CHAPTER 1

ENGINEERING OF MINERAL EXTRACTION

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1 INTRODUCTION

Mining may be defined as the removal from the earth of solid material, to be sold at a profit. Note that liquid and gaseous products, such as petroleum and natural gas, are excluded from this definition. Table 1 shows one way of classifying materials that are recovered by mining, including examples for each category. Mining of stone and sand is sometimes referred to as quarrying.

Activities associated with mining have direct and lasting effects on both the physical and the human environments. This chapter considers only the former. The social, economic, and political effects in the latter category are addressed as *sustainability* issues, and are extensively discussed elsewhere,[1] as are issues of worker health and safety.[2]

2 THE RANGE OF MINING ACTIVITIES

Mining includes the following activities:[2]

1. *Exploration:* Economic deposits are identified and their characteristics are determined to allow recovery.
2. *Development:* Preparations are made for mining.
3. *Extraction:* Valuable material is removed for sale or processing.
4. *Reclamation:* Disturbances caused by any of the preceding activities are corrected or ameliorated.

Table 1 Classifications of Mined Resources

Metals	Industrial Minerals	Stone and Sand	Fuels
Copper	Potash	Dimension stone	Coal and peat
Gold	Phosphate	Sculptural stone	Oil shale
Iron	Salt	Natural gravel	Tar sand
Lead	Trona	Crushed rock	Oil sand
Silver	Kaolin	Paving stone	
Platinum	Bentonite	Building stone	
Tin	Limestone		
Zinc			

5. *Closure:* Activity ceases and the area is abandoned or returned to another use.

Mining occurred in prehistoric times with the extraction of flint and other rocks for use in tools, and of red ochre, a hydrated iron oxide, for use in coloring the bodies of the deceased, possibly to give an appearance of continued vitality.[3] Mining activity has occurred on every continent except Antarctica, where it is prohibited by international treaty.

Mining is a basic activity, underlying all industrial and commercial activity. In 2003, mineral production in the United States was valued at over $57 billion, approximately one-half of one percent of the gross domestic product. Mining is an important industry in 51 developing countries—accounting for 15 to 50 percent of exports in 30 countries and 5 to 15 percent of exports in another 18 countries. It is important domestically in three other countries.[1]

3 TRADITIONAL MINING PRACTICES

In the recent past, mining was done with little concern for its effects on the environment. The consequences of this approach often resulted in significant damage to the natural environment, including (but not limited to) the following:[4]

- Unreclaimed mine pits, shafts, tunnels, and refuse piles may result in landslides and large amounts of blowing dust.
- Surface and groundwater may be contaminated by solid particulates and chemical contaminants released by active and abandoned workings.
- There are potential hazards to humans, livestock, and wildlife from falling into abandoned pits, shafts, and tunnels.
- Erosion, with its consequent loss of soil and vegetation in and around unreclaimed workings can be a significant problem.
- Abandoned, underground workings may cause with surface subsidence.

Examples of these kinds of mining-induced damages are readily found in any historic mining district. In fact, water contamination and abandoned waste piles left by ancient Roman mining activity in Spain resulted in rediscovery of the orebody on which Rio Tinto, one of the largest mining companies in the world, was founded.[3]

In most cases, the environmental damage caused by mining was accepted by society because of the economic benefits that derived from mineral extraction. There were some notable exceptions, such as the lawsuit by downstream farmers against gold miners in California's Mother Lode district. Those miners used a method called *hydraulicking*, in which entire hillsides were washed away with a powerful stream of water, so the gold-bearing gravels could be processed. This resulting debris clogged streams and rivers and flooded meadows and fields, causing serious damage to agriculture.[5]

The public's expectations of the mining industry began to change in the 1950s, and by the end of the 1970s, governments in developed countries had enacted broad environmental laws that had direct bearing on all industrial activities, including mining.[6] Although environmental standards still vary among countries, almost all major mining companies now state as policy that they will operate all their mines, regardless of location, to *first-world standards* of environmental protection and worker health and safety.

4 ENVIRONMENTALLY CONSCIOUS PRACTICES

This section describes the processes in each of the mining-associated activities already listed, then describes the procedures and precautions required to ensure that each process is completed in an environmentally conscious manner.

Before discussing the individual activities involved in mining, it is important to point out that, to be truly environmentally conscious, all activities must be conducted with the future in mind. This will not only minimize the environmental effects of each activity, but will also result in significant cost savings. Three examples will illustrate this principle:

1. Design and location of roads developed for exploration should consider future needs for mining and processing. This will minimize unnecessary road building and decrease effects on the local ecosystem.
2. When containment ponds are required for drilling fluids or cuttings, consideration should be given to the future use of those ponds for tailings impoundment, stormwater catchment, or settling ponds.
3. The overall mine plan should include consideration of the requirements of reclamation and restoration. Placement of waste piles, tailings ponds, and similar materials should be carefully planned to minimize rehandling of material.

The mining operation should be thoroughly planned, in consultation with government agencies and people living in the region. Historic, cultural, and biological resources should be identified, and plans made for their protection. This is especially important in areas where indigenous people have little exposure to the technologies used in mining. Mining companies should take the appropriate steps to ensure that the indigenous people understand the mining plans. The indigenous peoples' values and land use practices must be understood, and steps must be taken to protect them. In some locations, this will necessitate the involvement of anthropologists, sociologists, and other experts. It may also require a planning and approval process that differs from those to which the company is accustomed. For example, some indigenous peoples make decisions by group consensus, necessitating large community meetings that may last for several days.

4.1 Exploration

Exploration includes three activities: reconnaissance, sampling, and geophysical surveys.

Reconnaissance

Reconnaissance often begins with aerial surveying and photogrammetry. This is followed by work on the ground, in which topography, surface geology, and geologic structures are mapped in detail. Obviously, the ground work requires that geologists, surveyors, and other personnel have access to the prospective mining property, with the ability to conveniently move about.

The primary environmental concern during reconnaissance is the effect of personnel movement and habitation. The following precautions should be observed:

- When personnel are transported to exploration sites by helicopter or airplane, landing strips and pads should be carefully selected to avoid damage to sensitive habitat and endangered or threatened species.
- When personnel travel around the exploration site in motorized vehicles, care should again be taken to ensure that sensitive habitat and endangered or threatened species are not damaged by tire tracks, or disturbed by engine exhaust and noise.
- Campsite locations should be carefully chosen to minimize effects on habitat, flora, and fauna.
- Low-impact camp practices should be observed. All trash should be collected and stored for removal when the camp is vacated. In especially sensitive areas, such as permafrost tundra and designated wetlands, solid human waste should also be stored and removed.
- Metal and plastic survey markers should be used carefully, and should be removed if exploration ceases and no further development occurs.

Sampling

Sampling includes geochemical sampling and material sampling by drilling and excavation. *Geochemical samples* are relatively small samples of surface water and soil, which are analyzed for a suite of trace elements whose presence in certain concentrations can indicate the presence of a mineral deposit. Geochemical sampling often occurs concurrently with reconnaissance, and the environmental concerns and precautions are identical to those noted for reconnaissance.

In *drilling and excavation*, larger amounts of material are removed for analysis and process testing. Thus, the environmental concerns are greater. Power equipment, often large, must be delivered to the site and moved to each sampling location. Some small drills can be delivered by helicopter, but most drills are either self-powered or moved by truck or tractor. Drills must be set up and operated on a level, stable *drill pad*, which is usually prepared with powered excavating equipment. The process requires water as a drilling fluid, and may use additives in the fluid. Sample excavations may be small test pits sunk with a backhoe, trenches cut with a bulldozer, or large, bulk sample pits developed by drilling and blasting.

The environmental consequences of sampling vary considerably among the various activities of sampling. All sampling activities require that personnel and equipment be moved to and around the exploration site; thus, all of the precautions listed in the previous section apply to this activity as well. In addition, the following steps should be considered:

1. When any material is removed for samples, the disturbed surface should be restored as nearly as possible to its original condition. For small samples, taken for geochemical analysis, this will likely require nothing more than smoothing the surface with a shovel and carefully replacing any small plants removed in sampling. For larger samples, backhoe pits, dozer trenches, and large test pits should be filled, recontoured, and revegetated with an appropriate mix of seeds and planting, as described in more detail in Section 4.4 on Reclamation. The length of time for which large sample sites may be left open is usually stated in the exploration permit, based on the applicable government regulations.

2. Roads and drill pads should also be reclaimed as just described. In some cases, the jurisdictional government may wish exploration roads to be left in place.

3. Drilling fluids and drill cuttings not removed as samples should be disposed of properly. These materials should not be placed into surface waters. They should be placed in stable configurations, with embankments and diversions provided to prevent contamination of runoff water where necessary.

4. In the development of pits for bulk samples, more extensive design for environmental compliance is required:
   - **a.** Sample pits will likely require reclamation similar to that required for full-scale mining pits.
   - **b.** It will likely be necessary to strip and stockpile any topsoil, for use in reclamation. It may also be necessary to divert surface water flow, both in streams and runoff, so that water will not flow through the pit and be contaminated.
   - **c.** If the pit is deep enough to encounter groundwater, the groundwater monitoring procedures described in Section 4.3 on Extraction may be required.
   - **d.** If bulk sample pits are developed by drilling and blasting, correct procedures for the handling and use of explosives must be observed.

Geophysical Surveys

Geophysical surveys involve the measurement of certain of the earth's physical properties, anomalous values of which may indicate the presence of valuable minerals. These properties include electromagnetic and gravitational field strength, electrical conductivity or resistivity, seismic reflectivity, and natural or induced radiometric emission. Preliminary electromagnetic and gravitational geophysical surveys are usually conducted using airborne instruments, and thus have very few environmental consequences.

Electromagnetic and gravitational surveys on the ground require that the appropriate sensor or sensors be moved over the site following a surveyed grid, so that the sensor readings are correlated with location. Some sensors are small enough to be carried in a backpack, while others are carried on a motorized vehicle.

Electrical and seismic surveys require the delivery to site and emplacement of a number of sensing instruments, which are usually connected by cables to a survey vehicle. The survey vehicle generates required output signals, electrical or seismic, then receive and log the signals returned by the sensors. Seismic surveys require the inducement of high-amplitude, seismic waves into the ground. This is done using explosives, projectiles, or large, hydraulically actuated *pads* that directly contact the surface of the ground.

Radiometric surveys measure naturally occurring or artificially induced ionizing radiation. Measurement of naturally occurring radiation is made for two purposes. The first is to locate ores of uranium or other radioactive elements. Initial surveys of this type are often airborne, and are followed up by traversing the surface and taking readings with a Geiger counter or similar device, as is the practice with electromagnetic or gravitational surveys. The second is to locate strata or other geologic members that are known to emit ionizing radiation. For example, the marine shales that often overlie coal seams emit gamma radiation, because small amounts of radon daughters are concentrated there by the depositional process. This type of survey is almost always conducted by measuring the radiation in a drill hole, as a function of depth. This may be done by using an instrumented drill string, or by lowering a radiation sensor into a previously drilled hole.

Surveys of artificially induced ionizing radiation are based on the fact that bombardment with activated neutrons causes many elements to emit gamma rays. The various elements present in the activated material are identified by the characteristic wavelengths of the emitted gamma rays. These surveys are almost always conducted by measuring the induced radiation in a drill hole, as a function of depth. This may be done by using an instrumented drill string that includes a neutron source and gamma detector, or by lowering such an assembly into a previously drilled hole.

The environmental consequences of geophysical surveys vary considerably among the various activities just described. When geophysical surveys are conducted on the ground, seven precautions should be observed:

1. When personnel are transported to survey sites by helicopter or airplane, landing strips and pads should be carefully selected to avoid damage to sensitive habitat and endangered or threatened species.
2. When personnel travel around the exploration site by motorized vehicles, care should again be taken to ensure that sensitive habitat and endangered or threatened species are not damaged by tire tracks, or disturbed by engine exhaust and noise.
3. Campsite locations should be carefully chosen to minimize effects on habitat, flora, and fauna.
4. Low-impact camp practices should be observed. All trash should be collected and stored for removal when the camp is vacated. In especially sensitive areas, such as permafrost tundra and designated wetlands, solid human waste should also be stored and removed.
5. Metal and plastic survey markers should be used carefully, and should be removed if exploration ceases and no further development occurs.
6. All sensors, wires, and other electronic equipment should be removed from the survey site. This may not be an issue for electromagnetic and gravimetric surveys.
7. Roads and vehicle parking pads should also be reclaimed. For electrical, seismic, or radiometric surveys, it will likely be necessary to strip and stockpile any topsoil, for use in reclamation. It may also be necessary to divert surface water flow, both in streams and runoff, so that water will not by flowing across roads and pads. In some cases, the jurisdictional government may wish exploration roads to be left in place.

There are a few other precautions specific to the type of survey used. The effects of the induced seismic waves used in seismic surveys should be carefully analyzed, for potentially harmful effects on wildlife and nearby human structures. Also, when conducting radiometric surveys, drilling fluids and drill cuttings not removed as samples should be disposed of properly. These materials should not be placed into surface waters. They should be placed in stable configurations, with embankments and diversions provided to prevent contamination of runoff water where necessary.

4.2 Development

Development is the preparation the facilities, equipment, and infrastructure required for extraction of the valuable mineral material. It includes land acquisition, equipment selection and specification, infrastructure and surface facilities design and construction, environmental planning and permitting, and initial mine planning.

Land Acquisition

Land acquisition is the activity that results in attaining the required level of control over those properties that are necessary for the timely development of a mining project. It may include outright purchase, rental, or leasing of the pertinent land parcels. In some cases, a mining company may purchase or lease the rights to extract a particular mineral commodity, while another party may have rights to extract another commodity, or to use the land for some other purpose. For example, one company may have the right to mine coal under a tract of land, while another may have the right to extract oil and gas. Similarly, the respective rights to extract minerals and to harvest timber may be separately owned or leased, or one entity may have mining rights while another has rights to graze livestock on the surface.

In land acquisition, the following environmental considerations apply:

1. *The land acquired should include all areas that will be used in extraction of the mineral deposit*. This must include area for tailings ponds, waste piles, topsoil stockpiles, access roads, surface facilities, and so on. Care must be exercised to ensure that an inadequate land position does not force installation of surface facilities in unsuitable locations—a waste dump located too close to a river, for example.
2. *Acquisition of land parcels with preexisting environmental contamination may result in the obligation of the acquiring company to remove or ameliorate the contamination*. For example, a company may acquire an old mine site, with the intention of exploiting previously uneconomic material, and find that existing buildings on the site contain asbestos insulation. The new owner may be required to remove that asbestos, an expensive process.

3. *In areas where endangered species are known, those species must be protected*. It may be necessary to acquire additional land to provide replacement habitat for animals or plants disturbed by mining activity, or to allow design of mining operations that will disturb existing habitat.

Equipment Selection and Specification

All equipment to be used in the mine is selected and specified in the development stage. This includes production and support equipment. Two environmental considerations apply:

1. *The source of power for mobile equipment should be carefully analyzed*. This choice affects the gaseous emissions from engines in the equipment, and also the overall energy consumption balance of the mine. If electricity is readily available, electric or electric-assisted haulage equipment may be preferred. At high altitudes, internal combustion engines require modifications to ensure efficient and clean operation.
2. *Requirements for air quality control should also be analyzed*. These may influence the selection of power sources for mobile equipment, and will also determine the number and type of water trucks required for dust control on the surface.

Infrastructure and Surface Facilities Design and Construction

Infrastructure and surface facilities may include all the following:

- Roads and railroads
- Electric power lines and substations
- Fuel supply lines and tank farms
- Water supply lines, water tanks, and water treatment plants
- Sewage lines and sewage treatment plants
- Maintenance shops
- Storage sheds and warehouses
- Office buildings, parking lots, shower facilities, and changehouses
- Worker accommodations (housing, cafeteria, infirmary, and recreation facilities)
- Houses for pumps, fans, and hoists
- Waste piles and impoundments
- Ponds for catchment of surface and ground water, and mine drainage

Six general environmental considerations apply to the design and construction of all surface facilities and infrastructure:

1. *Select locations of surface structures and infrastructure to minimize the effects of their construction and utilization on surface water, groundwater, plant and animal ecosystems, and nearby human habitation*. Surface

structures and infrastructure include roads, railroads, and power lines, for example.

2. *Remove and store topsoil for future use from areas that will be later reclaimed*. This applies only to facilities and infrastructure that will be razed at the end of the mine's life.
3. *Control runoff so that all water exiting the boundaries of the permitted mine site is captured and treated as required to meet applicable discharge standards*. Many jurisdictions permit mines as *zero-discharge* facilities, meaning that all water or solid waste is contained within the permitted mine area.
4. *Protect surface water and wetlands, using buffer zones or stream relocation designed to protect streams and wetlands*. Because these features may exist directly over mineral reserves, their relocation may be necessary.
5. *Revegetate disturbed areas*. Recontour the land to a defined standard and revegetate with an approved mix of seeds and plantings.
6. *Control emissions of dust and noise to meet the requirements of local regulations and the reasonable expectations of persons living nearby*. In particular, if explosives are used, control air blast and ground vibration as required.

Specific considerations for certain types of surface facilities or infrastructure include the following:

- Maintenance shops should be designed to avoid contamination of soil and water by spilled fuel and lubricants.
- Surface facilities should be designed to minimize energy consumption, utilizing solar water heating and alternative electric power generation wherever possible.
- Surface facilities should also be designed architecturally to harmonize with the natural surroundings in the locale.

Environmental Planning and Permitting

The forward-thinking approach mentioned earlier is especially important in environmental planning and permitting. In the *permitting process*, careful planning is imperative, so that information is gathered efficiently, the applications submitted to regulators meet all requirements, including timely submission, and mine planning costs are minimized by avoiding redesign required after agency review. As pointed out by Hunt, "One of the most serious deficiencies encountered by many operators in the permitting process is to fail to adequately plan the time required to collect baseline data and to provide for public and agency review of applications."[7] Hunt goes on to list the major tasks and activities required during early phases of environmental planning:

- Identification of the regulatory agencies that will be responsible for permitting the proposed mining operation
- Acquisition of all necessary permitting forms and copies of applicable regulations
- Identification of possible legal or technical restrictions that may make approval difficult or require special attention in the permitting process
- Identification of environmental resources information that will be required and the development of a plan and schedule for collection of the required data[7]

After preliminary planning, permit applications must be completed. Many jurisdictions require a detailed environmental audit, which is then described in a report, often called an *environmental impact statement*, or EIS. Depending on local regulations, the EIS may be issued for public review and comment. Topics covered in an EIS usually include the following fifteen areas:

1. Permits required and permitting status
2. Ownership of surface and mineral rights
3. Ownership of the company or companies that will be operating the mine, including contractors
4. Previous history of the entities described in Item 3
5. Information on archaeological, historical, and cultural resources within the planned mine site and adjacent areas
6. Hydrology of the mine site and adjacent areas, including the presence of potential pollutants and plans for dealing with them
7. Potential for dust and air pollution, and plans for mitigation
8. Plans for use and control of explosives
9. Plans for disposal of mine waste, including methods for controlling dust generation, slope stability, and seepage of contaminated water
10. Plans for impoundments, and methods for preventing failure or overtopping
11. Plans for construction of backfilled areas during mining, and for backfilling of mine excavations when mining is finished, including methods for preventing slides or other instability
12. Potential for surface subsidence, both immediate and long-term, and proposed methods of preventing subsidence or compensating for its negative effects
13. Potential for fires in mine workings, at outcrops, and in spoil piles, and methods for prevention and control of such fires
14. Planned use of injection wells or other underground pumping of fluids

15. Information on previous mine workings, plans for reclaiming previous workings, and description of how the planned workings will interact with previous workings

Mine Planning

It may be said that all of the development activities described to this point constitute *mine planning*. However, the term as used here refers specifically to the planning of the mine workings, including gaining access to the mineral deposit, removing the valuable mineral, and handling any waste material produced. The activity as here comprehended also includes tasks described as *mine design*. Although the details of these processes are described in the next section, planning for them is begun in the development stage, and is thus discussed at this point.

In mine planning, the specific, day-to-day operations of the mine are set out, analyzed, and documented. Mine planning continues throughout the life of every mine, to account for changing geologic and economic conditions. The objective of mine planning at each point in time is to determine the manner in which the mine should be operated to optimize the goal(s) of the operating entity, usually the return on investment.

Although mine planning varies with site-specific conditions, the following points must be determined in the initial plan, and continually reevaluated throughout the life of the mine:

- The extent of the mineral deposit
- The market for anticipated products of the mine
- The manner in which the deposit will be accessed for extraction
- The equipment and personnel that will be used for extraction
- The operating sequence for extraction
- The disposition of extracted material, both waste and valuable mineral
- The interactions of mine workings with adjacent or overlying areas and properties

Initial mine planning will obviously take place concurrently with the environmental planning and permitting, and the consideration of environmental consequences of the initial mine plan will be included in this process.

4.3 Extraction

Mining methods may be classified according to a variety of schemes. Here it is convenient to distinguish *surface mining*, *underground mining*, *aquatic* or *marine mining*, and *solution mining*.

Solution mining is the removal of valuable minerals from in-place deposits, by dissolving the mineral in a suitable liquid that is then removed for recovery of the desired constituent. It may also be called *in-situ mining* or *in-situ leaching*. Solution mining uses techniques similar to those used in the extraction of petroleum and natural gas, and is thus not discussed further in this chapter. The operational details and environmental considerations of surface mining, underground mining, and aquatic or marine mining are discussed separately.

Surface Mining

Surface mining is the removal of material from the earth in excavations that are open to the surface. In some cases, material is removed directly from the earth's surface; for example, sand and gravel may be removed directly from deposits of those materials put in place by ancient lakes or rivers. In other cases, material that has no economic value (*overburden*) covers the valuable material, and must be removed.

A typical operational cycle for surface mining, described in detail by Saperstein, is as follows:[8]

1. Install erosion and sedimentation controls.
2. Remove topsoil from areas to be mined.
3. Prepare the first drill bench by leveling the bench with a bulldozer, inspecting and scaling the highwall as required, and laying out the blast holes.
4. Drill the blast holes.
5. Blast the rock.
6. Load the fragmented material.
7. Haul the fragmented material, waste to the waste dumps and product to loadout for sale or to subsequent processing.
8. Manage the waste dumps as required by contouring waste piles to stable configuration or returning waste to mine workings for use in reclamation.
9. Prepare mine workings for reclamation by
    - **a.** Recontouring to the original contour, or to another, approved and stable configuration.
    - **b.** Returning the stored topsoil to the mine site, and spreading it uniformly on the recontoured surfaces.
10. Reclaim the prepared surfaces by
    - **a.** Revegetating with an approved mixture of seeds and plantings.
    - **b.** Irrigate and maintain revegetated areas as required until a stable condition is reached.
11. Remove temporary drainage controls and stream diversions.

The environmental considerations that must be addressed during surface mining include the following:

1. Control drainage from mine workings to avoid contamination of surface water, groundwater, and the existing ecosystem. Treatment may be required to remove particulates or chemical contamination.

2. Control inflow or surface water and storm runoff so these waters are not contaminated by passing through the mine workings.
3. Carefully analyze the groundwater regime in and around the mine workings, and provide monitoring wells as required. In some cases, it may be advisable to minimize the interaction of the mine workings with groundwater by pumping out the aquifers in and around the mine, and discharging the pumped water to constructed wetlands on the surface.
4. Design and construct waste dumps to minimize erosion and protect surface and groundwater.
5. Control emissions of dust and noise to meet the requirements of local regulations and the reasonable expectations of persons living nearby. In particular, if explosives are used, control air blast and ground vibration as required.
6. When mining is done at night, consider the effects of artificial light on wildlife and humans living near the mine.
7. Control slope stability and landslides. Of course, this is also necessary for successful mining operation, but inadequate control of slope stability may also lead to environmental damage. Slope failure may block or contaminate streams, damage wildlife habitat, and cause flooding that endangers wildlife and humans living near the mine.
8. Consider the effects of increased traffic to and from the mine site, especially when product haulage will result in a marked increase in heavy truck traffic.

Reclamation and closure of surface mines are discussed in Sections 4.4 and 4.5.

Underground Mining

Underground mining is the removal of material from the earth in excavations below the earth's surface. Access to such underground workings may be gained through a *drift* or *adit*, a *shaft*, or a *slope*. Drifts and adits are horizontal tunnels, usually in a hillside, that connect to the mineral deposit. In the case of minerals like coal that occur in *seams* (near horizontal deposits of fairly uniform thickness and considerable areal extent), the drift may be developed in the mineral itself. Travel in drifts is by rail or rubber-tired vehicles. Shafts are a vertical tunnels developed from the surface to access mineral bodies below. Travel in shafts is by cages or cars, which are lowered and raised by a mechanism on the surface, similar to elevators in tall buildings. Slopes are tunnels neither vertical nor horizontal, and may be lineal or spiral. Travel in lineal slopes may be by rubber-tired vehicles or hoists, but rarely by rail. Travel in spiral slopes (also called *ramps*) is by rubber-tired vehicles.

Again, Saperstein has described in detail a typical operational cycle for underground mining in which material is fragmented by drilling and blasting, as summarized:[8]

1. Enter the workplace after the previous blasting round is detonated.
2. Ensure that the workplace is in good condition and safe for continued work by checking that ventilation is adequate and that blasting fumes have been removed; providing for dust suppression; checking for the presence or hazardous gases; and inspecting for and removing loose material.
3. Load the fragmented material.
4. Haul the fragmented material to the appropriate location.
5. Install ground support as required.
6. Extend utilities as required: ventilation, power (electricity or compressed air), and transportation.
7. Survey and drill blast holes for the next round.
8. Load the explosives and connect the detonation system.
9. Leave the workplace and detonate the round.

This cycle is typical for the mining of narrow, steeply dipping veins (typical of metal ores), and for massive deposits of limestone, salt, and dimension stone, where the vertical extent of the valuable mineral is 6 meters or higher.

The operational cycle for methods in which material is mechanically fragmented and removed in a continuous process may be similarly summarized:

1. Enter the workplace after the required ground support has been installed.
2. Ensure that the workplace is in good condition and safe for continued work by checking that ventilation is adequate and that blasting fumes have been removed; providing for dust suppression; checking for the presence or hazardous gases; and inspecting for and removing loose material.
3. Cut and load the fragmented material until the limit for advance is reached.
4. Concurrently, haul the fragmented material to the appropriate location.
5. Remove fragmentation, loading, and hauling equipment from the workplace.
6. Install ground support as required.
7. Extend utilities as required: ventilation, power (electricity or compressed air), and transportation.
8. Survey as required to ensure that the mined opening is maintaining the required dimensions and directional orientation.

This cycle is typical for mining in near-level seams of relatively soft material that have considerable areal extent and are thinner than 6 meters, such as coal, trona, phosphate, and potash.

Seven environmental considerations must be addressed during underground mining:

1. Locate ventilation fans and hoist houses to minimize the effects of noise on wildlife and humans living nearby.
2. Whenever possible, dispose of mine waste in underground mine workings.
3. When waste dumps are constructed on the surface, design them to minimize erosion and protect surface and groundwater.
4. Control drainage from mine workings to avoid contamination of surface water, groundwater, and the existing ecosystem. Treatment may be required to remove particulates or chemical contamination. Control drainage from mine workings to avoid contamination of surface water, groundwater, and the existing ecosystem. Treatment may be required to remove particulates or chemical contamination.
5. Control inflow or surface water and storm runoff so these waters are not contaminated by passing through the mine workings.
6. Carefully analyze the groundwater regime in and around the mine workings, and provide monitoring wells as required. In some cases, it may be advisable to minimize the interaction of the mine workings with groundwater by pumping out the aquifers in and around the mine, and discharging the pumped water to constructed wetlands on the surface.
7. Analyze and predict the subsidence likely to result from mine workings. Design workings to minimize the effects of subsidence on surface structure, utilities, and important natural features such as lakes, streams and rivers, and wildlife habitat.

Reclamation and closure of underground mines are discussed in Sections 4.4 and 4.5.

Aquatic or Marine Mining

Aquatic or marine mining is the removal of unconsolidated minerals that are near or under water, with processes in which the extracted mineral is moved by or processed in the associated water. This type of mining may also be referred to as *alluvial mining* or *placer mining*. The two major types of aquatic or marine mining are *dredging* and *hydraulicking*.

Materials typically recovered by aquatic or marine mining have usually been deposited in fluvial, aeolian, or glacial environments, and are thus unconsolidated. They include aggregate (sand and gravel), and materials deposited because of their relatively high specific gravities. The latter deposits are called *placers*, and include native (naturally occurring) precious metals, tin (as the oxide cassiterite), heavy mineral sands (oxides of zirconium, hafnium, titanium, and others), and precious stones. In some cases, placer deposits are mined by methods described in the section on surface mining; in such cases, the environmental precautions given for those methods apply.

Dredging is the use of a powered mechanism to remove unconsolidated material from a body of water. The mechanism is almost always a type of bucket or shovel. In the simplest case, it may be a metal bucket moved by chains or steel cables that are attached to a pole. The bucket is dropped through the water and into the solid material on the bottom. As the bucket is retracted, its weight and trajectory force its leading edge into the solid material, and the bucket fills. When the bucket comes to the surface, it is emptied. This type of dredge is usually installed on the shore, near a body of water that covers a valuable mineral deposit.

More complex dredge mechanisms attach several buckets to a wheel or a *ladder*. A ladder is structure designed to support a series of buckets attached to a chain, which moves continuously in a loop. Both mechanisms are usually installed in a floating vessel, the *dredge*. While moving, the bucket wheel or the dredge ladder is lowered into the unconsolidated material below the surface, picking up that material and returning it to the dredge, where it is either further processed or transferred to the shore for further usage. The dredge vessel may operate in a natural body of water or in an artificial body called a *dredge pond*. A typical operational cycle for dredging is shown below:

1. If dredging in a dredge pond, complete the steps a–g; if not, proceed to Step 3.
   - **a.** Locate a source of water for filling the pond.
   - **b.** Install erosion and sedimentation controls, and divert surface water as required.
   - **c.** Prepare dikes or dams required for the dredge pond. The perimeter of the dredge pond must extend beyond the extent of the mineral to be recovered, to allow for deposition of overburden or tailings removed in the first pass of the dredge.
   - **d.** Fill the dredge pond.
   - **e.** Remove vegetation.
   - **f.** Remove and stockpile topsoil.
   - **g.** If necessary, remove overburden with excavating equipment, and place overburden in stable piles.
   - **h.** Proceed to Step 3.
2. If dredging from the shore, prepare the site for installation of the dredge mechanism.
3. Install the dredge.
4. Remove by dredging any overburden that was not removed in Step 1 g.

   - **a.** When dredging in a natural body of water, the overburden will be deposited under the water, in an area from which the valuable mineral has already been removed, or in an area under which there is no valuable mineral.
   - **b.** When dredging in a dredge pond or from the shore, the overburden will be deposited beside or behind the dredge, in an area from which the valuable mineral has already been removed, or in an area under which there is no valuable mineral. When mining in a dredge pond, the overburden will for a time be at least partially under water; when mining from the shore, it will not. However, in both cases, the overburden will over time drain and be left exposed. It will thus require reclamation as described below.

5. Remove the valuable material by dredging.

6. Process the valuable mineral as required, to concentrate the valuable constituent(s). This processing is almost always done on the dredge, and is integrated with the dredging of the material.

   - **a.** When dredging in a natural body of water, the tailings will be deposited under the water, in an area from which the valuable mineral has already been removed, or in an area under which there is no valuable mineral.
   - **b.** When dredging in a dredge pond or from the shore, the tailings will be deposited beside or behind the dredge, in an area from which the valuable mineral has already been removed, or in an area under which there is no valuable mineral. When mining in a pond, the tailings will for a time be at least partially under water; when mining from the shore, it will not. However, in both cases, the tailings will over time drain and be left exposed. They will thus require reclamation, as described below.

7. Remove the valuable constituent(s) for sale or further processing off site.

8. Deposit the tailings under the water, in an area from which the valuable mineral has already been removed, or in an area under which there is no valuable mineral.

9. Continue dredging until reaching the limits of the dredge's cables and other connections, the limits of the pond, or the boundary of the deposit.

10. If dredging in an artificial pond, prepare and fill the next pond as in Step 1, and transfer the dredge. If dredging in a natural body of water, move the dredge to the next location.

11. Begin dredge operation in the new location by returning to Step 3. Simultaneously, and in accordance with the approved reclamation plan, reclaim overburden and tailings piles from previous work, according to Step 12 and 13.

12. Prepare mine workings for reclamation:
   a. Recontour to a stable the original contour, or to another, approved and stable configuration.
   b. Return the stored topsoil to the mine site, and spread it uniformly on the recontoured surfaces.

13. Reclaim the prepared surfaces:
   a. Revegetate with an approved mixture of seeds and plantings.
   b. Irrigate and maintain revegetated areas as required until a stable condition is reached.

14. Remove temporary drainage controls and stream diversions.

There may be considerable variation in the cycle, depending on how the dredge is transported between sites.

Hydraulicking is a method of mining placer deposits that was used extensively in the past, but has fallen into disfavor because of the potential for serious effects on the stability of the remaining surface and on nearby surface waters.

Hydraulicking required a large deposit of auriferous alluvium and a source of water that would provide sufficient volume and pressure head. Overburden and pay gravel were both removed by high-pressure water that flowed through a *monitor*—a large nozzle that could be rotated horizontally and vertically. Material removed by the flow from the monitor moved to the bottom of the valley, where the flow was controlled so that overburden passed directly into the stream channel and pay gravel flowed through a sluice or similar recovery device for recovery of the gold. Tailings from the sluice also flowed into the stream channel.

As already mentioned, hydraulicking of the placer gold deposits in the famous California Gold Rush of 1849 led to severe contamination of the rivers that drained the area of the gold deposit. The solids from the hydraulicking operations filled rivers with solids, which were eventually deposited downstream, with serious consequences for agriculture in the downstream areas.

Hydraulicking is still a very inexpensive method for moving large volumes of unconsolidated material, and is still used on a limited basis, with five precautions:

1. Material discharge from a hydraulicking operation must be captured and treated to remove solids, including, in particular any fine, suspended solids. This will require a settling pond, and chemical flocculants may also be necessary. Even water that appears to be clear must be tested by appropriate methods, and treated on the basis of those tests.

2. Tailings, overburden, and deactivated settling ponds must be reclaimed appropriately, usually be recontouring and revegetation. It may be necessary to remove and stockpile top soil for use in reclamation. Coarse gravel, which may accumulate in separate piles, should receive special attention to ensure that it is reclaimed properly.

3. The area of the mining operation should be isolated from the flow of surface streams and runoff, to prevent contamination of those waters.
4. Discharge of water from the hydraulicking operation should be managed to prevent interference with the existing flow regimes in the drainage. The quantities and velocities of discharge should not modify the existing stream flow in a manner that will cause erosion, undercutting of banks, or flooding.
5. Highwalls and embankments produced by hydraulicking should be reclaimed, again by recontouring and revegetation. Even when top soil is removed and stockpiled, there may not be enough topsoil for the reclamation required. In such cases hydroseeding will likely be required.

4.4 Reclamation

In the most general sense, reclamation is the gaining or recovery of land for a purpose that is perceived as higher or more beneficial, as in the recovery of low-lying coastal land by the building of dikes, or the recovery of desert lands by irrigation. However, as applied to mining activities, "... *reclamation* is a response to any disturbances to the earth and its environment caused by mining activity."[9]

The terms *restoration* and *rehabilitation* are often used synonymously with *reclamation*. However, *restoration* implies that a given site is returned to the exact conditions that existed before the disturbance, and *rehabilitation* indicates that the disturbed land is returned to conditions that conform to a prior use plan (often agricultural). In fact, it is often neither possible nor desirable to return disturbed land to its previous condition or use.

Reclamation is often considered only in association with surface mining, but, as reflected in the previous discussion, the activities of underground mining may also necessitate reclamation. However, the reclamation activities required in association with underground mining are almost always less numerous and less extensive.

Reclamation practice varies widely, depending on the type of mine, its location, and the applicable legal requirements. In all cases, it is important from the beginning to include reclamation, and the required planning for reclamation, in the mining plan. As summarized by Ramani et al. and Riddle and Saperstein, there are four required planning steps:[10,11]

1. Make an inventory of the premining conditions.
2. Evaluate and decide on the postmining requirements of the region, consistent with legal requirements and the needs and desires of the affected groups and individuals.
3. Analyze alternative mining and reclamation schemes to determine how the postmining requirements can be most easily met.

4. Develop an acceptable mining, reclamation, and land-use scheme that is optimal for the technical, social, economic, and political or legal conditions.

Detailed descriptions of the reclamation procedures and requirements for all situations are beyond the scope of this chapter. Instead, a detailed description will be given for surface coal mining, with additional comments for other cases that are considered noteworthy.

Premine Planning and Permitting

The following description of reclamation requirements for surface coal mining is based on requirements in the United States, as given in the Surface Mining Control and Reclamation Act (SMCRA) of 1977.[12]

Under SMCRA, specific requirements are given for obtaining a mining permit. A formal Reclamation and Operations Plan is required to document the information and conclusions of the planning process. The reclamation plan should include descriptions of the following:

- The uses of the land at the time of the permit application, and if the land has a history of mining activities, the uses that predate any mining activity
- The capability of the land, prior to any mining, to support a variety of uses, based on soil and foundation characteristics, topography, and vegetation
- The proposed use for the land following reclamation, including a discussion of the utility and capacity of the reclaimed land to support a variety of alternative uses
- The manner in which the proposed postmining land use is to be achieved, and the activities required to achieve this usage
- The consideration given to making mining and reclamation operations compatible with existing surface owners' plans and applicable, governmental land-use plans
- The consideration given to developing the reclamation plan in a manner consistent with local physical, environmental, and climatological conditions

The Reclamation and Operations Plan must specifically address the following:[13]

- Air pollution control
- Protection of fish and wildlife
- Protection of the hydrological balance
- Postmining land uses
- Ponds, impoundments, banks, dams, and embankments
- Surface water diversions
- Protection of public parks and historic places
- Relocation or use of public roads

- Disposal of excess spoil and mine waste
- Transportation facilities
- Development of new workings near existing underground workings
- Subsidence control
- Maps, plans, and cross-sections

A large amount of information is required for preparation of the Reclamation and Operations Plan. Table 2 summarize those requirements.[9]

Land-Use Analysis

The Reclamation and Operations Plan also requires an analysis of suitable uses for the land after reclamation. It is not always necessary to restore land to its premining condition and utilization. Often, a utilization of higher value is acceptable. For example, a previously forested hillside adjoining pastureland might be acceptably restored as pasture. In areas with high relief, mountaintop removal and valley-fill methods may be used to create new flat areas, which have positive use for agriculture and residential development.

SMCRA identifies 10 categories of postmining land use: crop land; pasture or land occasionally cut for hay; grazing land; forest land; residential development; industrial or commercial development; recreation; fish and wildlife habitat; developed water resources; and undeveloped land. The most suitable postmining land use will be determined in cooperation with local residents and interest groups, and government agencies.

Reclamation Operations

Reclamation operations are complex and extensive. The time sequence for reclamation activities in surface coal mining is summarized as follows:[10]

1. During site preparation:
   a. Install control measures (diversion, sediment traps and basins, etc.).
   b. Clear and grub; market lumber if possible; stockpile brush for use in filters or chip brush for use a mulch.
   c. Stabilize areas around temporary facilities such as maintenance yards, power station, and supply areas.

2. During overburden removal:
   a. Divert water away from and around active mining areas.
   b. Remove topsoil and store as required.
   c. Selectively mine and place overburden strata as required.

3. During coal removal:
   a. Remove all coal insofar as possible.

Table 2 Information Needed to Prepare Reclamation and Operations Plan

Natural Factors

1. Topography
- **a.** Relief
- **b.** Slope

2. Climate
- **a.** Precipitation
- **b.** Wind patterns and intensity
- **c.** Humidity
- **d.** Temperature
- **e.** Climate type
- **f.** Growing season
- **g.** Microclimatic characteristics

3. Altitude

4. Exposure (aspect)

5. Hydrology
- **a.** Surface hydrology
  - Watershed considerations
  - Flood plain delineations
  - Surface drainage patterns
  - Runoff amounts and qualities
- **b.** Groundwater hydrology
  - Groundwater table
  - Aquifers
  - Groundwater flow amounts and qualities
  - Recharge potential

6. Geology
- **a.** Stratigraphy
- **b.** Structure
- **c.** Geomorphology
- **d.** Chemical nature of overburden
- **e.** Coal characterization

7. Soils
- **a.** Agricultural characteristics
  - Texture
  - Structure
  - Organic matter content
  - Moisture content
  - Permeability
  - pH
  - Depth to bedrock
  - Color
- **b.** Engineering characteristics
  - Shrink-swell potential
  - Wetness
  - Depth to bedrock
  - Erodibility
  - Slope
  - Bearing capacity
  - Organic layers

8. Terrestrial ecology
- **a.** Natural vegetation
  - Characterization
  - Uses and survival needs
- **b.** Crops
- **c.** Game animals
- **d.** Resident and migratory birds
- **e.** Rare and endangered species

9. Aquatic ecology
- **a.** Aquatic animals
- **b.** Aquatic plants
- **c.** Aquatic life systems
  - Characterization
  - Uses and survival needs

Cultural Factors

1. Location

2. Accessibility
- **a.** Travel distances
- **b.** Travel times
- **c.** Transportation networks

3. Site size and shape

4. Surrounding land use
- **a.** Current
- **b.** Historical
- **c.** Land-use plans
- **d.** Zoning ordinances

(*continued overleaf*)

Table 2 (*continued*)

5. Land ownership	**h.** Transportation/utilities
a. Public	**i.** Water
b. Commercial or industrial	**7.** Population characteristics
c. Private or residential	**a.** Population
6. Type, intensity, and value of use	**b.** Population shifts
a. Agricultural	**c.** Population density
b. Forestry	**d.** Age distribution
c. Recreational	**e.** Number of households
d. Residential	**f.** Household size
e. Commercial	**g.** Average income
f. Industrial	**h.** Employment
g. Institutional	**i.** Educational levels

b. To control postmining groundwater flows, manage the condition of the strata immediately below the coal seam. In some conditions, it may be desirable to break these strata, in others to preserve them intact.

4. Immediately after coal removal:

a. Seal the highwall if necessary.

b. Seal the lowwall if necessary.

c. Backfill or bury toxic materials and boulders.

d. Dispose of waste.

e. Ensure compaction.

5. Shortly after coal removal:

a. Rough grade and contour, taking into account the following:
- Time required for grading, as related to advance of mining and seasonal constraints
- Steepness of slopes
- Length of uninterrupted slope
- Compaction required
- Reconstruction of underground and surface drainage patterns

b. If necessary, amend mine spoil to condition the root zone for revegetation, taking into account the following:
- Type of amendment required (fertilizer, limestone, flyash, sewage sludge, etc.)
- Depth of application
- Top layer considerations, including temperature and color, water retention (size, consist, and organics), mulching, and tacking

6. Immediately prior to the first planting season:
  - **a.** Fine-grade and spread topsoil, accounting for seasonal fluctuations
  - **b.** Mechanically manipulate soil as required—rip, furrow, deep-chisel or harrow, or construct dozer basins
  - **c.** Mulch and tack

7. During the first planting season, seed and revegetate, considering time and method of seeding and choice of species.

8. At regular, frequent intervals, monitor and control slope stability, water quality (pH, chemical content, and particulate content), and vegetation growth.

Backfilling and Grading. In most cases, backfilling and grading must return the land to the contour that existed before mining, eliminating highwalls, spoil piles, and depressions. The resulting slopes must be stable, each with the appropriate angle of repose. Another important objective is the elimination to minimize erosion and water pollution. Mining often leaves exposed coal seams, acid-forming or other toxic materials, and combustible materials, all of which must be buried to eliminate interaction with surface waters.

Erosion is controlled by grading to create terraces and diversions that decrease slope lengths and direct runoff water to safe outlets. During backfilling, the permeability of the fill can be controlled to achieve the desired degree of water percolation. The requirements for backfill and grading in reclamation operations should be considered in the selection of mining method.

Soil Reconstruction. All topsoil must be removed as a separate layer and segregated. When the topsoil is less than 6 inches (15 centimeters) thick, the unconsolidated layer beneath the topsoil must be removed and treated as topsoil. When the topsoil cannot be redistributed immediately, it must be stored according to approved methods. When topsoil is redistributed, it must have a uniform thickness, not be excessively compacted, and be protected from erosion by wind and water.

The postmining land-use objective must be selected with the characteristics of the topsoil in mind. Chemical soil properties are more easily amended than physical properties such as texture. Thus, when adequate topsoil is not available, the substitute material must be selected with special attention to texture, coarse-fragment content, and mineral content. Bulk density and soil strength must be considered during soil handling. Methods and equipment used for redistribution of topsoil must be selected to minimize compaction, which can inhibit root penetration and movement of air and water.

Revegetation. The vegetative cover resulting from reclamation must be diverse, effective, and permanent. The extent of the new vegetation must be at least as great as that of the natural, premining vegetation. The soil must be stabilized from erosion. Normally, planting must be done during the first normal season suitable for planting after redistribution of topsoil. Specific standards defining successful revegetation depend on the approved postmining land use; the general requirement is the achievement of 90 percent of the established standard. This cannot be achieved in one successful growing season; thus, the responsibility period is 5 years in areas that receive more than 26 inches (66 millimeters) of average annual precipitation, and 10 years in areas that receive 26 inches (66 millimeters) or less.

Postmining land use must also be considered when planning revegetation, taking into account species selection, soil amendments, and methods of planting. For example, when reforestation is planned, a major concern is competition from herbaceous plants, which must be controlled by scalping or proper use of herbicides. Similarly, when reclaiming land for pasture or hayland, important variables are water control, species selection, seeding time, fertilizer selection, seedbed preparation, seeding method, and use of mulches.

Reclamation of Mine Waste Disposal Sites. Mine waste piles will include material resulting from mining, such as overburden, waste rock from mining, and tailings, slurries, and slimes from processing. Also included may be waste from treatment of air and water, ordinary garbage, debris from construction, and discarded equipment. However, many jurisdictions require that garbage, construction debris, and discarded equipment be disposed of in a separately sited and approved sanitary landfill. Although this may initially be more expensive, it will greatly simplify the reclamation of true *mine waste piles*, and is thus recommended even where not required.

Generally, about twice as much waste results from mining as from processing, with most of the waste being overburden. The stability and proper handling of mine waste are influenced by its chemical and physical properties. Chemical properties are primarily responsible for potential hazards to public health and effects on the physical and biological environment. Chemical properties also determine the suitability of the waste for further processing. Physical properties determine the appearance of the waste during and after reclamation, and may strongly influence the ultimate form of the postmining land surface.

4.5 Closure

All mines eventually close, though there are different degrees of closure. Mines that are not open for production but could be reopened may be referred to as *temporarily closed* or *semi-permanently closed*; in this chapter, only *permanent closure* is considered.

Permanent closure occurs when a mine ceases operation because of economic conditions, depletion of reserves, political conditions, or any other reason. Closure generally includes the following three steps:

1. Sealing of underground mine openings
2. Removal of surface facilities
3. Reclamation of surface mines and surface areas of underground mines[14]

By definition, *sealing* is the securing of mine entries, drifts, stopes, adits, shafts, and boreholes to protect against ingress and gas and water emissions for the safety of the public. Similarly, *abandonment* is the voluntary act of abandoning and relinquishing a mining claim or the intention to mine. This differs from *forfeiture*, which is involuntary surrender of mining claims or the right to mine by neglect.[15]

Mine Facility Removal

All surface facilities that do not serve a purpose in the postmining use plan must be removed. These include buildings, conveyors, rail lines, transfer stations and loading facilities, electrical lines and substations, pipelines, roadways, drainage ponds, and drainage channels. Any hazardous material must be removed from the site, and disposed of in an approved facility. Sanitary landfills and other waste disposal areas must be reclaimed.

Removal of buildings and structures is often done by a company specializing in such activities. Demolition should be accomplished using standard construction equipment wherever possible, exercising due care not to endanger life or property. After demolition, all debris must be removed from the area, including concrete, concrete block, timber, metal scrap, and so on. All foundations must be removed to a depth below the soil horizon as specified in the reclamation plan, usually 2 to 3 feet (0.6 to 1.0 meters). After removal of structures, the surface should be graded and backfilled as specified in the reclamation plan.

As soon as a decision for closure is reached, a complete inventory of all equipment, parts, and supplies should be made. Using this inventory, plans can be made for appropriate disposition of each item. Many items can be resold or transferred to another mine owned by the company. In the case of large underground mining equipment, such as coal longwall units, it may be less expensive to abandon the equipment underground than to recover it to the surface.

Sealing of Underground Mines

Seals for underground mines must be designed in accordance with good engineering practice, and in conformance with applicable regulations. A complete hydrological analysis is required to determine if there will be a hydraulic head on the mine seal. The shutdown of the mine's ventilation system must be planned to prevent accumulation of hazardous gasses, and to ensure safe working conditions throughout closure and sealing. During sealing, areas near the seal point must be continuously monitored for accumulation of explosive or flammable gasses, which might be ignited by construction activities. Temporary measured may be necessary, such as the erection of temporary stoppings and direct supply of fresh air to the area where the seal is being installed.

Methods of sealing are described in detail by Gray and Gray.[14] *Dry seals*, used where development of a hydraulic head is not expected, are constructed by placing cement blocks or another suitable material in the mine opening to prevent the entrance or air, water, and persons. *Wet seals* are constructed with water traps so that water can flow from the mine but mine gasses are retained. *Hydraulic seals* are designed to stop the discharge of water from the mine, and must be constructed to support the developed hydraulic head. A hydraulic seal will cause the mine to flood, excluding air and thus retarding the oxidation of sulfide materials that results in acid mine drainage.

Boreholes must also be sealed. In one typical method, the surface casing and protective cap are removed to a few meters below the proposed final surface elevation. A plug is then installed in a competent stratum that is as close as possible to the intersection of the borehole with the mine roof. Finally, the borehole is filled with a nonshrinking cement grout, usually to within 2 feet (0.6 meters) of the surface, and the remaining length is filled with dirt.

Sealing of shafts requires extensive planning. In almost all cases, the shaft is completely filled with inert material. In coal mines, or other mines where flammable or explosive gasses may be present, approximately 50 feet (15 meters) of the shaft at the bottom must be filled with noncombustible material. After filling, shafts are capped with at least 6 inches (15 centimeters) of concrete. Normally, the shaft cap is fitted with a 2-inch (50-millimeter) vent pipe that discharges 15 feet (4.5 meters) above the surface. Hydraulic shaft seals can also be installed, with no provision for ventilation or discharge. These are designed with using the same methods used in designing a surface dam. After sealing, the shaft should be fenced to prevent access by unauthorized individuals.

Maintenance

After closure, almost all mine sites will require several years of care and maintenance. Periodic inspections should be conducted to verify that all seals are intact and functioning correctly, and to ensure that water discharges are within the limits specified by the permits. It may also be necessary to clean out water diversion and containment structures, and to support revegetation by regrading, reseeding, applying fertilizer, and irrigating.

Postmining Liability

Even after reclamation and closure are completed, the mining company should take ongoing responsibility for water treatment and subsidence mitigation. The need for water treatment may continue indefinitely, and mine operations should be planned to support these activities. Similarly, subsidence may not occur until many years after mining has ceased. If necessary, the company should post a bond or provide some other means of assurance to regulatory agencies that water treatment will continue as long as necessary, and that subsidence damages will be properly dealt with.

5 CASE STUDY

The Island Copper Mine in British Columbia, Canada, operated from 1970 through 1995. The reclamation and closure of the mine represent an excellent example of environmentally conscious mining practice. Welchman and Aspinall provided a case history of the mine, which is summarized here.[16]

Island Copper was operated by BHP Minerals Canada Ltd., a subsidiary of BHP International of Australia. When the mine ceased operation, BHP carried out a comprehensive plan to achieve mine closure, while also making a transition to commercial and industrial use of the site.

At the peak of its operation in 1980, the mine had 900 employees. The orebody was mined by conventional open-pit, truck-and-shovel methods. A total of 400 million dry short tons (364 million metric tons) was removed, and processed for recovery of copper and molybdenum. An additional 600 million short tons (545 million metric tons) of overburden were excavated, resulting in an oval pit that was 7,900 feet (2,408 meters) long, 3,500 feet (1,067 meters) wide, with a bottom elevation 1,322 feet (403 meters) below sea level. The operation had two unique features: Mill tailings were deposited below the ocean surface in Prince Rupert Inlet, and a plastic concrete seepage barrier, 4,000 feet (1,219 meters) long, 108 feet (33 meters) deep, but only 2.8 feet (0.86 meters) wide, was installed along the original shoreline of the inlet.

Island Copper instituted a comprehensive water management program to control runoff from waste rock dumps, maintain pit dewatering, and recycle all site drainage through the concentrator. Reclamation of disturbed land and waste rock deposits began early in the mine's life—in the early 1970s—and continued through mine closure.

At startup, the mine purchased 100 acres (40 hectares) of municipal land for development of residential subdivisions for mine employees. The mining company paid all the costs for installation of roads, water, sewage, and other utilities to the new housing sites. The company also paid for an extensive upgrade to the municipal water system, including an upgrade of the existing dam, and a new trunk line and storage tanks. Increased tax assessments and an issue of municipal debentures purchased by the company permitted construction of a new sewage treatment plant. The mine also assisted in construction of a new hospital, ice arena, swimming pool, theater, and several parks.

Planning for closure began when the site was being cleared, in 1969. Five million short tons (4.5 million metric tons) of overburden and glacial till were stockpiled for use in recontouring and revegetation of the waste rock deposits that would be produced over the next 25 years.

The mine closure plan included four main areas: the open pit, the waste rock deposits, the marine environment, and the physical plant. The initial plan was submitted for discussion to the provincial authorities in 1990, and a revised plan was submitted in 1994. Copies of the plan were also distributed to government buildings and public libraries throughout the region, and several open houses and bus tours were held for the public.

In 1996, the open pit was decommissioned by flooding it with seawater from the adjacent Inlet. This created a 528-acre (214-hectare) lake, which stabilized the pit walls and provided an effective receptacle for the moderate amount of acid drainage from the waste rock. The acid drainage is diluted by the large volume of the lake, and heavy metals are precipitated to the bottom by the action of sulfate-reducing bacteria. Precipitation and surface drainage have formed a cap of fresh to brackish water on the surface of the lake.

Land reclamation included recontouring and planting of four waste rock deposits covering 500 acres (202 hectares), and a 650-acre (263-hectare) landfill created by deposition of waste rock in Rupert Inlet. Revegetation had been ongoing throughout operations, with the planting of 600,000 alder and lodgepole pine seedlings. This will eventually produce a cedar-hemlock forest of a type typical to the region. The reclaimed area will be monitored until it is clearly seen that the new forest is sustainable, after which the property will be returned to the provincial government.

The waste rock landfill in Rupert Inlet was graded to the low-tide mark. To provide a varied habitat for marine organisms, six bays were sculpted into the shoreline. This area is visually indistinguishable from a reference station selected earlier. Benthic recolonization and populations of key marine species have returned to premining levels. Physical, chemical, and biological monitoring of the marine environment continued through December 1998.

Finally, the mine's physical assets were removed and disposed of. All fuel, chemicals, and designated special wastes were removed and disposed of according to applicable regulations. Contaminated areas were rehabilitated. Buildings, machinery, and equipment were sold through an international firm specializing in disposal of such items. Structures not purchased for ongoing use on site were dismantled and their sites were reclaimed as wildlife habitat.

Welchman and Aspinall noted eight lessons to be learned in regards to reclamation and closure:[16]

1. *Shutdown, closure, and postclosure costs should be a capital expenditure item beginning with the prospect-approval feasibility study*. While in the present value sense it may be inconsequential, nevertheless the importance of early environmental planning for reclamation and closure must be spotlighted.
2. *The direct closure impact in terms of tailings handling, disposal of chemicals and hydrocarbons, and pit shutdown should be an integral part of*

the design criteria employed during the detailed engineering phase of the project. Specifically, locations of dumps should not only be dictated by transportation costs but also by reclamation and final closure suitability/plans. Ongoing reclamation and the last stage of production should be integral parts of the final closure plan.

3. *The selection of key reclamation and closure alternatives should be backed up with a full suite of technical information generated by in-house experts and competent credible consultants*. Supporting information should be open for inspection and both company and consulting experts should be available to provide corroborating testimony.

4. *At times, a Catch-22 condition may arise in that regulators can require a finalized closure plan to approve a mine project's startup*. However, company management tends to be reluctant to authorize detailed engineering of any facet of a project without prior regulatory approval.

5. *Closure is a distinct phase of the mine life*. During construction and operations it is taken for granted that plans must be modified to allow for changing conditions. Similarly, the closure plan, no matter how detailed, should be sufficiently flexible to allow minor adjustments and even major changes as the unfolding circumstances warrant.

6. *Constant communications with regulators are essential, and all efforts should be made to keep them fully informed of decisions and problem*. They must also be protected from either surprise and/or embarrassment. Whenever possible, it pays to take the initiative before being asked to do so by the regulators. Island Copper's frequent response was: "Been there, done that, here's the report." This attitude cannot be bettered.

7. *Before the fact, constructive criticism should be actively sought from environmentalists*. There are several reasons for that:

- They may notice anomalies while the project is still in the planning stage, therefore saving on costly retrofitting.
- It is better to have people working with you than against you.
- It provides background credence to the effort.
- It supplies a good public relations image.

8. *A sufficient closure fund/bond should be established when either construction starts or production begins*. This should be done even if it is not mandated.

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