-middle portion of the photograph. Photograph courtesy of Freeport-McMoRan Copper & Gold Inc.; used with permission.

**Table 1.** Engineering and operational parameters for a conventional copper flotation circuit with a 50,000-metric ton-per-day ore feed capacity.

[Mt, million metric tons; t, metric ton; TSF, tailings storage facility]

| Engineering and operational parameters for a modeled copper porphyry deposit using conventional flotation | Value |
|---|---|
| Daily plant capacity | 50,000 t |
| Operating days per year | 350 |
| Annual plant ore capacity | 17.5 Mt |
| Copper ore feed grade | 0.50 percent |
| Copper recovery | 90 percent |
| Metric tons of concentrate per year | 292,000 |
| Final copper concentrate grade | 27 percent |
| Final concentrate moisture content | 10 percent |
| Tailings deposited in the TSF per year | 17.2 Mt |
| Solids contained in tailings slurry (percent solids) | 50 percent |

**Table 2.** Total water requirements, water losses, and makeup water for a conventional copper flotation circuit with a 50,000-metric-ton-per-day ore feed capacity located in a semiarid environment.

[Mt, million metric tons; N/A, not applicable; t/t, metric ton of water per metric ton of ore; TSF, tailings storage facility]

| Type of water use or water loss | Estimated total annual water requirements (includes process water, water to TSF, water losses, and makeup water)[1] | Estimated percentage of total annual water requirement | Estimated annual water losses (percent) |
|---|---|---|---|
| Total annual process plant water requirement. | 44 Mt[2] | N/A | N/A |
| Flotation circuit process water requirement (includes grinding). | 2.5 t/t ore | N/A | N/A |
| Water contained in copper concentrate. | 0.03 Mt | Less than 0.5 | Less than 1 |
| Water contained in tailings slurry and deposited in the TSF.[3] | 17 Mt | 39 | 63 |
| Water entrained in the TSF. | 6.9 Mt | 16 | 40 |
| Water deposited in TSF attributed to evaporative losses. | 3.4 Mt | 8 | 20 |
| Water deposited in TSF attributed to seepage losses. | 0.52 Mt | 1 | 3 |
| Water losses attributed to dust control, evaporative losses from plant flotation cells, and thickeners. | 0.17 Mt | Less than 0.5 | Less than 1 |
| Water reclaimed from the TSF pond for process water (reclaimed water is included as a component of makeup water). | 6.4 Mt | 15 | 37 |
| Water acquired from other sources for process water (“fresh” water is a component of makeup water).[4] | 11 Mt | 25 | N/A |
| Total annual makeup water requirement.[5] | 17 Mt | 40 | N/A |

[1]Calculations are rounded to two significant figures and may not add because of rounding.

[2]One metric ton of water is equivalent to 1,000 liters or 1 cubic meter.

[3]The balance of the process water, 27 Mt, is recirculated and recovered from thickeners and filters.

[4]Also referred to as “fresh” water. Sources may include natural bodies of water, wells, and reservoirs and captured runoff and precipitation into the TSF. Captured runoff and precipitation into the TSF are not included in the model.

[5]Reclaimed water from the TSF, plus water from other sources.