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Chapter 12

Sustainability in Mining

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Sustainability is often defined as: *the ability to continue a defined behavior indefinitely.* However, considering the nature of mining operations, this cannot be meant with the phrase "Sustainability in Mining". Sustainability in the mining industry should be understood in the same way as sustainability in environmental science: *meeting the resources and services needs of current and future generations without compromising the health of the ecosystems that provide them.* A number of aspects of this are addressed in this chapter: use of energy, use of water, land disruption, reducing waste (involving solid waste, liquid waste, and gaseous waste), acid rock drainage when dealing with sulfide minerals, and restoring environmental functions at mine sites after mining has been completed. To do everything in an environmentally sound way is costly, but in the end necessary. Regarding this, it is concluded that governmental regulations concerning emission of waste, storage of waste and re-use of the land after mining are essential to provide a sustainable form of mining and mineral processing.

12.1 Introduction

Sustainability is often defined as: *the ability to continue a defined behavior indefinitely.* Clearly, this cannot be meant with the phrase "Sustainability in Mining". Once you have taken the ore, or coal, or industrial rocks, or industrial minerals out of the Earth, they are gone. The material will be processed and used. You cannot then put them back again. Therefore, sustainability in the mining industry should be understood in the same way as sustainability in environmental science: *meeting the resources and services* *needs of current and future generations without compromising the health of the ecosystems that provide them.*[1]

For the mining industry this means: to reduce the environmental impact of mining and minimize the footprint of its activities throughout the mining cycle, including work to restore ecosystems when mining has been terminated. In 1972, the Club of Rome predicted that many critical resources would soon be exhausted.[2] Although their prediction was proven to be false, nowadays again many people think that many critical resources may soon be completely depleted.

There is, however, no limit in sight for the supply of raw materials.[3] Advances in technology, product substitution, and reduction in pollution ensure a "sustainable" supply. The concept of a usable resource is an economic definition. Therefore improvements in extraction and processing technology allow the redefinition and transformation of previously uneconomic "waste" into economically viable ore. (e.g.[4]). This is clearly shown for copper. Calculation of available resources and reserves has steadily increased over time and increased demand has been met by increased supply (e.g.[5]). Available supplies are currently estimated to be in excess of 40 years. This figure has remained relatively constant between 30 years and 60 years of supply from the 1980's up to the present day.[6]

There are a number of aspects that should be addressed[7]:

- *Use of energy*
- *Use of water*
- *Land disruption*
- *Reducing waste*
- *Acid rock drainage when dealing with sulfide minerals.*
- *Restoring environmental functions at mine sites after mining has been completed.*

12.2 Use of Energy

Mining and metal processing often are very energy-intensive processes. Trucks and excavators use diesel fuel, and for grinding ore, a lot of electricity is used. Also to refine copper, aluminum and zinc a lot of energy is required. Coal (usually in the form of coke) is needed to smelt iron ore, and subsequently make steel. Other environmental impacts arise from the extraction of fossil fuels (coal, oil, and gas) and from the infrastructure required to produce energy. Also these processes produce greenhouse gases, and there is an increased risk of environmental contamination.

If the energy consumption in mining can be reduced, this can lead to reduction in the emission of greenhouse gases. Sources of fossil fuels will last longer, and additionally, operating costs are reduced. This again leads to a decrease in the cost of the commodity which is being mined.

12.3 Use of Water

In mining, water is used for a number of activities.[8,9]

- Lubrication
- Cooling
- Agglomeration
- As a medium enabling particles to be acted on (grinding and separating)
- Dust control
- Meeting the needs of the workers on site
- Mineral processing and metal recovery
- Preventing the mine from flooding

The amount of water used by a mine depends on the size of the mine and the activities. The latter are:

- the mineral being extracted
- the extraction process used

A mine that produces a metal may use the process of flotation[1,a] to separate ore minerals from waste. On the other hand, coal mines, salt mines and gravel mines use much less water.

Water needed for lubrication is usually applied in drilling. Water for cooling is used in many types of machinery in the mine. In agglomeration, water is used to obtain a suspension from which particles may settle through the process of flocculation.[b]

[a] *Flotation is a separation process, where finely ground ore is mixed with water to which additives have been added that alter surface properties of ore minerals and waste minerals. The particles become either hydrophobic (water shunning) or hydrophyllic (water loving). By blowing air bubbles through the suspension while stirring, the hydrophobic particles will adhere to the air bubbles, and rise to the surface, forming a foam layer. The hydrophyllic particles stay in the suspension. The foam is skimmed off at the surface, while the remaining ore pulp is removed as waste.*

[b] *Flocculation in the field of chemistry, is a process wherein colloids come out of suspension in the form of floc or flake, either spontaneously or due to the addition of a clarifying agent. The action differs from precipitation in that, prior to flocculation, colloids are merely suspended in a liquid and not actually dissolved in a solution.*[10]

Dust control is necessary. Dust must be prevented by spraying water, for a number of reasons. Dust is harmful to people, and harmful for equipment. Dust in the atmosphere may also lead to a dangerous situation where combustible dust particles become statically charged, and may discharge leading to a so-called dust explosion. Other sources of ignition in such a case may be sparks from machinery, friction or electric arcing, hot surfaces, or simply fire. Dust explosions have frequently happened in coal mines, often cause a large amount of damage, and may cause loss of lives.[11]

The workers on site need water to drink, and water to clean themselves after completion of their work (taking a bath or shower).

In mineral processing and metal recovery, water is used in a number of separation techniques, such as density separation techniques (for instance the *shaking table*,[c] see Fig. 12.1; and *the jig*,[d] see Fig. 12.2, and by surface chemistry methods[12] (*froth flotation, Fig. 12.3*).

Even in coal mining (in a coal washery) water is used to separate small coal particles (which float) from fine rocks particles (which do not).

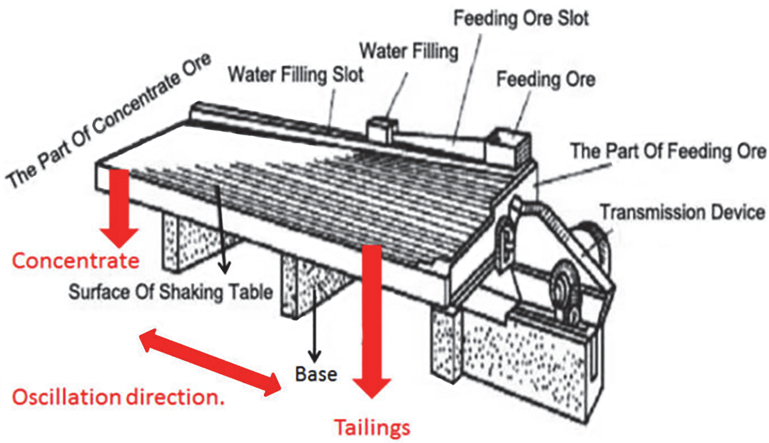

Fig. 12.1. Shaking table. Original image from.[13] Adapted.

[c] *The shaking table is a piece of equipment where a thin film of water loaded with ore particles is floated over a vibrating, inclined surface, leading to a separation of particles due to differences in specific gravity, size, and shape.*

[d] *A jig is a piece of equipment, in which ore is brought into a tank with water, of which the floor can go upward and downward in a slow pulsating movement, as a result of which the particles are thrown upwards and consequently sink according to specific gravity, which in the end results in a bed of particles that is stratified on basis of density of the particles.*

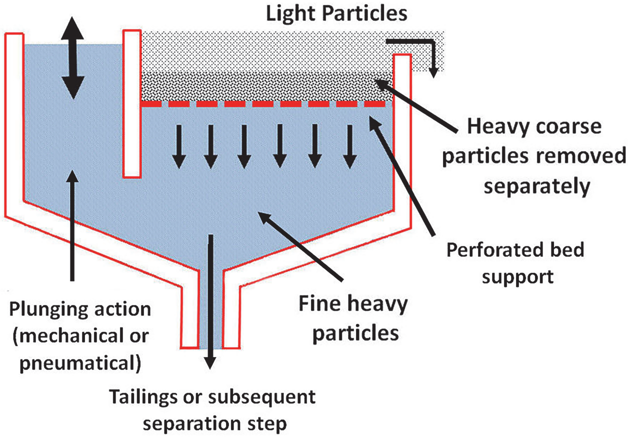

Fig. 12.2. Schematic picture of the operation of a jig. Original image from.[14] Redrawn.

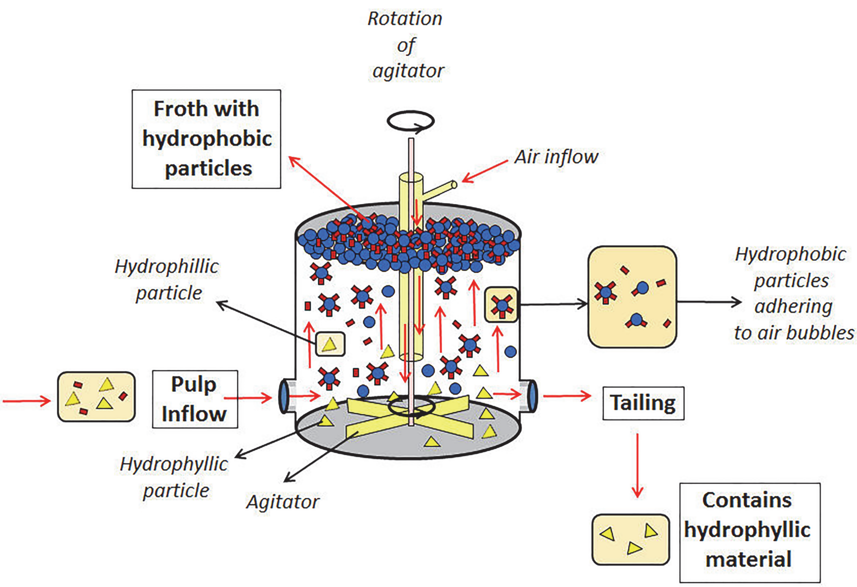

Fig. 12.3. Froth flotation, image from.[15]

To prevent a mine from flooding, usually water has to be pumped away (except in desert areas). This may have in itself a harmful effect. The large scale pumping of ground water in the German open pit lignite mines near Cologne also cause a significant lowering of the water table in adjacent Dutch areas, including the Dutch natural reserve "De Meinweg", near Roermond. Here, because of the pumping of water in, for instance, the German open pit lignite mine at Hambach, the land is drying out and many species of plants and animals are becoming endangered. The Hambach mine is currently some 370 m deep.[16]

12.4 Land Disruption

Mining activities use land at every stage of the mining cycle (exploration, construction, operation, closure, and post closure). However, the use of land can be diminished. The overall footprint of the mining area can be reduced by reducing the amount of waste produced and stored, and by planning mining sites around existing infrastructure where possible. Although at present, production of metals requires excavation of the ore, in the future, bio-mining, using bacteria to break down the ore minerals, may lead to an even larger reduction in the area of land used. In theory, only wells would need to be drilled, the solution with the bacteria pumped down, and, after a certain predetermined amount of time, pumped up again.[7,17] However, land disruption can never be completely avoided.

12.5 Reducing Waste

Mine waste includes solid waste, mine water, dust from mining, and waste from mineral processing (solid waste, process water, dust particles). Their composition can vary significantly, and so does their potential for environmental contamination.[18] Waste management plans are required to design and build appropriate storage facilities for the large amounts of waste produced at most mining sites. This includes rock waste dumps for rocks that had to be excavated, but are not mineralized, and tailing ponds for waste water from mineral processing plants.[7]

Using the proverb "prevention is better than cure", it is more economical and more effective to prevent pollution than to clean it up later. Therefore dedicated plans should be made for handling the anticipated waste before the mining operation starts.

What can be done to minimize waste?[7]

(1) Use of cleaner production techniques.
(2) Environmental control technologies.
(3) Use of waste as a raw material.
(4) Process re-engineering to reduce the amount of waste.

Water management strategies should be used to minimize the amount of waste water, and if possible, to clean it to an acceptable quality before releasing it. Over the past decades, in many countries, formal legislation has been passed in order to set acceptable standards for human impact on air, water and land.[7]

12.5.1 *Solid waste*

Solid waste from mining include overburden and waste rock, tailings remaining after mineral processing, and residues from any further treatment, such as leaching residues, water treatment residues, and slags.[8]

Mine wastes can be used on-site or off-site, stored in waste heaps, or used in leaching operations in order to recover additional valuable elements. Similarly, tailings may be used on- or off-site, stored in tailing ponds, or used in leaching operations.

However, the presence of waste disposal and storage facilities results in loss of land and can be harmful for the environment (loss of natural ecosystems, erosion, and leaching of materials from such facilities by wind and rain). Tailing facilities and waste heaps can collapse, leading to disasters involving the environment and the humans living there.[8]

12.5.2 *Liquid waste*

Water produced on a mine site can contain a wide variety of contaminants. Some of the more common contaminants are listed in Table 12.1. Not all of these will always be found in a particular mining operation.

These, and other impurities in water, have to be reduced in concentration to levels acceptable for the purpose for which the water is intended to be used.

Several techniques are available to clean the water. The technique to be applied depends on the required water quality, and also on the quantity.

These techniques are[8]:

- *Thickening, clarification and filtration.*
  Well known, and widely used.
- *Precipitation.*
  A common pre-treatment method.
- *Membrane technologies.*
  Techniques employed are micro-filtration, ultra-filtration, nano-filtration, reverse osmosis, and electro-dialysis.

Table 12.1: Common Contaminants in Mine Water and their Sources. (after[8]). Not Every Contaminant is Present at Every Mine Site.

Contaminant	Typical Source
Metals, Fe, Mn, Cr, Zn, Cu, etc.	AMD (Acid Mine Drainage) from oxidation of pyrite in mines, waste rocks piles, and tailings dams
Sulfate ions	AMD from oxidation of pyrite in mines, waste rocks piles, and tailings dams
Acidity (H^+ ions)	AMD from oxidation of pyrite in mines, waste rocks piles, and tailings dams
Cyanide	Spilling from gold leaching operations, and seepings from gold tailings dams
Suspended solids	Inadequate underground settling, run-off from surface, tailings dams, rock piles etc.
Sodium ions	From groundwater, artesian water, and land-locked inland lakes, addition of sodium-based reagents
Chloride ions	From groundwater, see above.
Nitrogen compounds	Wastes from explosives, sewage and other domestic wastes
Phosphate ions	Sewage and domestic wastes
Radionuclides	AMD attack on radionuclide bearing rocks
Microbes	Human fecal contamination, run-off from livestock grazing.

- *Ion exchange.*
  Used to demineralize water, and to recover specific elements. Used mainly as a last step in water cleaning.
- *Biological processes.* Can be useful to remove organic materials, nutrients, and sulfate, and to neutralize Acid Mine Drainage (AMD).

12.5.3 *Gaseous waste*

The nature of gaseous waste depends on the process. When fuel (oil, natural gas or coal) is burned to produce heat, the major gaseous products are CO_2 and H_2O. When carbon (or coke) is applied as a reductant to reduce oxides, large quantities of CO_2 (and sometimes CO) are produced. During roasting or smelting of sulfide concentrates, SO_2 is a major product. Also small quantities of SO_3 may be produced.[8]

When air is used as input, Nitrogen is also invariably a part of the off-gas, but is not considered a waste product, since it is an input which generally passes through the process without any chemical reactions.[8]

Gas streams, however, almost always contain particulate matter: entrained fine solid or molten particles arising from the material in the reactor, or formed from reactions in the reactor. This off-gas usually also contains small quantities of other, possibly harmful, gases in addition to N_2, CO_2, H_2O, and sometimes SO_2.[8]

The basic functions of a gas handling system include some or all of the following[8]:

- Containment and capture of process gas at the reactor exit.
- Cooling of the gas to a suitable temperature for subsequent handling, cleaning, or both.
- Separation of particulate matters (fumes and dusts)
- Transfer of the gas to gas cleaning, sulfur fixation, or the stack.

Several types of devices are used for separating solids from gas streams: settling chambers, cyclones and other centrifugal separators, bag filters, scrubbers, and electrostatic precipitators.[8] Gas cleaning systems may also contain activated carbon filters, to remove harmful chemicals such as dioxins, which may form in some reactors, e.g. as happened in the sinter plant of former Dutch phosphorus producer Thermphos.[19]

12.6 Acid Rock (Mine) Drainage

Acid Rock Drainage (ARD), also known as Acid Mine Drainage (AMD) is produced when sulfide-bearing material is exposed to oxygen and water. The production of AMD usually, but not exclusively, occurs in iron sulfide-aggregated rocks. The process occurs naturally, but mining can promote AMD simply through increasing the amount of sulfides exposed to water and air. Naturally occurring bacteria can enhance AMD production by assisting in the breakdown of sulfide minerals.[20]

AMD is often the major source of contaminated water at a mine site. The major mineral involved is usually pyrite, which oxidizes when exposed to water and air. The process is actually complex as it involves chemical, biological, and electrochemical reactions. Also it varies with environmental conditions. Factors of influence are, for instance, pH, pO_2, the specific surface and morphology of pyrite, the presence of bacteria and/or clay minerals, as well as hydrological factors.[21] Pyrite in mining waste or coal overburden is initially oxidized by the atmospheric O_2 producing H^+, SO_4^{2-}, and Fe^{2+}. The divalent iron can be further oxidized by O_2 into Fe^{3+}. This in turn hydrolyses, and precipitates as amorphous iron hydroxide releasing additional amounts of acid.[21] In the initial stage, pyrite oxidation is rather slow, but as acid production increases, and the pH in the vicinity of pyrite decreases to below 3.5, formation of ferric hydroxide is hampered, and the activity of Fe^{3+} in solution increases.[21] Then oxidation of pyrite by Fe^{3+} becomes the main mechanism for acid production in mining waste. At low pH, an acidophyllic, iron oxidizing bacterium (Thiobacillus ferrooxidans) catalyzes and accelerates the oxidation of Fe^{2+} to Fe^{3+}.[12]

The following reaction equation summarizes the process[22]:

$$4FeS_2 + 15O_2 + 14H_2O = 4Fe(OH)_3 + 8SO_4^{2-} + 16H^+$$

Prevention of acid mine drainage can be opted for ("source control"), but is not always realistic. Another possibility is "migration control". As both oxygen and water are needed to continue the formation of AMD, excluding either one (or both) should lead to prevention of AMD. However, completely sealing off abandoned mines from an influx of air and/or water is not easily done, and therefore usually, other approaches are better. One of these approaches is to minimize the production of AMD by blending acid-generating and acid-consuming materials (Johnson and Hallberg, 2005). This may be, for instance, adding apatite to pyritic mine waste in order to precipitate Fe^{3+} as ferric phosphate. In that way, its potential to act as an oxidant of sulfide minerals is reduced. Due to formation of coatings on the added phosphate, this technique often is only a temporary solution. The only alternative is to minimize the impact that polluted mine water has on the environment: migration control measures. These can be the continuous application of alkaline materials to neutralize acidic mine waters and precipitate metals, or the use of natural or constructed wetland ecosystems.[22]

12.7 Restoring Environmental Functions at Mine Sites after Mining has been Completed

Mining is a temporary activity. The life time of a mine ranges from a few years, to several decades. A mine is closed once the mineral resource is exhausted, or the mining operation is no longer profitable.[23] Usually, before a mining permit is granted, plans for closure of the operation are required. Also it must be demonstrated that the mine site will not be a threat to the health of the environment or society in the future. Depending on the site, the mine may be intended for other human uses, or restored to its pre-mining use. Such matters should increasingly be included in the original mine plan, and financial assurances are often required, in the event that the responsible company is unable to complete the closure as planned.[9]

After termination of mining activities, land restoration should be carried out. As a matter of fact, three different terms should be considered:

- Restoration
- Reclamation
- Rehabilitation

Restoration is defined as "the replication of site conditions prior to disturbance".[24]

Reclamation is defined as "rendering a site habitable to indigenous organisms".[24]

Rehabilitation is defined as "disturbed land will be returned to a form and productivity in conformity with a prior land use plan including a stable ecological state that does not contribute substantially to environmental deterioration and is consistent with surrounding aesthetic values".[24]

In some cases, restoration in the strict sense may be impossible.

Mining is also a destructive activity. To reduce environmental harm, careful management and regulation are necessary. In developing countries, this may, however, become second to economic growth. In brief, the environmental impacts caused by mining, are[24]:

- Ecosystem disturbance and degradation
- Habitat destruction
- Adverse chemical impacts (from improperly treated wastes)
- Loss of soil-found carbon (to the atmosphere).

12.8 Concluding Remarks

As can be learned from the previous discussion, sustainability in mining and mineral processing has many aspects, ranging, among others, from use of land for waste rock dumps, use of water, use of energy, up to the use of poisonous chemicals, and emission of waste gasses, waste fluids, and gaseous waste. To do everything in an environmentally sound way is costly, but in the end necessary, although especially in developing countries the economic aspects will probably be most important. Regarding the latter, governmental regulations concerning emission of waste, storage of waste and re-use of the land after mining are essential to provide a sustainable form of mining and mineral processing.

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