A HISTORY OF MINERAL CONCENTRATION:

A HISTORY OF TAILINGS[1]

by

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Abstract: The extraction of mineral values from the earth for beneficial use has been a human activity since long before recorded history. Methodologies were little changed until the late 19th century. The nearly simultaneous developments of a method to produce steel of a uniform carbon content and the means to generate electrical power gave man the ability to process huge volumes of ores of ever decreasing purity. The tailings or waste products of mineral processing were traditionally discharged into adjacent streams, lakes, the sea or in piles on dry land. Their confinement apparently began in the early 20th century as a means for possible future mineral recovery, for the recycling of water in arid regions and/or in response to growing concerns for water pollution control.

Additional Key Words: Mineral Beneficiation

"...for since Nature usually creates metals in an impure state, mixed with earth, stones, and solidified juices, it is necessary to separate most of these impurities from the ores as far as can be, and therefore I will now describe the methods by which the ores are sorted, broken with hammers, burnt, crushed with stamps, ground into powder, sifted, washed...."

Agricola, 1550

Introduction

The term "tailings" is often misapplied when identifying mining wastes. It is frequently used mistakenly to identify all mineral wastes including the piles of waste rock located at the mouth of mine shafts and adits, over-burden materials removed in surface mining, wastes from concentrating activities and sometimes the wastes from smelting operations. For the purpose of this discussion, the following definitions shall apply:

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Tailings: Tailings are the finely ground gangue or host rock materials from which the desired mineral values have been extracted during the concentration process. Tailings may contain the residues of reagent materials that were added to enhance mineral separation (Young 1976, PEDCO 1984). Tailings will usually have the same mineralization as the host rock. "Chat" is a term used in certain regions of the United States for tailings. Waste materials derived from the processing of coal, including the terms "refuse," "slack," and "gob" are often incorrectly referred to as tailings (Thrush 1968).

Slag: Slag is the impurities and reject material formed during the smelting or refining of ores or mineral concentrates by pyrometallurgical methods (Thrush 1968). Slag is the generally accepted term in the United States for wastes produced from the smelting process, but may occasionally be used to define any or all of the mineral industry waste products.

Beneficiation: Beneficiation is the upgrading of ore by sizing, removal of impurities or otherwise improving the quality of the ore (Thrush 1968). Beneficiation can apply to any ore grade improvement from sorting in the mine through concentration prior to smelting.

Concentration: Concentration is the separation and accumulation of economic mineral values from gangue (Thrush 1968). Concentration is generally limited to ore quality improvement after mining but before smelting and which includes the milling process.

Mining, concentrating and smelting of ores for their metals have been a part of human activity since before recorded history. The mineral processing methods remained basically unchanged from ancient times until the latter part of the 19th century.

The disposal of mineral wastes did not present much of a problem to human health and welfare until the first part of the twentieth century. However, as the modern mining industry continues to satisfy the increasing demands for metal and other mineral products, mine wastes and tailings will also expand in ever increasing proportions. About 362,872,000 metric tons of tailings were generated annually in the United States alone in the early 1970's (Dean et al 1974). A decade later, it had increased to 598,771,900 metric tons, exclusive of uranium mining (PEDCO 1984).

Early Methodologies

There is little doubt that the first discoveries of gold, silver and copper were found in their free or native state as nuggets lying on the surface of the ground or in pools of water in streams and rivers. Such finds were opportunistic, but early man quickly learned where to look for these metals. It was soon discovered that by digging and washing sands and gravels in certain streams, or from their banks, gold nuggets would be found. Where water was not available, the earth could be winnowed or tossed into the air from an animal hide or perhaps a woven fabric, and the lighter materials would be carried away by the wind in much the same manner that chaff was separated from kernels of grain. This was the beginning of what is commonly termed placer mining, forms of which are in common use today. It is a method that many consider among the most ancient methods of separating metal from waste (Young 1976).

Placering, with the most rudimentary pans, or the more sophisticated sluices, strakes, rockers and jigs, then as now, is the mechanical separation by gravity of native or free metal and heavy metallic salts from naturally crushed rock (Young 1976). These methods are most often associated with gold recovery. The waste products of early placering, tailings if you will, were carried away to be deposited elsewhere with little or no apparent consequence.

The next step in the recovery of metals was the discovery that these metals, along with tin and lead, could be found in their native state in outcrops of rock, but first had to be broken loose. This was the beginning of mining in the sense that it is commonly perceived; the excavation of metal-bearing rock, initially as surface expressions and then tunneling underground. The tools of excavation were stone, horn, bone, and in time, bronze and iron. A fire, the primary loosening agent, would be built against the metal-bearing face and the rock heated. Then water would be dashed against the hot rock causing it to fracture. The pieces were then hammered or pried free to be carried to the surface. Particles of the host rock were often attached to the metals and had to be broken free and discarded.

Somewhere along the way, ancient man learned that some of the mineral forms of metals could be refined to an almost pure state by the use of fire and heat. The discovery of smelting by fire made additional ores useful, mainly the oxide and carbonate ores of copper. Smelting also provided the ability to separate silver from lead, to refine gold by removing the often naturally alloyed silver and to mix tin with copper to make bronze.

The desirability of removing the largest possible amount of gangue or earthy matter from the valuable metal before smelting had been recognized for thousands of years and was regularly practiced by ancient peoples (Aitchison 1960). The earliest apparent indications of mineral concentration are found as inscriptions on Egyptian monuments dating from the IV Dynasty (about 4000 BC). Other monuments dating from the XII Dynasty (2400 BC) specifically suggest the working of gold ore (Hoover and Hoover in Agricola 1912). Written accounts of ancient mineral concentration techniques are limited, most descriptions tracing back to the lost works of Agatharchides, a Greek geographer of the second century, BC, who described Egyptian mining and concentration methods (Hoover and Hoover in Agricola 1912). The process involved breaking mine-run rock into smaller pieces using stone mortars and stone or iron pestles. The small pieces, "the size of a vetch," were then taken to a mill where they were further ground "as fine as meal." This finely ground powder was spread over a broad board or rough stone slab, somewhat inclined or sloping, where it was washed by pouring water over the powdered rock. The material would be worked by hand over the board or slab, the water washing away the earthy material and the gold, being heavier, was retained (Hoover and Hoover in Agricola 1912, Poss 1975).

The famous ancient Greek silver mines at Mount Laurion were extensively worked before 500 BC, but it is unclear when the ores were first concentrated before being smelted. At some time before the Third Century, BC, an extensive system of milling and concentration had been developed. One estimate suggests that the Mount Laurion area produced more than 6,350,000 metric tons of reject (tailings) over the several centuries of its activity (Hoover and Hoover in Agricola 1912).

The crushing appliances described by the ancient authors and confirmed by Greek and Roman artifactual remains scattered over Europe were hand mortars and millstones of the same order as those used to grind flour (Hoover and Hoover in Agricola 1912). Such appliances were relatively simple affairs, and with a few refinements, were employed into the twentieth century. These included the most primitive of mechanical implements, a stone lashed to a forked stick that in turn was supported by another forked stick that acted as a fulcrum. A flat rock with a slight depression served as a mortar. The ore was placed on the mortar and crushed by repeatedly raising and dropping the stone (Young 1976).

The arrastra was a common tool of the ancients. It was widely used in the Americas by the Spanish Conquistadors during the sixteenth century, and it found continued widespread use in the western Americas into the twentieth century. The arrastra also employed stones lashed to a pole. However, the pole was attached to a center pivot in a tub made of very hard rock spaced closely together to form a tight, smooth floor. Men or animals would push on one end of the pole and the stones lashed to the other would finely crush or grind the ore placed in the tub by an abrasive action. The finely ground ore was recovered for further processing of the metal values. The arrastra was simple to build and could be operated as either a wet or dry grinder or as a separator. Mercury could be added for its gold (and subsequently silver) amalgamation properties (Young 1976).

The next apparent crushing development was the Chilean Wheel, also known as an edge runner. This device was constructed and operated in a similar fashion to the arrastra, except that the stone drags were replaced by stone wheels that performed the crushing and grinding. As with the arrastra, the Chilean Wheel would have to be dismantled frequently so that the fine grindings that had fallen between the stones of the tub could be recovered. Because it was more awkward to dismantle and reassemble than the arrastra, there is conjecture that this implement, as well as other wheeled variations, may have seen more use as a primary crusher rather than as a tool for fine grinding (Young 1976). Young also points out that the Chilean Wheel was used in biblical times for olive seed crushing and therefore the name has no connection to its origin.

The products of these early grinding procedures, including those from the hand operated mortar and pestle, were native metals, oxide, carbonate or some sulfide ores of metals, mixtures of the ores and gangue or barren gangue. The grindings would be collected and washed, utilizing the principle of gravity to separate the heavier metalliferous material from the gangue. The barren gangue would be discarded as tailings.

Mercury amalgamation of gold was known as early as Roman times (Hoover and Hoover in Agricola 1912, Young 1976) and became increasingly more common over time as more mercury deposits were discovered. Mercury was often added to the ore during these early grinding processes and the amalgamated ore was subsequently washed to separate the gangue from the amalgam. In these instances, some mercury would be lost with the gangue as tailings.

There is little in the written record to document early metallurgical processes other than those of the Greeks and Romans already referenced. It was not until Georgius Agricola compiled the classic *De Re Metallica* about 1550 AD that the first detailed description of mining, concentrating and smelting practices was produced. This work was translated into English by Herbert Clark Hoover and Lou Henry Hoover in 1912.

Agricola described in detail the many methods and variations of ore washing, including the common forms of placer mining as well as the washing of crushed and finely ground ores. He described a form of jigging as an ore washing technique that had been recently adopted by miners at the time. The jig consisted of a sieve that was filled with ore and sifted in a vertical motion in a tub nearly full of water. This action, coupled with the movement of the water in the tub, caused the heavier metal-bearing particles to sink while the lighter gangue floated to the top of the tub and was skimmed off for discarding.

Another device described by Agricola was a machine "...that one in the same time can crush, grind, cleanse and wash the gold ore and mix the gold with quicksilver...." This device evidently included a stamp mill, along with a wheel-type millstone arrangement and a three-tub washer equipped with mechanical paddles that agitated and mixed the mercury with the pulp. This system was water powered and water was used to carry the ores through the amalgamation and washing stages as well as to carry away the tailings.

A new development of significance, the stamp mill, was described by Agricola. It was invented sometime in the late fifteenth or early sixteenth century. It was a water, animal or man powered device that employed a shaft with cams which lifted heavy wooden rods that had iron shoes attached to their base. At the top of the lifting stroke, the cam released the rod and the force of its fall crushed the ore fed beneath it. The stamp mill was more a result of an emerging mechanical technology rather than an increase in the knowledge of metals and metallurgy. Significantly, the methods of separating metal-bearing components from barren gangue in his time were the same as of old: water separation, and in the case of gold, water separation of mercury amalgamated gold particles.

Metallurgists in Agricola's time had a working knowledge of only nine metals, not including such alloys as bronze, brass, pewter and electrum. These were the seven metals of antiquity: gold, silver, copper, lead, iron, tin and mercury; and antimony and platinum (Aitchison 1960). Aitchison further noted that the pseudo-science of alchemy, based upon the Aristotelian principles and beliefs concerning the origin of matter, provided the basis of knowledge concerning the extraction of metals and other elements. Modern chemical concepts, upon which our present knowledge of metals is based, did not become an accepted science until at least two hundred years later. This limited knowledge of chemistry and metallurgy restricted man's ability to recognize, let alone utilize, the multitude of metal ores known today. Of necessity then, minable ores were limited to the native or free metals and a very few of their oxide, carbonate and sulfide forms. In all cases, the pure metal content of the ores was very high relative to today's common cut-off grades.

19th Century Developments

The 19th century brought several major developments that would have everlasting impacts on not only the metallurgical science and industry, but on all of human-kind as well. Explosives, in the form of gunpowder, were first used in Germany for loosening rock in mines about 1627 AD (Poss 1975), but their widespread use for this purpose would wait until the development of dynamite in the latter part of the 1800s (Young 1976). Electricity, first described by Volta and produced in wet cell batteries by Humphrey Davey in 1807, would wait until the invention of the dynamo in the latter part of the 19th century before it could be made available for widespread domestic and commercial application (Aitchison 1960). The steam engine, improved upon by Watt in 1781, opened the way for a huge expansion in the development of mechanical power. Aitchison further suggests that the outstanding metallurgical development of the early 19th century did not occur in that science, but was the result of a vast increase in the development and application of mechanical power. This development resulted in a tremendous magnification of the scale of work, an increase in the size of plant and furnace facilities, the sum of which was an overall higher productive efficiency. World copper production figures bear this out: 1810, 9100 metric tons; 1870, 159,000 metric tons. British pig iron figures show a similar trend: 113,400 metric tons at the beginning of the 19th century, increasing to 2,268,000 metric tons by 1850 (Aitchison 1960).

By 1850, the knowledge of metals had progressed in a similar fashion. Some 39 additional metals had been discovered since Agricola's time, though not necessarily isolated into their free or pure form. These included arsenic, zinc, cobalt, nickel, molybdenum, tungsten, uranium, chromium and others. Some 23 more would become known in the next fifty years: vanadium, potassium, sodium, barium, calcium and aluminum being among the more commonly known in today's everyday usage (Aitchison 1960).

The 19th century was a time of many discoveries and inventions which laid the foundation for much of the 20th century's social and economic needs. It could be argued endlessly which discovery or invention was the most critical, but the independent discoveries made by Henry Bessemer of England, and William Kelley, a Kentucky ironmaster, can be considered among the most important. These individuals ushered in the "Age of Steel" with their steel-making processes developed between 1850 and 1855. Some credit this development as the greatest purely metallurgical advance in the one hundred years from 1850 to 1950 (Dennis 1963). Although steel was known in early times and its use in the fine blades of Damascus is legendary, the carbon content of those early steels was highly variable and unevenly distributed. World production of steel in 1850 amounted to no more than 59,900 metric tons per year (Aitchison 1960). Cast and wrought iron were used almost exclusively in construction at that time (Aitchison 1960, Dennis 1963). Mild steel, a low carbon product, was not known in 1850. But following the processing developments of Bessemer and Kelley, together with Siemen's open hearth process that came about ten years later, the ability to produce large quantities of uniform quality steel was attained by the latter 1880's (Dennis 1963). Dennis further suggests that these three developments in steel making were the foundation upon which the Age of Steel was established and which brought so many subsequent developments which dramatically influenced industry (Dennis 1963).

The rapid strides in the use of iron and steel, once these processes were refined, brought about great increases in the demands for other metals, particularly copper, tin and lead. Not only was this expressed as a demand for greater production of known metals, but also as a demand for a greater variety of metals. Aluminum, a metal almost unknown in the mid-19th century, experienced astronomical growth during the first half of the twentieth century following the nearly simultaneous developments in 1886 by Heroult of France and Hall of the United States. Their application of electrolytic refining principles for reducing bauxite ores to alumina was the catalyst. (See Table I.)

mines, the slag from the smelters and the tailings from the fine grinding of concentration increased exponentially as new technologies were developed for extracting the metals from ores of ever decreasing grade or purity.

TABLE I

WORLD PRODUCTION OF SOME NON-FERROUS METALS (Dennis 1963)
Production (Metric Tons)

Metal	1850	1875	1900	1950	1960	1989[1]
Copper	50,000	118,235	476,000	2,289,000	4,164,000	7,100,000
Lead	118,235	290,300	771,100	1,518,620	2,322,380	2,572,000
Zinc	14,970	149,685	435,450	1,650,160	3,184,200	5,130,000
Tin	16,300	32,650	77,110	146,963	163,020	152,000
Nickel	--	450	7,250	166,000	324,770	574,900
Aluminum	--	--	6,620	1,420,640	4,544,970	14,295,000
Uranium(U_3O_8)		--	--	--	37,300	42,085

[1]Engineering and Mining Journal, 121st Annual Survey and Outlook, MacLean Hunter Publishing Co., Chicago, Illinois, Vol. 191 No. 3, March, 1990.

Whatever conclusion is drawn regarding the critical turning point in metallurgical development, be it mechanical power, advancements in chemistry, the steel making process or electrical power, it becomes clear that the 19th century was, at the least, a most dynamic period in the advancement of the arts and sciences upon which modern society and civilization is based. With this growth in knowledge and demand for metals, came a corresponding growth in mining for metallic ores and in the processing of these ores into useful metals. Likewise, the quantity of waste products from this growth increased. Waste rock from the

Contemporary Concentracting Methodologies

The importance of concentrating the metal content of ores prior to smelting or refining to the pure form cannot be overemphasized. Ore consists of a complex of minerals disseminated through barren rock material known as gangue. Elimination of as much of the gangue as possible before smelting is an economic necessity in order to save transportation costs from mill to smelter and to reduce the unnecessary costs and complications caused by the gangue in the smelting and refining process (Agricola 1550, Richards and Locke 1940, Aitchison 1960, Dennis 1963).

For thousands of years, the crushing of ore to a small or fine particle size has been the key to liberating the most amount of metal. From hand mortars and pestles through the various man and animal powered grinding mills such as the arrastra and Chilean Wheel, to the water and steam powered stamp mills, man has endeavored to improve upon the grinding process. The latter half of the 19th century saw the most recent development in ore crushing technology, brought about by two of the major breakthroughs of that period, steel and electricity.

Today, grinding is performed by machinery that had its origins in the 1880s. The predecessor of the modern milling machines was the short-lived barrel pulverizer, made of iron and invented in England in 1880. It was quickly replaced by the tube mill, a long, cylindrical steel container with a hard flint interior lining. It was the first successful modern grinding machine. Pebble-sized ore is fed into the tube and grinding is achieved by tumbling the ore pebbles as the tube rotates. Hard, durable rock pebbles such as flint may also be added as a grinding medium. Tube mills may also be divided into two or more compartments by screens to facilitate particle size control. The tube mill found great favor in the South African gold fields in 1904 to further grind stamp mill products.

The ball mill was introduced in 1885 and is also a rotating cylinder, but of greater width than length. It uses steel balls as a grinding medium. Hardinge improved the ball mill design in 1908 by giving the cylinder a conical shape that is able to provide greater control of the final product size (Dennis 1963).

The ball mill quickly replaced stamp mills where cyanidation had been adopted for gold ore concentration. However, it was not popular in mills that continued to use mercury amalgamation because the tumbling action of the balls would flour the mercury, rendering it useless. The rod mill was invented to resolve this problem. It is similar in size and shape to the tube mill and employs a charge of steel rods as long as the inside chamber of the mill to achieve the grinding (Young 1976).

Grinding of the ore into fine particles and the use of mercury for gold amalgamation, as we have seen, are processes used since early times to liberate the greatest amount of metal possible from the gangue or host rock. The use of mercury for amalgamation of silver ores was not known until about the middle of the 15th century. Developed initially in the silver mines of Spain, this procedure was extensively used in Mexico by the Conquistadors upon the discovery of local mercury sources. It was a most effective process for the oxide ores of silver, but as these sources rapidly diminished and more and more of the mines went deeper than the weathered zones near the surface and encountered the sulfide ores below the water table, it was found that the costs of extracting the silver by the normal smelting processes of the day became prohibitive. The Patio Process was developed to offset this problem. It employed a copper-iron-sulfate product added to mercury amalgamated silver sulfide ore. The ore, mercury, copper-iron-sulfate and salt amalgamate would be washed in water-filled vats. The amalgam would be retained while the gangue would be washed away (Young 1976). After 1850, a chlorine gas process was introduced that gained considerable use in silver ore beneficiation (Aitchison 1960). Mercury amalgamation, with salt and a few other reagents such as previously described, coupled with gravity separation by washing, remained the principal method of precious metal ore concentration up to the late nineteenth century. However, as late as the 1850s, most of the world's total gold supply came from placer mining, and in each of the new fields such as California, Yukon and Australia, the metal was won by the washing of gravels and alluvial deposits (Aitchison 1960).

All this changed with the introduction of the cyanide leach process. It was first used in New Zealand in 1889 and was introduced to the gold fields of South Africa a year later (Aitchison 1960). Its initial application was for the recovery of residual gold contained in tailings. At first, only the coarser sized "sand" particles could be effectively treated by cyanidation, and the fine sized particles, or "slimes," had to be separated for treatment or discarded. In time, methods were developed to effectively treat the slimes and now nearly all ore is finely ground to the slime fraction (Dennis 1961).

Cyanidation, in the first ten years of its use, made every gold mill and milling practice then in use nearly obsolete. This method replaced mercury amalgamation and opened the door for large volume fine-grinding and the new opportunities for greater metal recovery from lower grades of ore (Young 1976). Nearly every tailings heap from previous gold washing activities in the world was reworked with the cyanide process to recover the metal values lost in the previous milling practices (Young 1976). The resulting impact of this tailings reworking activity was a gold boom as big as the rush to the Yukon or to Wittwatersrand in South Africa (Young 1976).

The introduction and development of the flotation process during the period 1893 to 1902 for concentrating metal values from ore proved to be of major significance to metallurgical science (Rickard 1932). The basic principle is simple; when vigorously agitated with a mixture of water, oily substances and bubbles of air, the metal-bearing particles become coated with oil, attach themselves to the bubbles which rise to the surface and are floated off into collectors. The gangue sinks and is discarded as tailings (Aitchison 1960, Dennis 1963). The flotation process is effective for only one metal. However, by adding additional flotation circuits, complex ores containing two or more metals can be treated allowing each metal to be recovered instead of discarded with the tailings.

Flotation became widely used in the non-ferrous metal industry after 1910, and may be considered the salvation of the copper industry in the western United States. Up until the development of flotation, ores of less than 2 percent copper were very difficult to process (Young 1976). In spite of flotation's widespread success and application in the mineral industry, cyanidation is still the more favored method for precious metal concentration (Young 1976).

Present iron technologies (blast furnaces) require lump forms of feed stock and the finely ground concentrates from flotation are not acceptable. However, the advent of pelletizing, briquetting and scintering techniques for iron concentrates to achieve the necessary large particle feed stocks has made the benefits of flotation available to the iron and steel making industry (Dennis 1963). The first commercial all-flotation iron ore concentrating mill was put into service in Michigan in 1954 (Dennis 1967).

Rickard (1932) provides an indication of the efficiency of the flotation process in mineral value recovery with an example of copper content in tailings before and after a flotation circuit was installed by the Anaconda Copper Mining Company in Montana. The ore in both cases had a copper content of 3 percent and was subjected to the same milling processes. Tailings generated from a water-gravity separation method contained 0.62 percent copper, those from a flotation process installed a year later had a copper content of 0.15 percent, or one fourth that of the gravity method. The increased recovery of copper as a result of flotation amounted to 24,947,800 kilograms per year with no change in ore grade or tonnage put through the mills (Rickard 1932).

Another example of copper recovery as a result of both fine grinding and flotation can be found in the reprocessing of stamp mill tailings deposited in the 1860s in the Upper Peninsula of Michigan. It was estimated that there was as much as a 25 percent loss of copper in the early stamp mill process. These tailings were reprocessed during the period 1916 through 1952 by modern grinding mills, leaching with ammonia and flotation. The recovery of copper amounted to some 266,798,500 kilograms over a thirty-six year period (Stevens 1972).

Other forms of mineral concentration are also noteworthy. Water-gravity separation, as we have seen, has been practiced since time immemorial, and the methods of washing ores have been only slightly improved during all this time. Major gravity separation methods, which still find considerable use today, include a variety of tables over which a water and finely ground ore product flow, some of which have riffles to trap the heavier particles, most of which have a mechanical movement or jigging action to assist in the gravity separation of ore from gangue (Dennis 1963). A major addition was made to gravity separation in 1891 with the development of sink-float technology. This process is based upon adjusting the specific gravity of the floating medium. An early application of this method was the addition of sand to increase the specific gravity of water for separating coal, which floats off, from slate, shale and clay, which is heavier than the sand-water, and sinks. This process, with various materials used as a heavy media, is widely used today in iron ore concentrating and coal processing (Dennis 1963).

Magnetic separation was first developed in Sweden in 1883. As the name suggests, it has a very wide application in the processing of magnetic iron ores such as magnetite, franklinite and ilmenite (Dennis 1963). Electrostatic separation, developed in the United States in 1901, is based on the principle that minerals will take on an electrical charge if brought into contact with a source charged at a high potential. The readiness and degree of the charge varies with the mineral (Dennis 1963). This process has been useful in the separation of many minerals including zinc blende from galena, graphite from molybdenite, rutile from zircon and ilmenite, titanium recovery and the separation of the tin mineral cassiterite from columbite (Dennis 1963).

The waste products from these mineral concentrating processes are discarded as tailings.

Mill And Tailings Production

With the developments in the metallurgical technologies that took place in the latter half of the 19th and first quarter of the 20th centuries firmly established, it is now appropriate to examine examples of mineral production, and in turn, tailings. An account of the Comstock silver district of Nevada noted that in October, 1859, Hastings and Woodward had two water-powered arrastras at work which reduced 4.5 metric tons of ore per day (DeQuille 1889). In August of 1860, a nine-stamp portable battery had been set up and dry ore production was one ton per day, but wet crushing increased production to 9 metric tons from the Bowers Mine (Rickard 1932). On August 11, 1860, A.B. Paul started a stamp mill in the district and the first lot of ore to be milled was 4.5 metric tons of tailings from the Gold Hill arrastras (Rickard 1932). Rickard also noted that metal recovery during the early days of the Comstock was only 60 to 65 percent, but by 1867, retreatment using settling tanks or by concentration increased recovery up to 85 percent.

In contrast to the relatively low daily tonnages of ore milling in the Comstock District in the mid 1800s, a gold operation in Alaska was processing 10,650 metric tons of ore per day in 1930, using gravity separation and flotation. Of this production, 5013 metric tons was waste rock, 5613 tons went to tailings and 6 tons was a lead-gold-silver concentrate (Rickard 1932).

During the early 1930s, the Anaconda Copper Mining Company concentrator in Montana had a mill capacity of 10,900 metric tons per day. Of this daily production, 8830 metric tons, or 81 percent was discarded as tailings while only 2070 metric tons of concentrate was produced; 599 metric tons of copper was recovered from the concentrate. The grade of the mill feed stock was 5.5 percent copper (Richards and Locke 1940).

A mill in Miami, Arizona, may be more representative of copper recovery and tailings production of a late twentieth century operation where low grade ores are the rule. In 1930, this mill had a capacity of 15,400 metric tons per day of 0.716 percent copper ore; 98.3 percent of the daily production, or 14,140 metric tons, was tailings (Richards and Locke 1940).

Some fifty years later, total United States copper tailings production was about 218,360,000 metric tons per year. Tailings produced in 1981 from other mineral processing activities in the United States included phosphate (155,128,000 metric tons), iron (145,149,000 metric tons) and molybdenum (27,578,270 metric tons). These figures amount to 87 percent of the tailings produced, the remaining 52,523,000 metric tons coming from the recovery and processing of some twenty five other minerals including bauxite, gold, silver, lead, titanium, diatomite, feldspar, sands and gravels, salt and talc. Uranium and other radioactive metals were not included in these tailings production figures (PEDCO 1984).

Tailings Disposal

Little has been written of the disposal of the waste products of mines and mills. Agricola, describing a washing process for tinstone, stated that "...the mud mixed with the very fine tinstone...which has neither settled in the large settling pit nor in the transverse launder...flows away and settles in the bed of a stream or river." (Agricola 1550). Hoover and Hoover noted in their translation of Agricola that before a stamp mill had been installed in Joachimsthal (Czechoslovakia) in 1521, a great many metal bearing particles were left in the washed sands "...which had been either thrown away or used as mortar for building...." (Hoover and Hoover in Agricola 1912). Some of the more recent historical accounts confirm that tailings, as a rule, were discarded from the mill to go as they would in their own way. DeQuille notes that in the Comstock silver district of Nevada in the 1860s, "...untold millions (of dollars) in gold, silver and quicksilver were swept away into the Carson River with the tailings...." (DeQuille 1889). In early practice, tailings were frequently dumped into nearby lakes, rivers or the sea, or were placed in dumps and piles where the solid material accumulated and the water ran to waste (Lindgren 1909, Richards and Locke 1940, Kelly and Spottiswood 1982). These practices continued until recent times in the United States and elsewhere as evidenced by reports of tailings control activities in Idaho in 1968 and South Dakota in 1973 (Matthew 1973, Williams 1973, Kelly and Spottiswood 1982).

Tailings accumulations have been recognized for their potential as sources of additional mineral resources. We have seen in earlier discussions that tailings accumulations were reworked to recover gold and silver values with the coming of the stamp mills to the Comstock district of Nevada; to recover copper from stamp mill tailings with the advent of fine grinding, leaching, and flotation in Michigan; and the reworking of nearly every previous tailings heap to recover gold after the cyanidation process was developed. Other minerals may be recovered from tailings deposits in addition to the minerals that initially produced the tailings. Tailings produced from porphyry ore bodies frequently contain appreciable amounts of potassium and phosphorous. Tailings from some copper and gold ores have been reprocessed to recover radioactive and other heavy metal values (Bean 1973). Also, as previously noted, tailings have been used for mortar as early as 1521 in Europe. They have been used, or have the potential for use, in such areas as railroad ballast, agricultural uses, road building and other construction materials (Bean 1973, Mountain States Research and Development 1981). Perhaps the most common use of tailings is for the backfilling of underground mines after removal of the ores when there is little likelihood that recoverable ore values remain. In most cases, the tailings are separated, the coarse or sand fractions being used for the backfill and the fine fractions or slimes going to tailings ponds or otherwise discarded (Kelly and Spottiswood 1982). Lindgren noted as early as 1909, while commenting upon the loss of mineral values in ore concentration, that the confinement and storage of tailings should be regulated by governmental agencies in order to minimize such losses in minerals. As an accompanying side thought, he noted that confinement of tailings would also be desirable in order to avoid contamination of the water supply (Lindgren 1909).

The practice of tailings confinement as a specific and distinct part of the mineral beneficiation process appears to have started in the very late 19th century and gained rapid acceptance through the first half of the 20th century. The Anaconda Copper Mining Company's concentrator at Anaconda, Montana initiated a tailings confinement practice sometime in the late 1890s (Richmond and Sjogren 1972). Although the general literature is silent regarding the initiation and specific purposes of tailings confinement, a conclusion may be drawn that this practice had its origins with the spectacular developments in metallurgical extraction techniques that occurred at that time: fine grinding, chlorination, cyanidation and flotation. These developments demonstrated that significant changes in technology may likely result in today's waste becoming tomorrow's "gold mine." The urgings of Lindgren to store tailings for possible future mineral recovery and the observations of Bean and others that tailings accumulations are potential mineral storehouses support the conclusion that the confinement and discrete storage of tailings was brought about in anticipation of future mineral value recovery.

Other considerations that undoubtably made a major contribution to the practice of tailings confinement included the need to conserve and recycle process water, especially in arid regions where water is scarce, and for the control of water pollution (Lindgren 1909, Richards and Locke 1940, Kelly and Spottiswood 1982). Richards and Locke noted in 1940 that "...so many of the Western states have passed antidebris legislation aimed against the pollution of streams by the introduction of mill tailing, or slime." The Anaconda Company first built ponds specifically for water pollution control near Warm Springs, Montana in 1910. This, and subsequent ponds added in 1913 and 1957, were for the treatment of acid waters discharged from the mines and mills in Butte, several miles upstream. These ponds would occasionally receive and store tailings which would be washed down Silver Bow Creek during emergency situations (Richmond and Sjogren 1972).

Today, there are tailings deposits, large and small, old and new, active and inactive all over the world. Many of these deposits or accumulations are residual from the earliest milling activities and are still to be found in rivers, along the shores of lakes or as discrete piles among the remnants of historic mining and milling operations. Others, especially those laid down after the middle of the 20th century, are mostly in the form of discrete confinements.

In summary, man has always been engaged in the search and extraction of the earth's minerals. At first, man's needs were few, but as more knowledge was gained, needs became greater and more complex. We have seen that up until about 150 years ago, our needs were comparatively few and the demand made of the mineral resource correspondingly small. With the breakthroughs in knowledge that have occurred since, especially the understanding of chemistry and the industrial developments that occurred during the latter half of the 19th and first half of the 20th centuries, the growth of the world's increasingly technical civilization has made tremendous demands for those mineral products of the earth. As mining and milling practices have responded to meet these needs, greater quantities of mineral ores of ever decreasing purity have been utilized, resulting in an ever increasing growth of tailings and other associated waste products. At first, the disposal of mineral waste was of little or no consequence. As the volumes of these waste products increased, and more people became affected, their disposal became of greater concern. Once confinement of tailings became a general practice, additional problems became apparent. The stabilization of tailings against wind and water erosion and the return of lands to productive uses have long been two of these concerns. Efforts to address and resolve these concerns have been documented since the 1950s. More recent concerns such as heavy metal contamination and its associated health risks have become apparent only within the last two or three decades as detection technologies and modern health science knowledge have emerged to identify and understand them.

As mankind continues to move from a survival lifestyle to one dependent upon technology, new products and technologies will be developed to satisfy the growing needs. With the new products will come new problems and with new problems will come new solutions.

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