Sustainability Considerations in Innovative Process Development

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13.1 Introduction

The mining industry comprising extraction (mining), mineral processing (also referred to as beneficiation, milling, or concentration), and metallurgical processing (smelting and refining) is capital, water, and energy intensive with potential for significant environmental impacts, if the environmental aspects are not properly managed. In order to be sustainable, industry needs to carefully address all of these aspects.

The scope of this book is "mineral and metallurgical" processing, involving both physical and chemical processing and high- and low-temperature processing—namely, pyrometallurgical and hydrometallurgical processes. The industry needs to be innovative in how it goes about developing mineral and metallurgical processes. Due consideration consequently needs to be given to addressing capital intensity, water and energy use, environmental impacts, and industrial hygiene and safety considerations. How processes are developed today has a bearing on whether the industry is, and will remain, sustainable in the future.

In mineral and metallurgical process development, addressing these aspects starts at the conceptual stage and continues through bench-scale testing, pilot plant testing, commercial demonstration, and ultimately commercial operation. Finally, how a new process is integrated into other unit operations at a facility requires careful deliberation, calling for a holistic approach through all aspects of mining, mineral and metallurgical processing, looking at both upstream (mining and exploration) as well as downstream (fabrication and production of end-use product) operations, product use, and ultimate end-of-use recycling or disposal.

The examples used to illustrate some of the essential considerations of sustainable development are drawn from the primary copper industry because of the author's experience with that sector. There are two routes for primary copper production: (1) hydrometallurgical—leach, solvent extraction, and electrowinning and (2) pyrometallurgical—milling, froth flotation, smelting, and refining. For a more detailed understanding of these processes, the reader should refer to a standard textbook such as Schlesinger et al. (2011).

In this section, we discuss the importance of sustainable development and environmental management considerations in the mining and metallurgical industry and their implications for innovative process development.

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13.1.1 Is Mining Sustainable and What Are Sustainable Mining Practices?

We start by examining whether mining and mineral development is sustainable (Rajaram and Parameswaran 2005) because at first blush it appears it is not. The reason for such a view is that no mine lasts forever because mineral resources are finite and nonrenewable. The other reason is that certain historic mining practices, which are no longer acceptable, have had significant negative impacts on the environment. However, mining is important for the economic development of nations. In addition, because every item in modern commerce is made from something that is either mined or grown, it is impossible to contemplate sustainable development, or for that matter, any development that is not to some extent based on mineral development.

The 1987 World Commission on Environment and Development report "Our Common Future," also referred to as the "Bruntland Commission Report" defines sustainable development as:

> Development that meets the needs of the present without compromising the ability of future generations to meet their own needs. (WCED 1987)

It is true that mines run out of ore and, therefore, a mine at some point has to cease operations. This makes consideration of sustainability in mining even more important because:

> Sustainability encompasses many more values than the continuing availability of the resource being developed. Indeed, it is the very fact that mineral development will end some day that makes integration of those other sustainability considerations into the mining process highly appropriate. (Pring 1998)

With respect to being a nonrenewable and finite resource, there are several examples of copper mines with long lives. One good example in the United States is the Bingham Canyon copper mine, 25 miles southwest of Salt Lake City, Utah, operated by Kennecott Utah Copper Corp. and owned by Rio Tinto has been producing copper since 1906. Over that period, the mine has produced around 19.5 million tons of copper, 27 million troy ounces of gold, 240 million troy ounces of silver, and around 1.1 billion pounds of molybdenum, and the Cornerstone Project is expected to increase mine life well beyond 2019 and there is significant mineralization beyond the Cornerstone Project. It is estimated that the remaining mineralization equals what has been mined to date.

Examples of other copper mines, mills, and smelters with long lives in Arizona include ASARCO LLC (Asarco) Ray Mine and the Hayden Concentrator, which celebrated their centennial in 2011 and the Hayden Smelter which celebrated its centennial in 2012. Freeport-McMoRan Inc. (FMI) Morenci mine started underground mine operations in 1881 and transitioned to open-pit mining in 1937. FMI's Bagdad mine started underground mine operations in 1928 and transitioned to open-pit mining in 1945 and its Chino mine started open-pit operations in 1910 and concentrator in 1911. Asarco's Mission mine celebrated 50 years of operation in 2011 and FMI's Sierrita mine started open-pit operations in 1957. Asarco's Silver Bell mine commenced open-pit operations in the mid-1950s and operated through 1984. It has operated its Leach, SX-EW facilities since 1997.

Very few manufacturing facilities can rival that record of longevity. However, there are other mines that may have ore sufficient for 10 years of operation, particularly in gold mining. We therefore argue that because we are dealing with a nonrenewable and finite resource, it is imperative to incorporate sustainable development considerations in all aspects of development of a mineral project.

Further, as demand for metals grows so do proven and probable resources. This is due, in part, to the discovery of new resources through continued exploration, even as mining proceeds and, in part, due to technological advances that allow the economic processing of lower grade ores and even wastes. Examples of technological advances in primary nonferrous metals production include: froth flotation for the concentration of nonferrous metal sulfide ores; Solvent Extraction-Electrowinning (SX-EW) for leaching of copper ores and cyanide heap leaching for gold ores. Each of these advances has added considerably to the inventory of economically mineable reserves.

Additionally, continued exploration by mining companies concurrent with production and research, development, and adoption of new technologies can further the sustainability of mining.

While we mine today to satisfy current demand for metals, we provide future generations with knowledge on where the ore bodies are and the methods for extracting them.

Another attribute contributing to sustainability of metal mining is the recyclability of metals. Many metals once produced are capable of being recycled, smelted time and again to their original elemental form and refined to demanding specifications. Furthermore, recycling can conserve energy since recycling processes are much less energy intensive than the primary metals production processes. Recycling also contributes to the conservation of natural resources by providing an above ground virtual mine. As a result of recycling, the majority of all copper ever mined is still in use, as is at least 99 % of the gold ever produced and upward of 60 % of the silver mined is still in existence as bullion, coins, or fabricated products. Metals are through recycling, infinitely renewable and, therefore, useful as a store of value to future generations.

Once a metal has been mined and refined, it is available at the end of its life cycle to augment the supply of metal that is available to society in the future. It will become increasingly more important to tap these sources of supply especially as primary mineral and metal resources diminish. However, there are challenges associated with recycling, especially if the metal is in the form of all alloy or mixed with other scrap-containing impurities that may be difficult to remove. In the future, cost-effective processes have to be developed that can make it feasible to recover primary metals from alloys and mixed scrap-containing deleterious impurities. If recycling involves adding these materials as supplementary feed to the primary metal production process they may have to be added to unit operations at the front end of the primary metal production process. Although the energy used and associated cost in the recycling process can be small when compared to primary metal production, the scrap collection chain, which in most cases is complicated, results in additional costs principally labor, thereby increasing the cost of recycling.

According to the Copper Development Association Inc., "of the world's reserves of copper about one-quarter of the deposits are economically recoverable now or in the near future. Of this reserve base, about 16 % (198 billion pounds of copper) is in the United States. Every year roughly three billion pounds are withdrawn from the earth as US mine production, a barely discernible amount compared to the reserve base. The copper already mined through history amounts to 700 billion pounds, most still in recycling use. Interestingly enough, although copper is continuously mined and put into use, the estimated US reserve base has stayed relatively constant in recent years, and has increased fourfold from estimates made in 1952 as new deposits have been found and, even more important, because better extraction techniques have allowed leaner deposits to be added to the reserve base. There is every reason to believe that these dynamics will continue well into the twenty-first century. Three additional factors will also influence copper supply: US self-sufficiency, energy efficiency, and recyclability" (Copper in the United States—Bright Future Glorious Past: http://www.copper.org/education/history/us-history/g_fact_future.html).

Mining is sustainable when it is conducted in a manner that balances economic, environmental, and social considerations, i.e., by paying attention to the "triple bottom-line." It should be noted that these are not three separate bottom lines but a single integrated one. Therefore, sustainable mining practices are those that promote this balance. These practices should begin with exploration, continue with mine development, metallurgical facility design, through operations and until mine reclamation and metallurgical facility closure is completed. The emphasis throughout a mining project, which could last several decades, is one of communication with the local community and all other stakeholders, employing technologies for efficient production and minimizing environmental impacts and worker exposure throughout the production chain, including while a mineral or metallurgical process is being developed. We also need to incorporate tools such as life cycle analysis so that environmental, economic, and social implications can be comprehensively evaluated.

13.1.2 Importance of Environmental Management and Environmental Management Systems

Environmental Management Systems (EMS) provide a useful framework that helps companies in achieving environmental goals through consistent control of its operations. It does so by instituting “plan,” “do,” check,” and “act” approach, with the objective of continual improvement. The expectation is that incorporation of EMS will translate to better environmental performance for the company. For more details, see references such as (Von Zharen 2001).

13.1.3 Regulatory Context: Applicable Environmental Laws and Regulations

In considering environmental impacts of processes, it is necessary to have an understanding of the regulatory framework and the applicable environmental regulations. This will vary with the jurisdiction where the process being developed will be implemented. A discussion of the regulatory framework in the United States is provided by Parameswaran (2005) and is summarized in this section.

In the United States, the Clean Air Act, the Clean Water Act, and the Resource Conservation and Recovery Act and their implementing regulations govern the control of gaseous and particulate emissions, the control of effluents and stormwater, and the management of solid and hazardous wastes, respectively.

13.1.3.1 Clean Air Act of 1970 and 1990 Amendments

The primary focus of the air regulations required by the Clean Air Act (CAA) is the setting, attainment, and maintenance of national standards to protect public health. Regulation focuses on two categories of air pollutants. The first category consists of six commonly found “Criteria Air Pollutants” (sulfur dioxide, nitrous oxides, particulate matter, lead, ozone, and carbon monoxide) for which air standards must be shown to be achieved in ambient air. These six pollutants are controlled by federal-based programs requiring technology-based controls on emissions from certain pieces of equipment or operations, and by additional methods as needed to keep concentrations at or below the human-health-based standards. The second set of regulated pollutants focus on a different set of 187 listed “Hazardous Air Pollutants.” Unlike the first set of six, these pollutants are controlled by federal-based programs requiring technology-based controls on emissions from certain enumerated pieces of equipment or operations.

In addition, regulation of greenhouse gas (GHG) emissions is in the early stages of implementation. The U.S. Environmental Protection Agency (EPA) has made an endangerment finding for GHG emissions as it relates to climate change and finalized additional permitting requirements. However, the U.S. Supreme Court has set aside some of these requirements. There is still no consensus of how climate change would ultimately be addressed. EPA has recently proposed carbon standards for existing power plants in addition to those already proposed new power plants.

For criteria pollutants, EPA is required to set National Ambient Air Quality Standards (NAAQS), “requisite to protect public health with an adequate margin of safety.” States and local air pollution control agencies have the responsibility to implement the program, usually done by establishing State Implementation Plans to implement these programs. States, along with EPA, have enforcement responsibility.

There are two main federal programs requiring technology-based limits for emissions in new mine, mineral and metallurgical processing facility construction and operation (known as New Source Review and as New Source Performance Standards) for criteria pollutants.

Additional limitations on emissions may be set for the local airshed (where the mine, mineral or metallurgical facility would be located), if needed, to maintain the NAAQS for those six criteria pollutants. Generally in a rural airshed, such additional limits are minimal but they can be more significant in urban areas where there are many more sources of pollution or in rural airsheds with a history of exceeding the health-based standards.

Under Section 112(r) of the Clean Air Act Amendments, EPA has published regulations and guidance for chemical accident prevention at facilities that use extremely hazardous substances. These regulations and guidance are contained in the Risk Management Plan (RMP) rule. The information required from facilities under RMP helps local fire, police, and emergency response personnel prepare for and respond to chemical emergencies. Making RMPs available to the public also fosters communication and awareness to improve accident prevention and emergency response practices at the local level. The RMP rule was built upon existing industry codes and standards. It requires companies that use certain flammable and toxic substances to develop a Risk Management Plans. Certain chemicals might trigger an off-site consequence assessment to model worst-case release scenario.

13.1.3.2 The Federal Water Pollution Act of 1972 (aka the Clean Water Act)

The goal of the Clean Water Act (CWA) is to restore and maintain the chemical, physical, and biological integrity of the nation's waters. The CWA set up a mechanism for federal funding of infrastructure improvements intended to improve water quality and also established two primary programs to achieve this goal: (1) a permit program—the National Pollutant Discharge Elimination System (NPDES) program—to control discharges of pollutants to navigable waters; and (2) a mandate to states to adopt (with EPA review and approval) surface water quality standards for navigable waters within their boundaries that would result in a level of water quality sufficient to protect fish and wildlife, as well as human health and recreational uses (often referred to as the "fishable, swimmable" goal). Today, administration of the NPDES program has with few exceptions been delegated to states (with EPA oversight). Applicants for NPDES permits must show that a proposed discharge will not violate the surface water quality standards set by the state for the receiving water and will comply with any technology-based effluent limitation guidelines established by EPA. Such guidelines have been established for over 50 industry sectors to date, including ore mining and dressing and nonferrous metals manufacturing—smelting and refining. The effluent limitation guidelines may establish numeric limits on the concentration of pollutants in a discharge and/or may limit when a discharge may occur.

Stormwater discharges into navigable waters from industrial activity (including mining and construction), as well as from large and medium municipalities, also are regulated under the NPDES permit program (or a state delegated program). Such discharges are commonly regulated under general permits, but in some cases an individual permit may be required.

The discharge of one class of pollutants—dredged or fill material—into navigable waters is not regulated under the NPDES program, but rather under a different permit program established by the CWA (referred to as the Section 404 permit program). The Section 404 permit program is administered primarily by the United States. Army Corps of Engineers, although EPA has a significant role in reviewing and enforcing these permits.

Over the years, the concept of "navigable waters" has been construed broadly. In addition to territorial seas, large flowing waters, lakes, and wetlands, it has been interpreted to include smaller waters that flow only on a periodic basis, including small washes that flow only briefly in response to precipitation.

13.1.3.3 The Resource Conservation and Recovery Act

The Resource Conservation and Recovery Act (RCRA) of 1976 requires EPA to regulate the management of hazardous wastes from generation to disposal, i.e., cradle to grave. It also sets forth a framework for the management of nonhazardous wastes, underground storage tanks, and medical wastes. RCRA focuses predominantly on active and future facilities and generally does not address abandoned or historical sites unless present at an active facility engaged in treatment, storage, or disposal of hazardous waste, requiring a permit. As with other environmental laws, RCRA allows EPA to delegate permitting and enforcement authority to the states.

With a few exceptions (waste in domestic sewage, irrigation return flows, discharges regulated by CWA permits, and radioactive materials regulated under the Atomic Energy Act) RCRA defines all "discarded" materials as solid waste regardless of whether a material is solid, liquid, or contained gas. The scope of discarded materials has been subject of considerable debate and litigation. EPA's regulatory definition of solid waste includes materials that are "abandoned," "recycled," or "inherently waste-like," all of which are defined in regulations. EPA's definition of "hazardous wastes," with certain exceptions includes solid wastes that:

- Are on a list of hazardous wastes: nonspecific source wastes, wastes from specific sources, and commercial chemical products.
- Exhibit characteristics of ignitability, corrosivity, reactivity, or toxicity.
- Is a mixture of a listed hazardous waste and a solid waste or is a solid waste derived from a listed hazardous waste (with some exemptions).

EPA regulations also identify the kinds of recycling activities that are classified as hazardous and those that are not. EPA published a final rule on January 2015 revising several recycling-related exclusions associated with the definition of solid waste used to determine hazardous waste regulation.

One of the exemptions to EPA's definition of hazardous wastes arising from statutory provision called the Bevill amendment, which required EPA to study extraction, beneficiation, and "mineral processing" wastes (*note that "smelting and refining" is defined in the RCRA regulations as "mineral processing"*) and make a regulatory determination on how these wastes should be regulated. EPA determined that all uniquely associated (i.e., those that derive their characteristics from the ore being processed) extraction and beneficiation wastes and 20 large volume "smelting and refining" wastes should be regulated as "nonhazardous." These 20 wastes include primary copper, lead smelting slags, copper slag tailings, and calcium sulfate wastewater treatment sludge from primary copper processing would be regulated as nonhazardous. The complete list of the 20 wastes can be found at 40 Code of Federal Regulations (CFR) §261.4 (b) (7).

EPA's hazardous waste regulations impose requirements for generators, transporters, and operators of treatment, storage, and disposal (TSD) facilities. Generator requirements include obtaining an EPA I.D. number; determining whether their wastes are hazardous; preparing their waste for transportation (according to Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) packaging and placarding requirements); preparing the Uniform Hazardous Waste Manifest (manifest); and complying with storage, training, planning, record keeping, and reporting requirements. The manifest is the key ingredient of RCRA's cradle to grave regulatory scheme. Each time a waste is transferred (from generator to transporter, from one transporter to another, or from transporter to the designated facility) the manifest must be signed to document receipt. The designated facility on receipt of the waste sends a copy of the signed manifest back to the generator. There are three categories of generators: Large Quantity Generators (LQG), Small Quantity Generators (SQG), and Conditionally

Exempt Small Quantity Generators (CESQG), depending on the quantity of waste generated per month. An SQG can generally store hazardous wastes for up to 180 days and a LQG up to 90 days, without having to obtain a TSD permit.

Transporters of hazardous wastes must obtain an EPA I.D. number, comply with manifesting requirements, meet DOT transportation requirements, must properly deal with accidental spills and accidents, and report serious accidents and spills to the National Response Center and DOT.

TSD facilities are subject to RCRA's Subtitle C permitting requirements and have to meet standards for TSD units, e.g., containers, tanks, surface impoundments, waste piles, land treatment, landfills, and incinerators. TSD facilities must comply with citing requirements. They must analyze incoming wastes, meet security requirements, inspect their facilities, and comply with employee training and record keeping requirements. Other requirements may include groundwater monitoring and reporting, control of air emissions, closure and postclosure, and financial assurance. In addition, as part of the issuance of a RCRA permit, EPA and authorized states require corrective action to remediate past releases of hazardous constituents or wastes.

The Hazardous and Solid Waste Amendments (HSWA), the 1984 amendments to RCRA, require phasing out land disposal of hazardous waste. Hazardous wastes have to be treated to meet land disposal restrictions levels, thus increasing the cost of disposal. Some of the other mandates of HSWA include increased enforcement authority for EPA and a comprehensive underground storage tank program.

13.1.4 Regulatory Context: Applicable Health and Safety Regulations

In the United States, the laws that govern workplace safety are Mine Safety and Health (MSH) Act and Occupational Safety and Health (OSH) Act and their implementing regulations. The Mine Safety and Health Administration (MSHA), an agency of the U.S. Department of Labor, has responsibility for administration and enforcement of the MSH Act of 1977, which protects the safety and health of workers employed in the nation's mines. It applies to all mines and mineral processing operations in the United States, regardless of size, number of employees, or method of extraction. The Act requires MSHA to inspect all mines each year to ensure safe and healthy work environments for miners. In addition to setting safety and health standards for preventing hazardous and unhealthy conditions, MSHA's regulations establish requirements for: (1) immediate notification by the mine operator of accidents, injuries, and illnesses at the mine and (2) training programs that meet the requirements of the MSH Act.

The Occupational Safety and Health Administration (OSHA), another agency of the U.S. Department of Labor, administers and enforces the OSH Act of 1970. Safety and health conditions in private industries, including manufacturing facilities such as smelters and refineries, are regulated by OSHA or OSHA-approved state plans. There is also a general duty to provide work and workplace free from recognized serious hazards. Federal and state regulators work to ensure worker safety and health through worksite enforcement, education and compliance assistance, and cooperative and voluntary programs.

OSHA regulations also include process safety management requirement for highly hazardous chemicals aimed at preventing or minimizing the consequences of catastrophic releases of toxic, reactive, flammable, or explosive chemicals. These releases may result in toxic, fire, or explosion hazards. These regulations also prescribe permissible exposure limits for toxic air contaminants such as inorganic arsenic, lead, cadmium, etc. These can be met by use of respirators, protective work clothing and equipment, or by implementing engineering controls. In addition, there are exposure monitoring provisions, medical surveillance, and removal provisions.

In addition, both Acts have hazard communication standards (HCS) requiring mines, smelters, and refineries to develop, implement, and maintain a written hazard communication

(HazCom) program. Operators must identify chemicals used by workers; make a hazard determination; ensure that containers have labels; make available a Material Safety Data Sheet (MSDS) for each hazardous chemical used or produced at the mine or facility; and instruct workers on the physical and health hazards of the chemicals encountered at the work place, protective measures, and the contents of the HazCom program. OSHA updated its Hazard Communication Standard in March 2012, incorporating the United Nations' Globally Harmonized System of Classification and Labeling of Chemicals (GHS). Major changes to OSHA's HCS include a new system of classifying types and degrees of hazards, changes to labeling requirements, and changes to the Safety Data Sheet (SDS, formerly called MSDS).

13.1.5 Implication for Process Development

In mineral and metallurgical process development, sustainability considerations need to be evaluated upfront. In particular, we need to evaluate opportunities for resource, energy, and water conservation. We would also need to look at measures that would be required for the control of emissions, effluents, and the management of wastes. Another important consideration is assessment of industrial hygiene and safety requirements for the protection of the health of workers, associated with the process being developed. Finally, the community needs to be informed and their views solicited regarding the new technology being developed and its benefits and how environmental impacts will be avoided or mitigated. This communication needs to occur throughout the process development cycle and community concerns need to be addressed.

In the remainder of the chapter, these considerations are discussed with illustrative examples, followed by a case study, of how such considerations are being currently addressed by industry and finally a checklist is provided to determine whether these elements have been adequately addressed by the process developer.

13.2 Opportunities for Resource Conservation

The production of many nonferrous metals involves the processing of low-grade ores and hence it is important to evaluate opportunities for resource conservation. For example, the U.S. copper mining industry works with ores that typically have around 0.5 % copper. In addition, the ores may contain minor constituents, which might include precious metals like gold, silver, platinum; valuable recoverable constituents such as lead, zinc, rhenium, molybdenum, bismuth, nickel, selenium, and tellurium, and constituents of environmental concern such as arsenic and cadmium. Rare earth elements have been detected in copper leach solutions. Ignoring opportunities for recovering these constituents means foregoing potential coproduct revenue streams and resulting in more waste generation. A few percent increase in the yield of a process can improve the process economics considerably.

It should be recognized that the composition of the ore body is determined by geological occurrence, and therefore, there is little discretion over the composition of the raw material. This restricts opportunities for source reduction with respect to impurities of environmental concern but also provides the opportunity to recover valuable constituents, providing the potential for additional revenues through coproduct sales. For example, copper ores in Arizona contain molybdenum, rhenium, rare earth metals, and zinc. Whether these are recovered will depend on the economics of coproduct recovery and will vary with metal and commodity prices. When they are not recovered, these constituents may end up in tailings or concentrates, ultimately reporting to discarded smelter slag, when the concentrates are smelted. Resource conservation in the mineral processing step, therefore, involves the evaluation of the recovery of these coproducts such as molybdenum and zinc from an economic and environmental standpoint.

Resource conservation in the copper smelting step is usually accomplished by the resmelting of copper-rich flue dusts or filter cake, as part of the smelter charge or, if they are enriched with respect to lead or bismuth, they can be shipped to off-site facilities for metal recovery. Acidic scrubber solutions can be reused for leaching copper ores. Copper-bearing secondary materials from electrorefining of copper can be resmelted at the smelter. They include: "sharp" slag, precious metals bearing furnace bricks, copper telluride leach residue, foul cathodes, and copper residues.

Some of the impurities present in copper ores such as Pb, As, Sb, and Bi accumulate in the copper electrolytic refining stage in the electrolyte and their concentrations gradually increase with time. The concentrations of these impurities have to be maintained at acceptable levels, as some of these impurities in refined copper can cause grain boundary cracks in wiredrawing. Novel technologies such as Molecular Recognition Technology (MRT) have been implemented at Asarco's Amarillo Copper Refinery to remove bismuth from copper refinery electrolyte as a bismuth sulfate product, replacing the conventional methods, i.e., bleed stream withdrawal and controlled arsenic additions to the electrolyte (Izatt et al. 2015).

In order to recover the acid and some of the other valuable metals present in the copper electrolyte such as nickel, U.S. copper refineries have installed Acid Purification Units (Sheedy et al. 2006) where, after the electrowinning process, the decopperized electrolyte bleed is sent to the Acid Purification Unit (APU), where sulfuric acid and arsenic are absorbed into the resin and then desorbed using water that is then returned to the tank house to be reused as acid makeup and to increase arsenic concentration in the electrolyte. A by-product stream is generated that is high in nickel and other valuable metals that can be further processed and the metals recovered. This process eliminates the production of black acid and the use of evaporators with their associated high amounts of energy consumption, and also 70 % of the arsenic has been reported to be returned with the sulfuric acid. Nickel carbonate product can be precipitated by treating the deacidified electrolyte with sodium carbonate. The pH selective, two-step process first recovers a residue (at pH 6–6.2) containing copper, iron, arsenic, antimony, and bismuth that is returned to the copper smelter to recover copper. The final approximately pH 10 precipitate is the nickel carbonate product that is sold.

During the leaching of anode slimes, tellurium dissolves into the leach liquor together with copper and must be removed before the solution is sent to liberator cells for copper recovery. Leaching is conducted in atmospheric pressure tanks instead of a pressurized vessel and tellurium is recovered from the leach liquor by cementation using elemental copper.

In considering these opportunities, the regulatory status of the secondary materials needs to be considered, as further discussed in Sect. 13.6.

13.3 Opportunities for Energy Conservation

Mineral and metallurgical processing is inherently energy intensive—comminution, smelting, refining, and ancillary facilities such as scrubbers, electrostatic precipitators, double contact acid plants, and oxygen plants, which themselves are large energy consumers. Therefore, it is important that opportunities for energy conservation be thoroughly explored—blast optimization, energy efficient grinding methods, waste heat recovery in smelting, utilization of energy efficient equipment to reduce energy consumption and using renewable energy sources, where appropriate. Such assessment will impact not only the process economics but also achieve emissions reduction from the reduction in fuel and electricity consumption.

According to the Copper Development Inc., there are wide variations in the energy used to recover metals from the earth's crust. "Copper ranks near the middle for energy required for extraction—higher than iron, zinc or lead, but at considerable advantage to aluminum, titanium and magnesium, which require much larger quantities of energy to break down the ore (or seawater and brines in the case of magnesium) into metallic form." (Copper in the United States—Bright Future Glorious Past: http://www.copper.org/education/history/us-history/g_fact_future.html).

In the past, the objective of the blasting operation in hard rock mining was to convert an in situ rock mass into a muck pile with proper fragmentation size and shape for the excavation equipment (Oloffson 1988). Over the subsequent decades, it has come to be recognized as one of the most important comminution considerations because of its influence on the downstream steps of crushing and grinding and blast design has emerged as an important research focus for mine-to-mill optimization (Kim 2014). Over the years considerable efforts have been expended in the development of more energy efficient crushing and grinding technologies.

13.3.1 Energy Use in Copper Smelting Processes

In a paper in the Proceedings of Copper, Diaz (Diaz 2010) discusses technological advances, increased use of oxygen, pursuit of improved productivity, changing geography of smelting capacity, energy consumption, and greenhouse gas emissions associated with various copper smelting technologies. He notes that over the last three decades, increased oxygen usage in copper smelting and converting and the implementation of computerized process control have led to increased smelter concentrate processing capacity, reduced energy consumption, increased sulfur dioxide capture and that there has been a major realignment of world smelting capacity to China, India, and other Asian countries.

Coursol, Mackey, and Diaz (Coursol et al. 2010) in the same proceedings using thermochemical modeling and industrial data compare the energy consumption in copper smelting for various smelting routes. They reference the seminal paper (Kellogg and Henderson 1976), as pioneering life cycle energy analysis applied to copper extractive metallurgy. The analysis includes not only the fuel and electricity used for the various smelting alternatives but also the energy required to produce the main supplies. These are also referred to as Level 1 and Level 2 energy analysis. Other researchers have utilized similar methodologies to compare energy consumption in various copper processes (Nadkarni and Parameswaran 1975; Parameswaran et al. 1981). The latter paper estimated the energy requirements for a number of copper pyrometallurgical and hydrometallurgical processes using industrial operating data and material balances. The energy analysis included all operations from mining through production of refined copper. INCO and Outokumpu Flash Smelting/Batch Converting and Mitsubishi Continuous Smelting/Converting are in the lowest range of energy consumption because of the utilization of the fuel value of sulfur and iron in concentrates and the utilization of tonnage oxygen. The energy consumption ranges from 19.93 to 21.25 MMBTU/ton of cathode copper. To obtain the total energy required to produce a ton of cathode copper, the energies for mining and concentrating need to be added. For a 98.7 % recovery in the smelting operation, the estimated mining and concentrator energy consumption are 20.13 MMBTU/ton and 42.57 MMBTU/ton of cathode copper, respectively.

Coursol et al. estimate the energy consumption for four copper pyrometallurgical processing routes as follows: (1) Flash Smelting/Flash Converting 10,784 MJ/ton, (2) Isasmelt/Peirce Smith Converting 11,078 MJ/ton, (3) Mitsubishi Continuous Smelting/Converting 11,006 MJ/ton, and (4) Noranda/Teniente 12,746 MJ/ton. The authors compared their estimates of energy requirements of current processes with those studied by Kellogg and Henderson. Their comparisons show that the decreases resulting from technology advances in oxygen production and increased productivity as a result of increased oxygen usage in smelting and converting have more than compensated for increased energy requirements associated with the more stringent environmental controls that are currently required. They also note that the average electrical energy (processes 1–3) is not substantially higher since the time of publication of the Kellogg and Henderson study. Changes since that time include the increased use of tonnage oxygen in copper smelting and increased electricity consumption associated with use of double contact acid plants and the greater degree of control and capture of converter fugitive gases. Electricity consumption reduction is associated with the substantially lower consumption associated with the production of tonnage oxygen (285 versus 397 KWH/ton) and higher power plant efficiencies (38 versus 32.5 %). They find noteworthy the much lower fossil fuel consumption that is due to the utilization of the fuel value of iron and sulfur in concentrates. They attribute improved furnace design and operating practices, computerized process control, and higher furnace feed throughput for these achievements.

Compliance with more stringent sulfur dioxide NAAQS in the United States is likely to increase the electrical energy consumption as certain U.S. smelters install the necessary air pollution control equipment to meet these standards. The increased electricity consumption at the smelter would result in additional emissions of criteria and greenhouse gas emissions at the power plant.

As climate change regulations mature there will be greater emphasis on reducing greenhouse gas emissions resulting from restrictions on fossil fuel usage or imposition of a carbon tax. Life cycle energy use and costing will be increasingly used to properly evaluate these sustainability considerations.

The carbon footprint of a primary copper smelting process depends on the fuel mix used for heating and that used for electricity generation (Diaz 2010). He estimates that the fuel consumption to generate electricity is four times higher than the fuel directly consumed in mining, smelting, and refining and that three quarters of the electrical energy is consumed in milling. Based on the fuel mix at Chilean smelters, he estimates the average CO_2 equivalent emitted by Chilean smelters at 0.86. Diaz also notes that by contrast China and India where copper smelting capacity is rapidly expanding, thermal power (over 70 % coal) accounted for over 80 % of the electricity generated in 2006–2007. He identifies the following opportunities for reducing the carbon footprint at metallurgical processing facilities: (1) greater heat recovery from smelting, converting and anode refining off-gases; (2) greater heat recovery from the acid plant operation with high strength sulfur dioxide gas feed and (3) the implementation continuous anode refining technology.

13.3.2 Challenges and Opportunities Associated with Waste Heat Recovery from Copper Smelting Processes

There are several challenges and opportunities associated with recovering sensible heat from primary copper smelting off-gases (Safe and Russell 2010). The challenges presented by metallurgical off-gas heat recovery are due to high dust loadings, nature of the dust, corrosive gas, and thermal cycling in batch processes. The opportunities relate to the potential recovery of sensible heat that is currently being wasted. The authors discuss common heat exchanger technologies in use such as waste heat boilers and air to gas heat exchangers and the potential for utilizing heat recovery technologies employed in other industrial applications, such as thermal oil heat recovery, Organic Rankine Cycle heat recovery, and power generation to recover sensible heat from batch processes and lower temperature operations.

Copper smelting, converting, and anode refining produce significant off-gas volumes at high temperatures, usually in the range of 1000–1200 °C. Off-gas heat recovery is therefore an important means of reducing energy consumption and reducing operating costs. Smelting furnaces smelt copper concentrates to produce matte. Typically waste heat boilers are used with Outokumpu flash smelting furnaces, continuous converting furnaces, and Top Submerged Lance (TSL) smelting units such as the Ausmelt and Isasmelt processes, usually ahead of a hot Electrostatic Precipitator (ESP). The boiler includes a radiative section that cools the gas to about 700° C and a convective section that cools the gas below 400° C, which is suitable for entry into a hot ESP. The boiler uses the recovered heat to produce superheated or saturated steam for local power generation or for process uses. The Outokumpu flash furnace off-gas at 55,000–60,000 Nm^3/h contains around 7–9 MW of sensible heat at the ESP outlet and is relatively free of dust. The INCO Flash furnace uses technically pure oxygen and the low off-gas volumes do not justify installation of a waste heat boiler. The INCO flash furnace off-gas at 25,000 Nm^3/h contains around 3–4 MW. The off-gas is generally cooled further and cleaned in a wet gas cleaning system before it is sent to an acid plant for sulfuric acid production.

Converters are used to produce blister copper from copper matte. They are either continuous converting furnaces like Mitsubishi or Kennecott-Outotec flash *or* batch like Peirce-Smith or Hoboken converters. Modern Peirce-Smith converting departments employ three converters with two blowing and a third on standby. Often a fourth converter is offline undergoing repair or rebuild. The process gas exits a blowing converter at or slightly below the converter air blowing rate and at temperatures of 1100–1200° C. This is captured by a primary hood, which allows 100–120 % infiltration air into the hood, doubling the off-gas flow rate. The gas is cooled by evaporative or radiative cooling to below 400° C before entering a hot ESP. Some copper smelters have employed waste heat boilers or gas to air heat exchangers with limited success. Like the smelting furnace gases, the converter off-gas is cooled and cleaned in a wet gas cleaning system before being sent to the acid plant. Converter off-gas at a blowing rate of 30,000 Nm^3/h contains 8–12 MW of sensible heat at the ESP outlet per blowing converter and is relatively free of dust.

Flash converting and Mitsubishi converting both utilize waste heat boilers to cool the off-gas prior to dust removal in an ESP. Flash converting utilizes quite high levels of oxygen enrichment since the feed is solidified copper matte. This in turn yields a very high strength sulfur dioxide off-gas. A typical flash converting furnace off-gas will be 20,000 Nm^3/h at 35–45 % SO_2.

Anode furnaces used at copper smelters are generally batch operations to fire refine blister copper to anode copper, before it is electrorefined in a refinery. Most modern anode departments have two or three anode furnaces with one or two operating at any time. Anode furnace operations are batch operations, with each batch requiring 3 or more hours, consisting of an oxidation stage of 1 h with a reduction stage of 2–3 h. After completing a cycle, the furnace may sit for several hours in a hot standby mode. Process off-gas from an anode furnace is generally less than 10,000 Nm^3/h at 1100–1200° C. During the reduction stage, the off-gas can contain up to 25 % combustibles comprising carbon monoxide and hydrogen. The gas is captured by a primary hood with sufficient air infiltration to ensure combustion of combustibles. Generally, there is significantly additional air infiltration into the primary hood that further dilutes the process gas. In the oxidation stage, all of the air infiltration dilutes the process gas entering the primary hood. The gas is cooled by evaporative cooling to 200° C and then routed to a baghouse for particulate removal. Despite cooling the gas to below 200° C for the baghouse, it still contains 3.5 MW of sensible heat exiting the baghouse. In some smelters, anode furnace off-gas is sent directly to concentrate dryers for direct heat recovery and a common gas cleaning system.

The oxidation stage may take a few hours longer if processing higher sulfur blister copper from the Mitsubishi continuous converting process. Flash converting produces a lower sulfur blister copper and at the Kennecott smelter a 500 tonne charge of blister copper containing 0.2 % S can be oxidized, slag skimmed if required and reduced using a mixture of natural gas and superheated steam in less than 3.5 h. The chemical efficiency of the steam-gas refining is so high that the off-gas does not contain significant uncombusted hydrocarbons or hydrogen. In this facility, only pure oxygen-fuel burners are used which reduces the off-gas volume to the point that any heat recovery is uneconomic.

Waste heat boilers have been extensively used to recover waste heat from continuous smelting and converting processes. However, heat recovery from batch processes such as Peirce-Smith and Hoboken converters and anode furnaces has been largely overlooked.

The challenges presented by metallurgical off-gas heat recovery are due to high dust loadings, nature of the dust, corrosive gas, and thermal cycling in batch processes. Most waste heat applications involve dust-laden gas, which can lead to fouling and plugging of heat exchanger surfaces and pipes. Sticky dust in smelting gases is of particular concern. Fouling and plugging can result in reduced heat transfer, increased pressure loss, and can reduce fume capture efficiency. It can also lead to localized corrosion. Heat recovery equipment therefore needs to be designed with streamlined gas flow to avoid dropout or impingement onto heat transfer surfaces and rappers or sonic horns need to be incorporated to periodically knock off dust from the heat exchanger surfaces. At times air is added to smelter off-gas to convert sulfide in the dust to sulfates reducing its stickiness.

Corrosion occurs because as the gases cool, water and acid condense onto surfaces. Thermal cycling, fouling, or poor process control can lead to corrosion, which can increase maintenance cost and reduce equipment life. In designing heat recovery systems, it is important to have a good understanding of the water and acid dew points of the gas streams over the full range of operating conditions and the surface temperature profile throughout the heat recovery equipment. In addition, effective process control is necessary to ensure that gas and surface temperatures are maintained above the dew point to prevent condensation and attendant corrosion.

Thermal cycling is associated with processes that produce variable flow rates and temperatures and is of particular concern for batch processes. The expansion and contraction associated with temperature variations can cause metal fatigue, cracking, and leakage. Lower temperatures can result in condensation and corrosion. Heat recovery equipment should be designed to allow for expansion and process control implemented to minimize the range of thermal cycling and maintenance practices instituted to minimize leakage and maintain equipment integrity.

Batch processes because of variable off-gas characteristics present additional challenges resulting in inconsistent heat recovery with adverse impact on steam or power generation or preheated air availability. Usually this can be addressed utilizing thermal storage or common heat exchangers for multiple batch units such as converters. With thermal storage, the heat from the off-gas is transferred to a thermal medium such as oil. The quantity of stored heat will rise and fall, while a constant stream of heat (less than the operating heat recovery rate) would be bled from the storage system for production of steam, power, or preheating air. The other approach is to connect multiple batch units to a common heat recovery unit. For example, in a four converter operation with two converters blowing at any time, each converter operates 45 % of the time. By installing the heat exchanger after the converter off-gas ducts combine, that heat exchanger can operate with a steady off-gas stream from two blowing converters 90 % of the time. Batch processes provide some advantages as well. The reduced operating hours of individual units and the process flexibility it affords provide opportunities to optimize performance of the unit and time to clean out the unit and make necessary repairs. Process availability due to the heat exchanger is improved since maintenance on the unit can be performed during normal downtime for the vessel, while the smelter operations continue.

Low-grade heat from off-gas temperatures ranging from 50 to 300 °C is difficult to recover economically because of the small temperature gradient between the off-gas and the heat transfer fluid. Temperatures are not high enough to boil water and raise steam and air preheat is limited by the inlet gas temperature. Conventional waste heat boilers and air-to-gas heat exchangers are not suitable for this application.

The direct benefit of heat recovery is to reduce fuel consumption and associated costs. The ability to utilize the recovered heat to generate electricity presents an opportunity to control power costs, especially since electricity costs are expected to rise in the future as power plants are modernized to meet more stringent emission control regulations. Indirect benefits include increased production, if it is limited by energy availability and reduced greenhouse gas emissions.

13.3.3 Opportunities for Cogeneration

Opportunities for cogeneration should be considered where it makes business sense. For example, at the Kennecott copper refinery in Garfield, Utah, a natural gas fired turbine and combined cycle cogeneration produces 6.2 MW of electricity, while the waste heat from the combined cycle is used to heat the electrolyte at the refinery. At the Kennecott smelter waste heat from the flash smelting and flash converting furnaces is superheated and used to power the two main sulfuric acid plant blowers (2.5 MW each). The waste steam from the backpressure turbines is combined with steam recovered from the Monsanto Heat Recovery System (HRS) boilers and used to generate about 26 MW of electrical energy. This is sufficient to provide 65 % of the smelter's total electrical demand ((Newman et al. 1998) and (Newman et al. 1999).

13.3.4 Opportunities for Utilization of Renewable Energy

Opportunities for incorporation of renewable energy such as solar and wind power should also be considered as part of process development. Such approaches besides dealing with issue of energy costs which is a significant business risk for an energy-intensive business also enhance the sustainability credentials, promotes corporate social responsibility, and improves a company's public image.

Mining companies have not considered renewable energy as a viable alternative to conventional power generation because of its costs and because it is not compatible with the demand profile of a mining or metallurgical facility. Companies in the industrialized world have access to national and regional grids and their electricity costs are low because of the large loads. Although costs of renewable energy projects are coming down, projects require tax incentives and imposition of renewable energy mandates to make them viable. However, there are remote mining areas where renewable energy is already competitive with power generated from diesel.

A study by Accenture and the U.N. Global Compact (Accenture and U.N. Global Compact 2012) notes:

> "The metals and mining industry is uniquely positioned to not only drive business value related to energy efficiency and increased use of renewable energy, but also increased access to modern energy services as companies in this industry can be a catalyst for sustainable development in areas with little or no existing energy infrastructure. This characteristic—the operation of facilities in remote areas, provides the opportunity to link access to energy with core strategic business value drivers, such as risk management by protecting the "license to operate" and brand enhancement though community outreach and collaboration. This opportunity is one of collaboration and partnership as it relates to broader development concerns—of which access to energy is a primary enabler, and is reflective of metals and mining companies."

The study recommends the following industry actions: (1) Partner with local governments and utilities to provide energy services to communities surrounding operational locations; (2) improve the energy efficiency of current operations; (3) build advanced energy considerations into the design and development of new assets and operations; (4) diversify the portfolio to develop products and generate materials that drive energy efficiency; (5) use waste and process outputs as fuel sources; and (5) use more renewable energy sources to support operational power needs. The business levers are brand enhancement, cost reduction, and risk management and the objectives are energy access, energy efficiency, and renewable energy utilization.

Mining companies have large land holdings, most of which are not utilized. Some of the disturbed lands could be suitable for locating a renewable energy project. Asarco at its Mission mine in South Tucson has partnered with solar developers Clenera LLC, Panasonic Eco Solutions, and Coronal Group and the local utility Tucson Electric Power to host a 35-MW utility scale photovoltaic (PV) solar project called the Avalon Solar Project that commenced power generation in December 2014. A second phase to be implemented by year end will increase the solar farm capacity to 56-MW. This facility is located on disturbed agricultural land that Asarco acquired for water rights purposes.

EPA (EPA 2011) has conducted a preliminary evaluation of the potential for renewable energy development on Asarco reclaimed tailings areas in the San Xavier District on Tohono O'dham Nation lands. The study found:

> "Amidst this complexity, the ASARCO Mission Mine tailings area offers unique and potentially innovative opportunity to accommodate and potentially expand a utility-scale solar energy project at a single location. The tailings area has existing transmission capacity, roads, industrial zoning and other critical infrastructure in place for a utility-scale PV project. Additionally, installing a solar generation plant and associated infrastructure on a formerly impaired area can help take development pressures off of undeveloped, open land ("greenfield") areas."

In the future, Asarco would like to evaluate installation of PV solar project on reclaimed tailings and waste rock deposition facilities.

The primary copper industry operates electrowinning and electrorefining facilities, where the copper is plated onto cathodes. These are significant electricity consumers requiring direct current. It might make sense to evaluate solar and wind power to provide part of the electricity needs. The electrolyte in copper electrowinning and electrorefining needs to be heated and solar heaters may be considered instead of fossil-fuel fired boilers.

13.4 Opportunities for Water Conservation

Water is becoming an increasingly precious commodity. In arid and semiarid areas of the world such as the Southwest United States, South Africa, Australia, and Chile, where many large mining operations are located, water supplies are scarce. The ability to secure adequate water supply can very well determine whether a mining project involving large water use can be implemented.

A paper in the International Mineral Processing Congress (IMPC) Proceedings (Dunne 2010) reports on water stewardship initiatives undertaken by the mining industry over the last two decades and provides examples of water treatment projects that have been implemented. Although the mining industry uses considerably less water than other sectors such as agriculture, mining consumes significant quantities of water and is in competition with other more valued uses such as agriculture, livestock, and human consumption. Dunne notes that "water rights and availability are extremely contentious issues in mining regions around the world," as are "the amount and quality of water that a mine is able to discharge." He advocates "developing a responsible, sustainable and transparent water management strategy that is recognized as such by all stakeholders," in order to build confidence with the public.

The majority of the water used in the copper mining industry is for beneficiation, smelting, and refining operations. Most of the beneficiation water is used in the flotation process, followed by leaching of copper ores. It is estimated that water consumption by the mining industry is in the range of 0.6–1.0 cu.m./ton of ore processed by flotation (Brown 2003; Norgate and Lovel 2006; and Wiertz 2009), compared with the consumption for the Leach, Solvent Extraction, and Electrowinning route of 0.13 cu.m./ton of ore (Wiertz 2009) and smelting in the range of 2–4 cu.m./ton metal (Norgate and Lovel 2006).

The principal sources of water at a mine are groundwater and surface water from rivers, lakes, and reservoirs and, at some locations even seawater. Groundwater can have varying salinity and pH and can contain heavy metals of natural origin. Mine dewatering can also result in high salinity and metal contamination. Acid mine drainage occurs due to the oxidation of sulfides in waste rock and tailings and has very low pH, high metal content, and sulfates. Precipitation can result in run-on water which is usually directed around the mine so that the water is not impacted by the mining operation. Run-off water is usually impacted by the operation and therefore retained at the site to the extent possible, as it can have a slightly acidic pH, low metal content, and high suspended solids due to erosion. Suspended solids are controlled by settling in sedimentation ponds.

A mine site water balance is an important component of a good water management program. Water consumption at mines can be reduced by incorporating good water management practices such as increased recycling of process water, reducing water losses by evaporation and seepage. Most conventional tailings storage facilities recycle a considerable proportion of the tailings decant water from the tailings storage facility. Generally, water treatment of a bleed stream is needed only if the water is saturated with gypsum. Advances in thickener technologies over the last two decades have made it possible to produce higher underflow densities and allowed for the treatment of "difficult to dewater ores" (Schoenbrunn et al. 2009). The development of large capacity vacuum and pressure filter equipment (Mathewson et al. 2006) has made it possible to store tailings in the unsaturated state. The filtered tailings can be transported by conveyor or truck and placed, spread, and compacted to form an unsaturated dense and stable tailings stack. Alternatives to conventional tailings management and factors that favor dry stack tailings facilities are discussed in the literature (Davies and Rice 2001) (AMEC 2008).

When reusing process water, it is important to consider any adverse impacts of organic and inorganic contaminants on the metallurgy of the unit operation where the recycled water is used. A number of researchers have studied the effects of deleterious residual reagents and their decomposition products on the metallurgy of flotation and leaching (Knapp 1973; Frossberg and Hallin 1989; Rao and Finch 1989; Klimpil 1996; Johnson 2003; Schumann et al. 2009). Mixing of waters of different pH in a flotation circuit can lead to precipitation of hydroxides or impact the pH control needed for selective flotation. Because recycle water can contain both dissolved and suspended solids it may not be ideally suited for water uses such as pump gland sealing, water cooling, and water sprays (Cooper et al. 2006). However, a positive impact is the return of residual reagents, which lowers reagent costs in addition to the lower cost of purchased water or groundwater pumping.

In some instances, desalination processes for brackish groundwater or seawater may need to be implemented to supply or supplement water needs of a mineral or metallurgical process. Examples include utilization of hyper-saline groundwater (Dunne 2010) for milling and leaching applications at most western Australian gold mines and in nickel and gold flotation plants in the region. The author also references operating experience at Batu Hijau Mine in Indonesia, where sea water is used 7–8 months of the year and a mix of runoff from stockpile, waste, and mine dewatering. Based on a number of years of operating experience, it was noted that corrosion was considerably less with seawater only as compared to the blend and that there were no deleterious effects on froth flotation process or copper recovery (McCaffrey 2010). In Chile, the Michilla copper mine has been using seawater since the 1990s for copper leaching (Wiertz 2009).

The first big mining company to use seawater in Chile was Minera Esperanza, a joint venture between Antofagasta Minerals and the Marubeni Corporation. The company's copper mine uses untreated seawater, transported through a 145-km-long pipeline, in all of its processes. Seawater currently accounts for 30 % of all of the water the mine uses. The National Copper Corporation of Chile (CODELCO) will use seawater for the first time to exploit the sulfide reserves of the Radomiro Tomic (RT) mine. The Radomiro Tomic (RT) Sulphides project will extract seawater and desalinate it through reverse osmosis, a process that uses pressure to force water through a membrane which retains the dissolved solids. The treated water will be transported to the mine's facilities, located 3000 m above sea level, through a pipeline stretching 160 km. The operation will entail an expenditure of $2.60 per cu. m. (http://www.ipsnews.net/2013/08/mining-industry-plans-massive-use-of-seawater-in-arid-northern-chile/).

In copper smelters, the use of acid plants to control sulfur dioxide emissions in sulfide smelting results in the blowdown from the acid plant scrubber of weak acid streams containing heavy metals. Another source of wastewater results from cooling water from the acid plant cooling tower and from furnace cooling. Wastewaters from a copper refinery include bleed streams from the tank house, by-products department, and rod line which may need treatment prior to recycle or disposal.

Opportunities for recycle reuse of process water are therefore an important consideration and are more attractive if they can be done without further treatment. For example, the U.S. primary copper industry utilizes acidic scrubbing solution in the leaching of ores and hydrometallurgical processing of flue dusts (Gabb et al. 1995).

13.5 Effluent Management

Most mining, mineral, and metallurgical processing operations, at least in the United States are designed to have zero or minimal discharge. However, where discharge is necessary and permitted, the effluent must be treated to ever stricter discharge limitations promulgated by regulatory agencies. In response to the increasing number of environmental regulations all over the world in the last 30 years, nonferrous smelters and refineries have implemented treatment processes for acidic bleed wastewater streams containing heavy metals. Such treatment usually results in a gypsum-saturated solution containing salts such as alkali metal sulfates, chlorides, and fluorides.

The rising cost of fresh water and the need to meet increasing stringent discharge limitation regulations has made water recycling and reuse essential. The metallurgical industry has used water as a medium for dissolving and/or rejecting metals and chemicals in addition to removing heat from processes such as smelting equipment and acid plants. Any excess process effluent is collected and sent to end-of-pipeline treatment and ultimately discharged to a surface water body for discharge under a permit (Ramachandran 1997).

Several alternatives for treatment of wastewaters from nonferrous smelters and refineries streams containing high levels of total dissolved solids with emphasis on sulfate removal have been reviewed in the literature (Ramachandran 2012). They include: (a) chemical treatment for removal of various constituents that make up the total dissolved solids, (b) processes for sulfate removal—thermal and nonthermal—to recover and reuse treated water, and (c) brine use and treatment options.

The conventional and probably the cheapest way of treating acidic metal-bearing process effluent streams is neutralization of free sulfuric acid with lime, caustic, or soda ash and to precipitate the heavy metals as metal hydroxides. Any arsenic present in the water precipitates as calcium arsenite, if lime is used as the neutralizing agent. Additional heavy metals removal can be removed by sulfide polishing using sodium sulfide to produce a treated effluent that meets the regulatory agency limits, i.e., NPDES limits in the United States. Such treatment results in a stream containing low dissolved solids. Further, the precipitation and sulfide polishing steps result in precipitation of metal hydroxides and sulfides as a residue that has to be managed in accordance with solid and hazardous waste regulations, i.e., whether they can be legitimately recycled or whether they are hazardous or nonhazardous, if discarded. See Sect. 13.6.

The dissolved solids that remain are normally comprised of inorganic salts. The possible constituents are cations, calcium, magnesium, sodium, and potassium. The anions are sulfate, chloride, fluoride, nitrate, carbonate, and bicarbonate. In addition to these constituents, the treated effluent streams contain very small amounts of heavy metals, oxyanions such as arsenites, arsenates, selenites, and selenates. Process streams from gold operations contain residual cyanide. Small amounts of ammonium ions could also be present in these streams based on the pH of the solution.

With increasing stringent effluent limitations, it may be necessary to augment a conventional treatment plant with technologies for the removal of specific metals (such as Se, Sb, Cd, Pb, Mn, and Al), oxyanions, other anions, organics, or suspended solids prior to discharge. These technologies include: Ion Exchange, Reverse Osmosis, Electrodialysis Reversal (EDR), Nanofiltration Activated Carbon Adsorption, Deep Bed Sand Filtration, Biofix Beads, and pH adjustment.

The recovery of treated water as a distillate by evaporation results in a brine solution, the quantity of which is dependent on the amount of soluble salts present in the treated water. This is an expensive option because evaporation costs are generally high. Mechanical Vapor Recompression Evaporator (MVRE) technology uses mechanical vapor recompression to recover water for reuse from brines at a fraction of the energy needed in other types of evaporators (Bostjancic and Ludlum 1996). Typical energy costs are estimated to be around 60–100 KWH per 1000 gal, the equivalent of a twelve-effect crystallizer (Bostjancic and Ludlum 1996). In a typical MVRE unit, the necessary driving force is generated by mildly compressing the evolved vapor (steam) to increase its temperature and pressure and returning it to the steam chest. The evaporator can be adjusted to work on a small temperature difference so that the energy used for steam compression can be kept low. A distillate with less than 10 mg/L total dissolved solids (TDS) and a concentrated brine—with concentration up to 250,000 mg/L TDS can be obtained. The brine can be dried in a pond; crystallized or spray dried and the resulting salts sent to a land fill. The process is economical only when the boiling point rise is less than or equal to approximately 5° F.

13.6 Solid and Hazardous Waste Management

Metallurgical processing of many nonferrous metals generates large volume, low toxicity wastes, such as tailings and slag. Under the Resource Conservation and Recovery Act, EPA has determined that these wastes are to be regulated as solid wastes. Most mining and beneficiation wastes associated with the processing of ores and a few smelting wastes, such as slags, are classified as nonhazardous. As noted in Sects. 13.2 and 13.5, with regard to secondary materials destined for recycling or reuse, their regulatory status depends on how the materials are characterized, i.e., whether they fit the definition of by-products, sludges or spent material, scrap metal, etc., and the manner in which they are recycled, i.e., whether they are being reclaimed or are being used or reused as ingredients in an industrial product or as effective substitutes for commercial products (40 CFR § 261.2).

The difference in the cost of solid and hazardous waste management can be significant. In process development, there is a need to examine the regulatory regime in areas where the process will ultimately be implemented. Therefore, means for reducing the amount and character of the waste can have an important bearing on process economics as well as reducing environmental impacts.

Another approach to waste management is waste utilization, especially large volume wastes such as copper mine tailings (MT) and copper smelter slag (SG) as substitutes for naturally occurring raw materials. Ahmari, Parameswaran, and Zhang (Ahmari et al. 2014) have studied alkali activation of copper mine tailings and low-calcium INCO flash furnace slag to produce a geopolymer that can substitute for Ordinary Portland Cement (OPC). The results show that the addition of SG significantly improves the Unconfined Compressive Strength (UCS) and microstructure of the geopolymer. The improvement is mainly attributed to the high solubility of silica in the SG and the fine particle size of the SG. The inclusion of SG also leads to a decrease of the optimum curing temperature (i.e., the temperature at the highest UCS) because of its higher reactivity than MT. In addition, the MT/SG-based geopolymer sets fast and gains a major portion of its ultimate strength within only 7 days. Based on the results, it can be concluded that the MT/SG-based geopolymer is a promising sustainable construction material for civil engineering applications.

13.7 Control of Gaseous and Particulate Emissions

Control of emissions is of particular importance in the development of pyrometallurgical processes. It mainly involves control of particulate matter, acid mist, metal fumes, sulfur dioxide, nitrogen oxides, and carbon monoxide. In process development, it is important to determine the emission rates that can be anticipated in a commercial process, so that suitable capture and control methods can be identified. If the off-the-shelf control equipment is not available, collaboration with air pollution control vendors might be necessary. A good understanding of the mining plan is also important, since sulfur and impurity concentrations can fluctuate from year to year based on the ore grade mined. If it is anticipated that there will be periods where high sulfur or high impurity concentrations will occur, then the gas handling systems have to be designed to effectively handle these periods and comply with regulations.

Although attention to potential emissions is needed at all stages of process development, it is particularly important at the pilot plant stage. Designing the pilot plant to obtain dust emissions rates and the characteristics of the dust will help in selecting the air pollution control equipment and in designing heat recovery equipment. Dry dust collection technologies, such as hot ESP, enable easier dust collection and recycling. Using a hot ESP can also allow segregation of the dust to enable recycling of the desirable constituents such as copper in the first few fields and a bleed stream for the impurities such as lead and bismuth in the last fields. The air pollution control systems should be designed to be robust for changing operating profiles such as various air blowing rates and oxygen enrichment in sulfide smelting. Process development should also consider the potential for utilization of the sensible heat in off-gas and where the collected dust can be optimally reused. Baghouses generally have the highest collection efficiency but must operate at lower temperatures than an ESP. For this reason, ESPs are commonly used for the hot primary gases from smelting and converting operations, and baghouses are commonly used for dryer and anode furnace primary gases as well as fugitive and secondary gases from the smelting furnace and the converters.

In addition to point source controls, it is often necessary to capture and control fugitive emissions. Most fugitive and secondary emissions systems in the primary copper industry now employ at least particulate control. This is typically done using a baghouse. In addition, fugitive emissions that are not captured could result in worker exposure and this can be dealt with by implementing engineering controls or through the use of respirators, as discussed in Sect. 13.8. In sulfide smelting applications, SO_2 controls are almost mandatory. This can be done using traditional dry or wet scrubbing processes or potentially with regenerative processes depending on the SO_2 strength and other factors.

Computational fluid dynamics (CFD) modeling provides a powerful tool to assist with the design of ventilation and fume control systems. It is used to predict and evaluate:

- Performance of ventilation systems
- Airflow pattern and contaminant migration paths
- Hood designs and configuration for the optimum capture of contaminants
- Worker heat and contaminant exposure limits
- Combustion efficiency for a given geometry

CFD modeling has been applied to analyze the off-gas flow pattern exiting the mouth of a converter into a water-cooled hood and a drop-out box in order to optimize hood design (Safe and Stephens 2000).

System pressure loss modeling is used to size and specify fan performance requirement and optimize ductwork configuration, routing and damper controls to provide the desired exhaust flow distribution.

Dispersion modeling is used to evaluate the impact of emissions from various sources on ground level concentrations to ensure that a facility can comply with ambient air regulations.

13.8 Industrial Hygiene and Safety

As new processes are being developed attention must be paid to industrial hygiene and safety considerations. Both physical and health hazards associated with the new process have to be assessed. Process risk assessment must be an integral part of management philosophy and should involve evaluation of consequences of a catastrophic release both from worker safety and community perspectives. As noted in Sects. 13.1.3.1 and 13.1.4, the objective is to prevent or minimize the on-site and off-site consequences of catastrophic release of toxic, reactive flammable, or explosive chemicals.

The other main concern is the release of toxic air contaminants such as inorganic arsenic, lead, or cadmium in the workplace. The pilot scale testing and commercial demonstration protocol should include testing to obtain employee exposure estimates, as well as the feasibility of implementing engineering controls to minimize and reduce the exposure. Designing the appropriate measurements of exposures is a key to doing epidemiology assessments. There must also be consideration given to conducting occupation epidemiology on the workforce, especially if these constituents are already present in the workplace prior to introduction of a new process. Employee protection requirements can be met by the use of respirators, protective work clothing and equipment, or by implementing engineering controls. In addition, there are exposure monitoring provisions, medical surveillance, and removal provisions that have to be addressed in commercial operations.

13.9 Case Study: Kennecott-Outotec Flash Converting

The preceding sections illustrate how environmental, economic, and social considerations need to be considered in metallurgical process development so that the industry continues to be sustainable. The following case study illustrates how some of the considerations being advocated here were implemented in the development of the Kennecott-Outotec Flash Converting Process (David George and Rio Tinto 2015).

Kennecott-Outotec Flash Converting is a process developed in the 1980s and first applied as the basis for the large Rio Tinto Kennecott Copper smelter near Garfield, Utah. The technology has now been adopted by three new Greenfield copper smelters in China.

The process is based on the concept that if molten copper–iron–matte (~60–75 % Cu) is solidified and then ground and introduced into a flash smelting type furnace with oxygen, the resulting converting reactions will supply the heat to sustain the process. Since the flash converting process is decoupled from the smelting step, there is greater flexibility than the Mitsubishi Process, where the Converting Furnace is closely coupled to the smelting furnace.

The resulting off-gas from Flash Converting is a small volume, around 20,000 Nm^3/h, and very high strength, over 35 % SO_2. The Kennecott smelter, constructed in 1995, incorporated a very high level of heat recovery. The two flash furnaces each have waste heat boilers producing 6000 KpA saturated steam which is superheated and used to power the two main compressors in the sulfuric acid plant. The back-pressure turbines are each rated at 2.5 MW. The exhaust steam at ~1000 KpA is sent to a steam superheater in the sulfuric acid plant along with the waste heat steam recovered from the third Pass converter outlet gas and from the two Heat Recovery System (HRS). The HRS is a Monsanto Enviro-Chem process that recovers 1000 KpA steam from the acid absorption circuit. The combined superheated steam from the acid plant is sent to a 33 MW condensing steam turbine powering an electric generator. In normal operation, the electrical power generated from waste heat and some limited natural gas fired superheaters and auxiliary boilers provide 65 % of the smelters' electrical requirement, about 26 MW.

The development of flash converting followed a traditional route with initial pilot scale testing to confirm the concept followed by contract testing at the Outotec Pori Pilot plant and development laboratory in Finland. While the concept of making blister copper directly from very high grade (or low iron) concentrate was being developed at the same time as flash converting, there were some special considerations necessary for flash converting. Since one of the key steps in flash converting is the granulation of copper matte, full-scale tests were carried out at the Outotec Harjavalta copper smelter in Finland using their nickel matte granulator. Grinding the matte to a size suitable for feeding the pilot scale flash converting furnace was done using pilot laboratory equipment.

The actual pilot testing was done at a 1 t/h scale with some limited testing at 2–4 t/h. Since this pilot furnace had been used many times to test copper and nickel concentrate smelting, the scale up from test results to commercial scale furnace design had already been proven over several decades.

The design of the Kennecott smelter also includes special provisions to manage impurities such as bismuth, arsenic, lead, and cadmium. A hydrometallurgical treatment plant was conceived and progressed through laboratory testing to final design in 18 months. This plant also treats the various bleed streams from the copper refinery. The process is based on sequential separation and precipitation of bismuth to a waste, copper to a copper sulfide, and arsenic and cadmium to a combined As/Cd cake for ultimate management.

The Kennecott smelter is also unique because it integrates the impurity management at the copper refinery into the smelter waste treatment circuit. At the Refinery the Precious Metals Refinery (PMR), which recovers gold, silver, selenium, and other minor metals from the tankhouse slimes, was designed to control the recycle of bismuth and arsenic and provide an outlet for the lead. This is accomplished through a novel hydrometallurgical PMR circuit developed especially for Kennecott (Hoffman et al. 1995). The Hoffmann process is based on a hydrochloric acid and hydrogen peroxide leach of the decopperized slimes to dissolve gold and other elements. The gold is recovered using a solvent extraction technique and di-butyl carbitol as the extractant. The gold is directly precipitated from the loaded organic using an organic acid or salt such as oxalic acid or formic acid. The plant produces selenium and lead carbonate, both of which are sold for further processing.

13.10 Checklists

Presented below is a checklist for determining if environmental and sustainable development considerations have been addressed:

13.10.1 Conceptual Stage

Preliminary identification of whether the process is likely to be a significant water, energy consumer, based on the basic chemistry, theoretical considerations, and a conceptual flow sheet. At this stage there may be not be enough information to do a cost analysis.

13.10.2 Bench-Scale Testing

Bench-scale tests should be planned to verify proof of concept. The objective is also to develop a flow sheet for pilot scale tests. Consideration should be given to whether process has the potential to generate gaseous and particulate emissions, effluents, and process residues and that they may have to be properly disposed. With regard to gaseous and particulate emissions, it will be increasingly important to consider GHG emissions and how they will be controlled as climate change regulations mature. Consideration should also be given to see if the residues can be utilized beneficially. At this stage preliminary economics of the process should be done.

13.10.3 Pilot Plant Testing

The objective of this testing is to prove the process on a scale that is larger than bench scale. Bench-scale testing will identify potential environmental impacts; pilot design and testing should attempt to obtain better estimates of emission rates, effluent volumes, and residues generated. It should also be possible to make preliminary estimates of employee exposure to toxic air contaminants. Consideration should also be given to process control with a view to process optimization. Conversations should be initiated with environmental control vendors so that the necessary information for designing control equipment is obtained during pilot plant testing. The process economic information is further refined.

13.10.4 Commercial Demonstration

The objective of this stage is to verify the scalability of the process including the environmental control equipment, engineering controls for minimizing employee exposure to toxic air contaminants, and obtaining all other information that would be used to engineer a commercial operation. At this stage there should be a better handle on utility consumption. Process control and optimization is also important. Potential for water, energy, and resource conservation should be evaluated. Enough information is available from a technical and economic standpoint to determine the technical and economic feasibility for commercial operation. Up to this stage the focus has been on environmental, industrial hygiene, and safety and economic considerations. The community interaction thus far involves keeping the community briefed on community activities including new process development. It is essential that the community be kept informed on progress with respect to the various stages of process development and to consider any concerns that are raised.

13.10.5 Commercial Operation

During the planning process, prior to commercial operations, it is important to have the community thoroughly apprised of the new process that is to be implemented; its benefits; the environmental impacts; and how they are being avoided, mitigated, and/or managed. Due considerations need to be given to adequately address community concerns.

13.10.6 Impact on Upstream Operations

A new process may involve certain unit operations in a stage of the primary metal production process. Upstream impacts of a pyrometallurgical process on beneficiation, mining, and exploration need to be evaluated to determine if any operational changes are warranted. For example, a new continuous copper smelting process producing blister with higher impurity levels may impact where concentrates for the smelter are sourced.

13.10.7 Impact on Downstream Operations

Similarly, the impacts of downstream operations need to be evaluated. Again, the objective here is to see if downstream process changes are needed. For example, a new continuous copper smelting process might produce blister with higher impurity levels that might require modification to fire refining and/or electrorefining steps.

13.10.8 Use

The impact of the product in use is generally known because it is being produced to required specification, unless a new metal or metallic compound is being produced. Usually literature sources including Occupational and Safety Administration (OSHA) Material Safety Data Sheets (soon to become Safety Data Sheets (SDS) to comply with OSHA Globally Harmonized System) are available for this purpose.

13.10.9 Ultimate Disposal

These considerations are needed only if a new metal or metallic compound is being produced. Again MSDS and SDS are a useful source for this information.

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