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THE DESIGN AND OPERATION OF WASTE ROCK PILES AT NONCOAL MINES

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1.0 INTRODUCTION

The U.S. Environmental Protection Agency (EPA) is developing technical summary reports on several issues related to the management of wastes produced by the non-coal mining and beneficiation industry. This document provides summary information on the design and operation of waste rock piles. The intent of this and similar reports is to provide state and federal regulators with information on the newest technical designs and innovations used in the environmental management of mine waste.

Section 1.0 of this report introduces the subject of waste rock piles and provides information on research being conducted on waste rock piles by governmental agencies in the United States and internationally. Section 2.0 summarizes the current understandings of fundamental waste rock pile design and operation. Section 3.0 summarizes information on the prevention of acid rock drainage (ARD) through the design and operation of waste rock piles. Finally, section 4.0 presents a case study of a waste rock pile.

1.1 Waste Rock Generation

The act of mining involves the excavation of rock containing valuable minerals. This rock is known as ore. To access and excavate ore, miners must move and store or dispose of rock that does not contain economic mineral values. This rock is known as waste rock. This report summarizes recent and proposed future research efforts in the design and operation of waste rock piles, as they influence the potential for environmental impacts.

Waste rock consists of non-mineralized and low-grade mineralized rock removed from above or within the ore body during extraction activities. Waste rock includes granular, broken rock and soils ranging in size from fine sand to large boulders, with fines content largely dependent on the nature of the formation and the methods employed during mining.

Waste rock is produced at non-coal mines as a byproduct of excavating an identified economic mineral or metal deposit. Mines design their open pit and underground operations to provide the most cost-effective means for recovering the ore. Since removed waste rock is usually transported to some nearby location for disposal, mines generally attempt to limit the amount of waste rock removed as much as economically feasible. Modern mines use computer models to determine the most economical pit configurations, taking into account safety and reclamation requirements.

For open pit mines, the stripping ratio is the amount of overburden and waste rock that must be removed for each unit of crude ore mined and varies with the mine site and the ore being mined. Depending on the nature and depth to the ore deposit, mine waste rock may constitute the largest volume waste stream generated by a mining project and can amount to thousands of tons per day. The quantity of waste rock generated relative to ore extracted from a mine is typically larger for surface mines than underground mines, reflecting the greater costs of underground mining operation. The ratio of waste rock to ore (i.e., the stripping ratio) at surface mines may range as high as 10:1 for some areas, with typical values ranging from 1:1 to 3:1 for most mineral types.

Because ore grades in mined material are generally continuous, waste rock with mineral concentrations just below the "cut-off" grade (i.e., the grade at which the target mineral can be recovered economically) may be stockpiled separately from other waste rock; this material is often referred to as "subore" or "low-grade ore." In addition, the cut-off grade at a given mine may change with the price of the commodity, thus leading to more or less waste rock being disposed as the stripping ratio changes. The ratio of waste rock to ore is much lower at underground mines than at surface mines, reflecting the higher cost of underground mining. Because of the higher costs, underground mining is most suitable for relatively high-grade ores.

1.2 Environmental Impacts

Historic waste rock disposal practices provide evidence of the types of potential environmental impacts that may result from improper design, construction, or management of waste rock piles. For example, waste rock piles may experience slope or foundation failure. In addition, both abandoned and active non-coal mining sites have experienced problems that result in impacts to local surface and ground water quality. Both physical and chemical surface water impacts may result from increased sedimentation in the stream due to entrainment of waste material in runoff from the piles.

The generation of acid rock drainage (ARD) at waste rock piles is well documented in both U.S. and international scientific literature. Acid drainage is generated during all steps of the mining process via chemical oxidation of sulfide compounds, particularly iron sulfides, to sulfuric acid. Future uses for surface and ground waters that receive acid drainage from waste rock piles or other mining process wastes may be limited by the acidity of the waters.

Waste rock also is used in the construction of roads, tailings starter dams, buttresses for heap leach pads, and other on- and off-site construction. The formation of ARD from reactive rock used in these applications also has led to significant environmental problems caused by leaching of high concentrations of heavy metals to surface and ground waters.

1.3 Summary of Literature Review

Through the research conducted for the preparation of this paper, Canada, in particular, was found to be prominent in waste rock pile design research. In North America, most waste rock pile research is currently being performed by several different Canadian government and industry-sponsored groups. These groups include: the British Columbia Mine Waste Rock Pile Research Committee, the Mine Environment Neutral Drainage Program (MEND), and the Canada Centre for

Mineral and Energy Technology (CANMET).

Research conducted by the British Columbia Mine Waste Rock Pile Research Committee is focusing on the problems of stability experienced at mine waste piles constructed at coal mines in British Columbia. Although this research focuses on continual stability problems associated with coal mine waste piles, the results of the work sponsored to date by the committee can also be applied to non-coal mine waste piles. The British Columbia Mine Waste Rock Pile Research Committee has funded the development of five reports on design, operation, monitoring, failure characteristics, and review and analysis of failures of waste rock piles: Investigation and Design Manual (Piteau, 1991), Operating and Monitoring Manual (Klohn Leonoff, 1991), Methods of Monitoring (HBT AGRA Limited, 1992), Review and Evaluation of Failures (Broughton, 1992), and Failure Runout Characteristics (Golder, 1992).

The Mine Environment Neutral Drainage Program (MEND) has been very active in the research of acid rock drainage. This cooperative research program is sponsored and financed by the Canadian mining industry, the government of Canada and the governments of several Canadian provinces. Its purpose is to assist the mining industry and government agencies in developing and implementing techniques and technologies for minimizing and mitigating acid generation and its impacts at tailings and waste rock piles (as well as the associated environmental impacts).

The Canada Centre for Mineral and Energy Technology (CANMET) has provided funding to the MEND and British Columbia Mine Waste Pile Research Committee in their current research projects.

2.0 BASIC DESIGN AND OPERATION OF WASTE ROCK PILES

To design and operate stable waste rock piles, the operator must ensure proper foundation materials, allow for slope angles and construction processes that will ensure stability throughout the life of the mine, and provide for proper water drainage to minimize infiltration/seepage. The shear strength and durability characteristics of both the foundation and waste materials must be considered, as well as drainage patterns and predicted pore water pressures. This section addresses the major factors that affect the stability of waste rock piles and how they should be considered during the design and operation of the pile.

2.1 Preliminary Design Considerations

Generally, the first step in initiating the design of a waste rock pile is the assembly of all available information and data necessary to characterize the waste rock and proposed site. Much of the data is available from public or government organizations (e.g., topographic maps, climate information). This information is typically supplemented with field investigations that may include land surveying, sampling from test pits, trenches, or boreholes, groundwater monitoring, and piezometric and percolation testing. Further details on field testing requirements and techniques are provided in CANMET (1977), McCarter (1985), Piteau (1991), and Brodie et.al., (1992).

2.1.1 Waste Rock Characterization

Since mining sites vary in the types of materials encountered in the excavation of ore, a full characterization of the anticipated waste materials should be completed concurrent with mine design planning. However, Piteau Associates points out that the diversity of particle size and physical properties associated with waste rock leads to a difficult and complex sampling and analysis process relative to that required to characterize foundation soils and overburden materials. In addition, material properties may change over time due to stresses within the waste pile, weathering, chemical changes, and other types of degradation. Although abrasion and durability tests attempt to measure potential degradation, the effect of combined factors over time is difficult to predict.

The waste rock material to be disposed in the pile should be analyzed for both physical and chemical characteristics. The strength of the proposed pile may be assessed by such parameters as rock type (igneous, metamorphic or sedimentary), density, particle size distribution, and pore water pressures within the waste pile. The density and pore water pressures also are influenced by the pile construction method and subsequent amounts of consolidation and settlement. Pore water pressures decrease the stability of both the waste and foundation materials. With respect to shear strength, the most favorable pile materials are hard, durable rock with little or no fines present. Failure can occur when a pile containing material with excessive fines is constructed on a steep slope. In addition, waste fines may become saturated from water runon and snow melt and trigger a failure. Ideal waste rock would be of sufficient durability, hardness and coarseness to provide high shear strength and low pore water pressure. A description of the mineralogy of the pile material is necessary to identify, for example, the presence of sulfide materials such as pyrite, which indicate the potential for acid rock drainage. Likewise, the presence and amount of basic minerals (e.g., calcite) must be determined in order to evaluate the acid neutralization potential of the rock pile.

Once waste material characteristics are known, proper design and construction methods can be implemented. For example, as poor-quality waste materials are encountered during construction of a waste pile, specific sections of the pile can be prepared to receive the materials or additional protection can be installed. Overburden materials (e.g., soils), due to their fine nature, would contribute to instability in the waste rock pile and should, therefore, be placed in a separate location. Likewise, acid-generating rock may be segregated so that immediate measures may be taken to control acid generation. Lastly, since the physical and, particularly, the chemical properties of mined rock can change over time, there also should be a program of periodic or continuous characterization to ensure that changes can be made to design and operation as conditions warrant.

2.1.2 Site Characterization

A complete site characterization involves the collection and consideration of a diverse set of information that encompasses site activities, layout, terrain, hydrology, and climate. For example, physiographic data address the proximity of the location to the source of the waste, nearby mining activities such as blasting that could affect pile stability, the site capacity, and topographic features such as slopes and valleys that may determine placement of the waste rock pile and surface water flows. Hydrologic considerations address natural drainage and climate concerns include storm events, temperature, precipitation, and wind patterns. The MWRPRC data indicate that more failures have occurred during winter and spring seasons, which typically bring greater amounts of precipitation, than in summer and fall (Broughton, 1992). The hydrogeology of the site, including the position of the water table, groundwater flow systems, distribution of discharge and recharge areas, and groundwater usage, assists in identifying pathways for potential environmental and human health risks. In addition, ground and surface water quality, air quality, fish and wildlife habitat and productivity, vegetation, and existing and future land use must all be determined in order to assess potential environmental impact (Piteau, 1991).

2.2 Stability Factors

A close look at the factors that affect waste dump failures provides important information relative to the stability parameters that should be considered during the design and operation of waste rock piles. The Canadian Mine Waste Rock Pile Research Committee conducted an in-depth study of over 40 failures of waste rock dumps from coal mines aimed at improving the design and operation of future dumps (Broughton, 1992). The research committee identified numerous factors that potentially contribute to waste dump failures. For example, the data indicated that most waste dump failures occur on foundation slopes exceeding 20 degrees. Piteau and Associates (1991) identify seven major factors that affect pile stability: dump configuration, foundation conditions, waste material properties, method of construction, dumping rate, piezometric and climatic conditions, and seismic and blasting activities.

2.2.1 Foundation Stability

An important aspect of site characterization includes an accurate characterization of foundation stability. Soil tests for shear strength, permeability/hydraulic conductivity and consolidation, and depth determinations for any loose or incompetent soils, are important in assessing the strength and preparatory requirements of the foundation. Competent foundations refer to foundation material with higher shear strength than the waste materials; weak foundations have lower shear strength than the waste materials (CANMET, 1977). Level foundations are also more stable than sloping foundations. The strength and durability of the underlying bedrock should also be evaluated.

Foundation soil conditions, including the type of soil and the amount of pore pressure, have a large effect on overall waste pile stability. In addition, excess pore pressures may result from high loading rates and steep foundation slopes. Where sloped foundations are present (*i.e.*, greater than 10 degrees), a stability analysis is necessary to determine the maximum potential displacement due to base shearing.

Where a level foundation (i.e., less than 10 degrees) is provided, the pile will generally not be susceptible to mass sliding along the base unless it is constructed on very weak foundation materials (e.g., organic soils). In general, sloped foundations present greater risks associated with sliding than level foundations (foundations are less stable and material may move farther and more quickly). Therefore, CANMET recommends higher safety factors for waste rock piles on sloped foundations (CANMET, 1977). In addition, foundation stability also may be affected by temporal conditions that are not considered during a site characterization. For example, the Mine Waste Rock Pile Research Committee found that winter freezing of foundations, before loading, may also contribute to some failures (Broughton, 1992).

2.2.2 Waste Rock Pile Stability

The size and configuration of a waste pile directly affect its stability. The variables that need to be considered in the configuration of a waste pile are height, volume, and slope angles. The height of a pile is defined as the vertical distance from the ground at the toe of the pile to the pile crest. Piles may range from 20 m up to 400 m (Piteau, 1991). In the U.S., the size of waste rock in a pile is usually defined as tonnage or acres covered; however, the Canadian protocol describes the size of a waste rock pile as a volume unit. The slope angle of a pile is determined by the type of construction method used. End-piled materials result in slopes at the angle of repose, approximately 37 degrees, the average angle of repose for free-piled cohesionless rockfill. Steeper slopes may result if the piled materials have some cohesive properties (such as significant fines) or consist of largely angular boulders.

At sites where waste rock consists of frictional, coarse materials, the maximum slope at the pile perimeter is the angle of repose (as indicated previously, typically about 37 degrees). Where competent foundation materials are found and adequate drainage is provided, the height of the pile is generally unlimited. Where foundation materials are weak, stability analyses must be performed to determine the maximum height and slope to ensure the desired level of stability. (CANMET, 1977, provides guidance on such analyses, depending on the specific characteristics of the foundation materials.) Compacting foundation materials along the perimeter slopes (where maximum stresses are found) can increase stability and allow for greater slope angles and/or pile heights. However, compaction reduces permeability, thereby increasing the need for drainage controls.

In addition to pile overall height, volume, and slope angle, the presence of lifts or benches is an important pile configuration factor for aiding the stability of the pile. Lifts and benches reduce the overall angle of the pile slope and control runoff from the pile. Benches are slightly sloped horizontal surfaces constructed into the slope of a waste rock pile. They are typically constructed in piles as part of reclamation, be it concurrent with construction or during final reclamation. Lifts are the working levels of a waste rock pile. A specific area of a waste rock pile may be worked at a particular lift level until the lift is completed. Another lift may then be constructed on top of the previous lift. Constructing a pile in lifts, or utilizing benches, during the active operation of the pile typically results in lower slope angles and, therefore, increased stability. Other pile operation methods can affect pile stability as well. Most importantly, a rapid rate of waste dumping can contribute to the instability of a pile and has been attributed to several pile failures. High dumping rates can lead to increased pressure in the dump and not allow for adequate time for consolidation and settling of the pile to ensure stability (Piteau, 1991). The direction of crest development is another operational factor that should be closely monitored; deviations from the design plan may direct the waste pile to foundations of greater slope and lead to reduced stability.

2.2.3 Assessing Waste Pile Stability

The common method of assessing the overall stability of a proposed waste rock pile is to calculate a factor of safety (FS). The FS represents the ratio of the shear strength to the shear stress. As noted above, the stability is directly related to the foundation and waste rock materials and drainage, along with general dump features, including size, volume, slope angle, degree of confinement, method of construction, and dumping rate. The acceptable FS for an individual pile will depend upon site-specific conditions related to the potential impacts/risks of a slope failure. CANMET (1977) recommends an FS (greater than unity) to account for differences between predicted design parameters and actual conditions within the pile. Methods used to calculate safety factors generally focus on shear stress and pore water pressure along "critical surfaces" within the pile (including the variability in these parameters along such surfaces). Selection of the methodology to be used at a specific site depends on the operator's determination of the most likely failure mode. Piteau (1991) includes a description of the types of failure modes associated with waste rock piles (edge slumping rotational failure, liquefaction, etc.). Mine dumps located in areas of high seismic risk require specialized safety analyses.

For piles constructed on sloped foundations, the following equation can be used to determine the maximum possible foundation slope angle (assuming no hydrostatic pressures, i.e., proper drainage exists) (CANMET, 1977):

$$\tan i = \tan \delta / FS$$

i = foundation slope angle
δ = friction angle between waste and foundation materials
FS = factor of safety (stability factor)

Where uneven foundation slopes are encountered, the Wedge method described in CANMET (1977) can be used to determine whether the calculated factor of safety is acceptable to the operator.

Piteau (1991) includes a dump stability rating system to provide a "semi-quantitative" method for assessing waste rock pile failure potential. Based on the results of the rating analysis, dumps can then be placed in one of four dump stability classes. The classes are correlated to "negligible," "low," "moderate," and "high" failure potential. The purpose of this system is to guide operators in waste rock pile design (in conjunction with information on the site-specific risks associated with a failure).

2.3 Types of Waste Rock Pile Configurations

Taylor and Greenwood (1985) presented a classification system for non-impounding waste rock pile types based on the topographic setting and the configuration (geometric shape) of a pile. This classification system was developed ostensibly to provide waste rock pile vocabulary common to industry and government representatives. The pile types identified in Taylor and Greenwood (1985) are illustrated in Figure 2-1 and discussed further below.

Valley-Fill

A valley-fill waste rock pile partially or completely fills a valley. It is typically constructed by dumping waste rock at the head of the valley and extending the pile by continuous dumping of waste rock on the downstream slope. A valley-fill also can be constructed by building horizontal lifts at the farthest downstream location of the pile toe and then proceeding upstream toward the head of

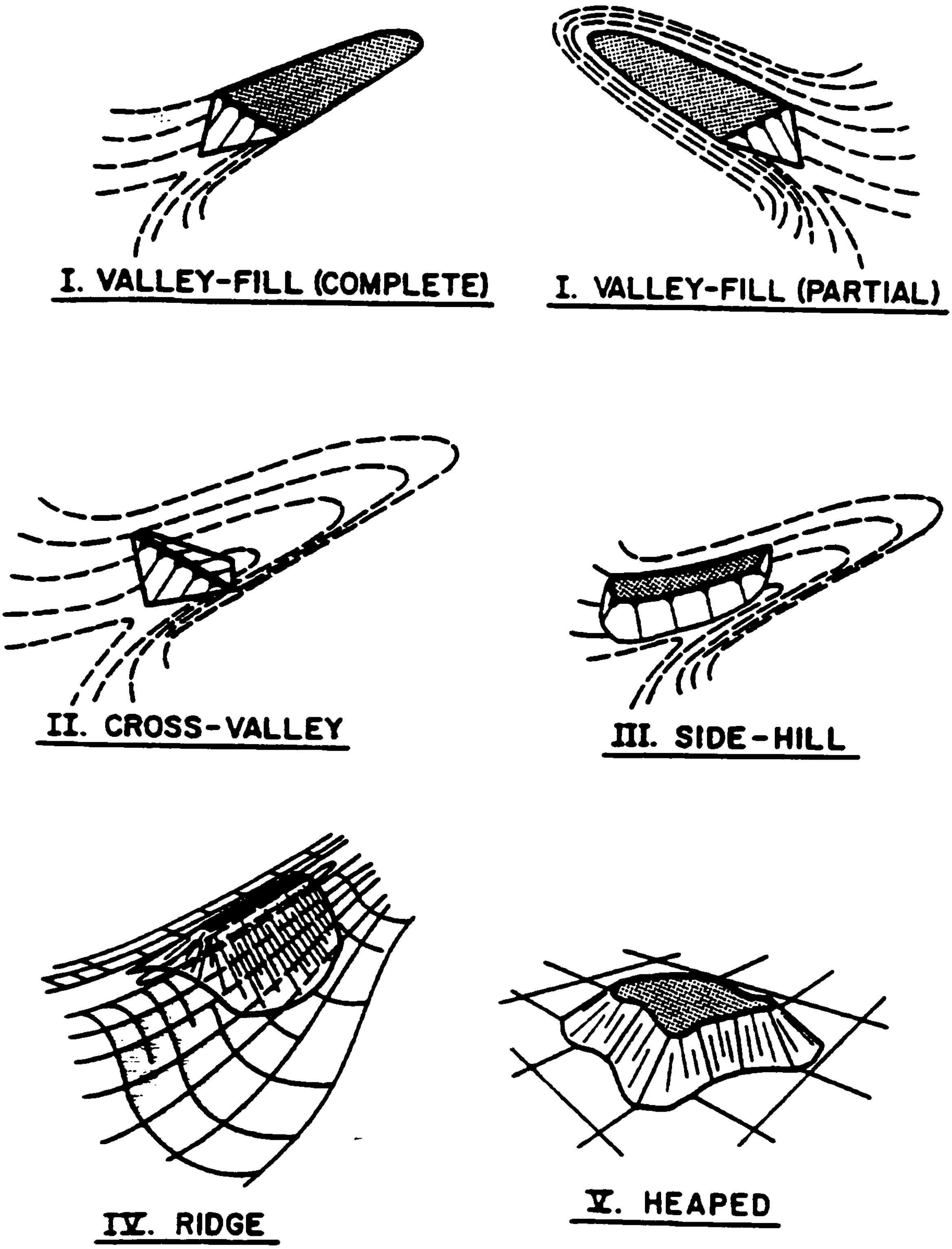


Figure 2-1. Classification System for Waste Rock Pile Configurations (from: Taylor and Greenwood, 1985)

the valley. In this type of construction, surface water controls (i.e., diversions) are required to divert upstream runoff from collecting behind the pile lifts. The surface of valley-fill waste rock piles is graded or sloped to prevent ponding and to limit infiltration of surface water runon and precipitation.

Cross-Valley

A cross-valley waste rock pile is constructed from one side of a valley, across the drainage, to the other side of the valley. It does not completely infill to the head of the valley as in a valley-fill waste rock pile. The crest of this type of pile may be horizontal or sloped and the fill slopes can be established in either the upstream or downstream direction. This type of pile requires surface water controls (i.e., diversions, culverts or flow-through rock drains) to avoid impounding water behind the pile. A valley-fill waste rock pile constructed in an upstream progression can essentially be considered a cross-valley type pile until the head of the valley is infilled.

Side-Hill

A side-hill waste rock pile is constructed on the side of a valley but does not cross-over the floor of the valley. The pile slopes are usually inclined in the same direction as the foundation (i.e., hill slope). These waste rock pile types do not block major drainages.

Ridge

A ridge waste rock pile is constructed on the crest of a ridge, with the slopes of the pile extending down both sides of the ridge. The crest of the pile may be sloped or horizontal.

Heaped

A heaped waste rock pile is constructed by stacking or piling mounds of waste on a relatively flat surface that is horizontal to moderately inclined.

Hybrid Types

Waste rock piles, while generally classified as one of the above five types, may be hybrids. Further, waste rock may be backfilled into open pits or disposed in in-pit piles. In addition, waste rock is often used as slope fill to construct roads or level ground surfaces for mine/mill buildings. Waste rock is also used for starter dams and/or buttresses in tailings impoundment construction.

2.4 Construction/Operation

Construction of waste rock piles begins concurrently with the excavation of waste rock from the mine workings after all necessary siting and design work has been completed. This section addresses measures that may be required to prepare the foundation for construction of a waste pile, common techniques for constructing the pile, and methods for controlling surface water, run-on, and run-off.

2.4.1 Foundation Preparation

Preparing the land area that will serve as the pile foundation is the first step in constructing a waste rock pile. If possible, the siting and design work should have resulted in the selection of a site that requires minimal preparation. However, if the foundation conditions are poor, and no other site is available, the following measures may be used to promote stability of the waste rock pile. All of these measures require various levels of equipment accessibility to the toe or "footprint" of the planned waste rock pile.

Clearing Vegetation and Stripping Soils

Unless topsoil has to be salvaged, the removal of trees and vegetation from a site is not normally performed since it requires additional expenditures and the vegetation can provide strength to the underlying soils. If logging of timber resources on-site is required prior to construction (due to U.S. Forest Service regulations or other reasons), it should be completed as close to the initiation of pile construction as possible. In special situations, clearing vegetation from a site may be necessary. For example, if heavy vegetation exists on a steep slope that is to form the foundation of the pile, clearing may be advisable to prevent the covered vegetation from forming a weak zone beneath the pile. Also, if the site investigation indicates weak soils that require removal prior to dumping, clearing would be necessary. Finally, areas of the pile that will be constructed to convey water (e.g., rock drains) should be cleared of all vegetation that could potentially impair the hydraulic performance of the structures.

As stated above, weak soils, such as organic soils, may require excavation if it is determined that the pile will not provide sufficient consolidation for an adequate foundation. After excavation of soft soils, the ground surface should be compacted to ensure that the new foundation is sufficiently dense to support the pile. The excavated surface may also require grading or drainage if water is present.

Underdrainage and Prelifts

In areas of shallow groundwater or surface discharges/seepage (i.e., wetlands), saturated soils need to be drained to support waste materials. Finger drains (constructed of sand and gravel) and gravel blankets can be installed to collect water from the area beneath the pile footprint and convey it to a central collection ditch. If the ground water seepage rate is significant, perforated pipes may be placed in the gravel drains to increase the hydraulic capacity. Typically where underdrainage is necessary, rock drains are needed to convey upstream surface water flow and surface water infiltration through the pile.

An alternative to the excavation of soft soils is the construction of prelifts. Access to the foundation area is a limiting factor. A prelift of pile material from 5 to 15 m in thickness can be used to consolidate, span, or contain weak soils.

2.4.2 Methods of Piling/Material Placement

Mine waste piles are built using either ascending or descending construction methods. Materials may be end-dumped into their final resting place or bulldozers may be used to push the waste rock into or distribute it across a specific area of the waste rock pile.

Ascending construction is considered the preferred method for creating a stable waste rock pile since each successive lift is built upon the preceding lift, which has been established and compacted through the movement of the waste rock haul trucks. Ascending construction begins at the toe of the pile and the pile is built upward (see Figure 2-2). In this manner, piled rock develops in layers called lifts that are constructed one on top of another. Lifts often vary in thicknesses, but in general may be 10 meters or more.

Descending construction is typically the more economical method for constructing a waste rock pile since trucks do not have to be used to haul rock uphill. Descending construction requires piling rock from a crest and new lifts are constructed around and downgradient of the initial lift. These added lifts are known as wrap-around lifts because they wrap around the initial and subsequent lifts in a downgradient progression.

Buttresses may be built at the toe of a pile to improve structural stability. Buttresses may be used when site conditions, such as steep terrain, prohibit or restrict more stable pile-construction methods. A buttress should provide enough mass to counterbalance the driving forces of the upper portion of the pile. Impact berms are constructed downslope of the toe, on flatter terrain, to intercept failure runouts and to protect structures or streams below the pile. They must be of sufficient size to contain the volumes of materials associated with a reasonable failure runout scenario.

During the placement of material, the waste rock may be dumped from a height of 500 meters or more. Segregation of the waste rock into size fractions is more pronounced if the material is dumped from an elevation of at least 20 meters above the pile surface. Finer size fractions are found near the surface of the lift, and coarser material is found near the base of each lift. In this manner, the waste rock pile becomes a heterogeneous deposit of graded layers (see Figure 2-3).

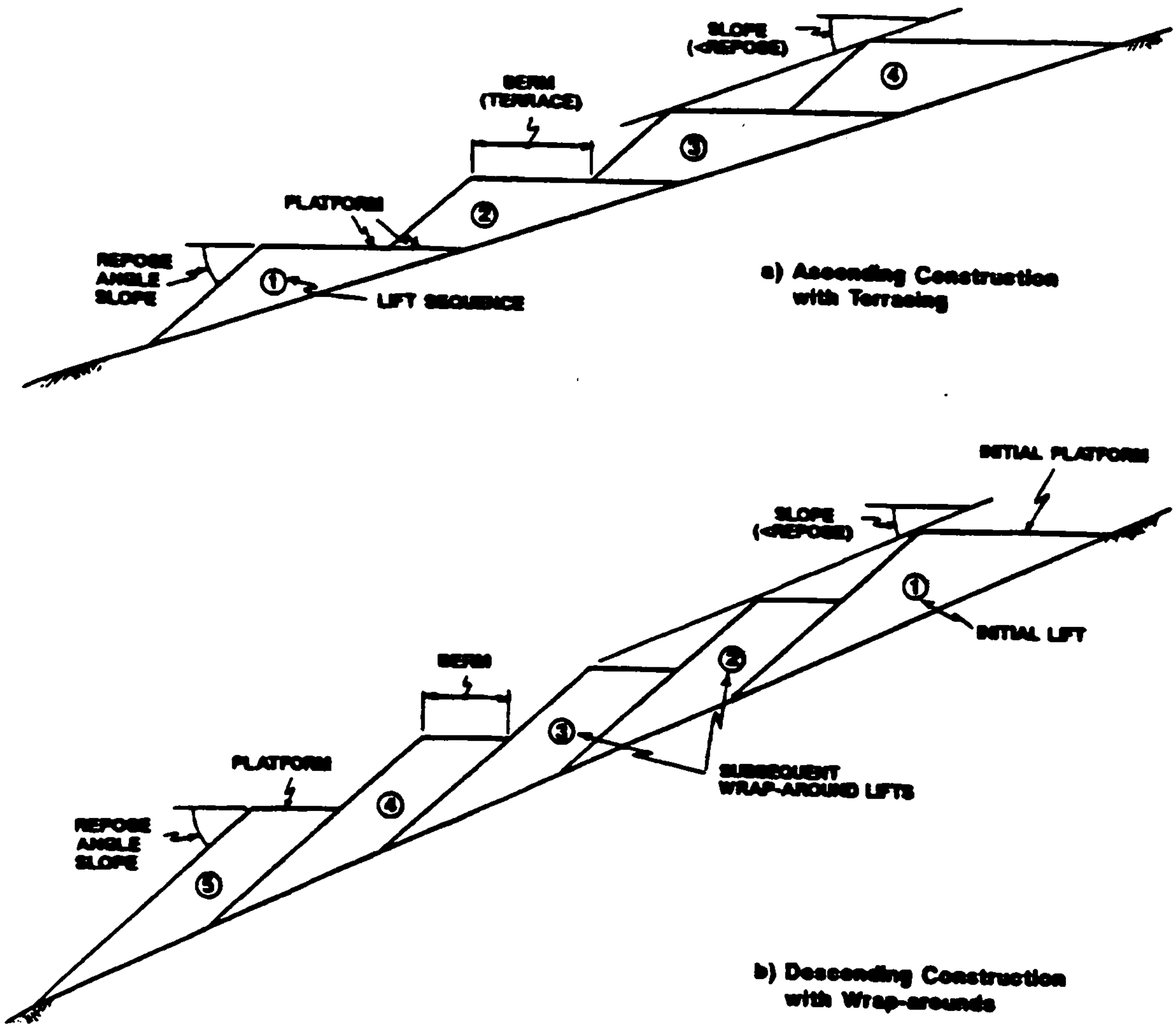


Figure 2-2. Ascending and Descending Methods of Construction
(from: Piteau, 1991)

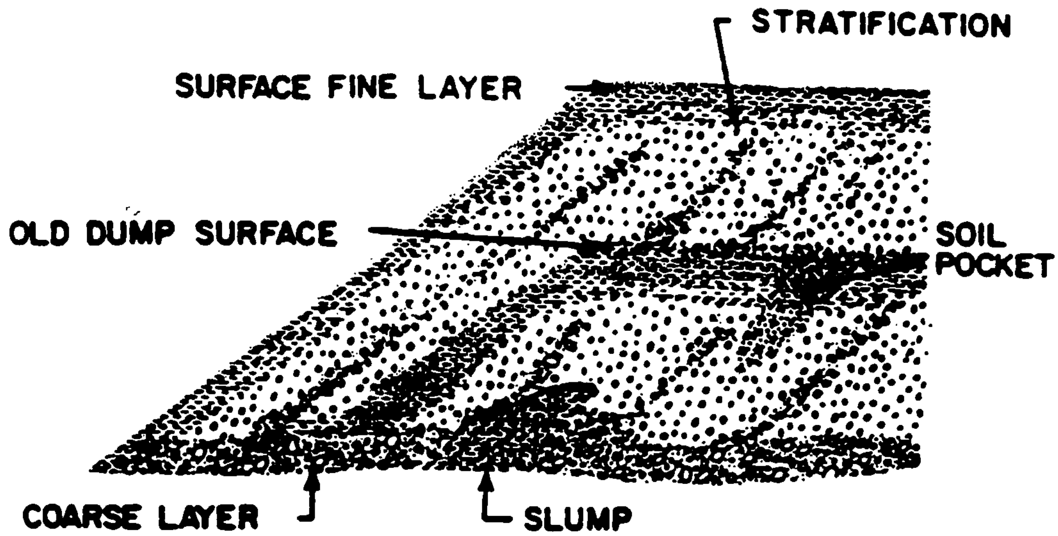


Figure 2-3. Stratification Within a Waste Rock Pile
(from: Call, 1985)

2.4.3 Constructing and Operating Surface Water Controls

Waste rock piles often cover significant land areas, and surface water run-on, run-off, snow, and snow melt control measures are frequently necessary to prevent saturation of slopes or development of phreatic surfaces in the pile, and to mitigate surface erosion, ARD, and other releases of toxic pollutants to ground or surface waters (Piteau, 1991). Environmental regulations and guidelines governing the design, construction, or operation of drainage control systems exist on the Federal, State, and local levels. In general, these regulations and guidelines attempt to achieve two primary objectives. First, the drainage system must be able to handle a calculated flood-event and, second, the system must result in a discharge of adequate quality (e.g., low toxicity, reasonable pH, low suspended solids) (Claridge, 1986). Designing these structures to meet these needs requires accurate precipitation data and the consideration of specific events that may result in extreme runoff volumes. The control measures discussed below are often most effectively used in conjunction with each other.

Direct precipitation onto a pile should be directed to a collection area to minimize infiltration into the pile surface. Slight grading of the pile crest and bench surfaces can be used to direct runoff away from the outer face of the pile and into ditches or rock drains that quickly convey runoff/runon to collection areas/discharges. In addition to rainwater, control of snow and ice accumulation also must be considered for waste piles in northern regions. There is some evidence to support the theory that failures in waste piles located in the Rocky Mountains have occurred as a result of weak zones forming in areas where snow and ice within the pile melted rapidly (Piteau, 1991).

There are several rules of thumb utilized to minimize the effect of snow and ice on waste pile stability.

- Waste rock should not be dumped on faces where significant amounts of snow or ice are present (greater than 1 meter)

- dump surfaces should be worked evenly so that depressions do not accumulate large amounts of snow

- snow removed from the mine should not be dumped on an active pile - a separate "snow-only" dump should be utilized

- snow should not be dumped in drainage areas or diversion channels that will be covered by waste rock materials

- dumping in the winter months should be planned so that it occurs on exposed windward faces with the least amount of snow accumulation (Piteau, 1991).

Surface water diversions should be constructed to convey upgradient flows (overland as well as channelized flow) around or through the base of the pile in engineered structures. These structures prevent surface water runon and surface water flows from infiltrating the pile materials and, in extreme conditions, over-topping the waste pile. There are three primary options for diverting surface waters in a waste pile. Water can be diverted 1) around the pile in a diversion channel 2) along the bottom of the pile in a rock drain, or 3) under the pile in a culvert (Claridge, 1986). The method or methods used are dependent on site-specific conditions and waste pile type. Diversion channels can be lined or unlined ditches and are often engineered to convey the upgradient flows associated with a specific calculated storm event. These channels must be regularly maintained or collected sediment and brush can impede the flow through the structures.

Even in those waste pile types where it is feasible to divert surface water around a pile (side-hill, ridge, and heaped designs), it is impossible to divert all surface water. As a result, subsurface rock drains are used in nearly all types of waste piles to enhance surface water flows through the pile (see Figure 2-4). A rock drain is constructed by one of two methods. First, waste rock material (non-reactive only) of the appropriate size can be placed directly into the area that will constitute the drain. Second, waste rock material (igneous or metamorphic and non-reactive) can be dumped from trucks directly onto the foundation (end dumping), which allows for natural segregation through the dumping action (Lighthall, 1986). A minimum pile height of 20 to 30 meters is generally necessary to ensure that natural segregation results in the formation of a coarse gradation rock drain (Das, 1990). If the pile is less than 20 to 30 meters in height or the waste rock material is not of adequate quality, coarse, durable rock may need to be hauled to the site and used in constructing the drain.

Igneous and metamorphic rocks are the preferred rock types to be used to construct rock drains due to their generally good resistance to mechanical degradation and compression (Das, 1990).

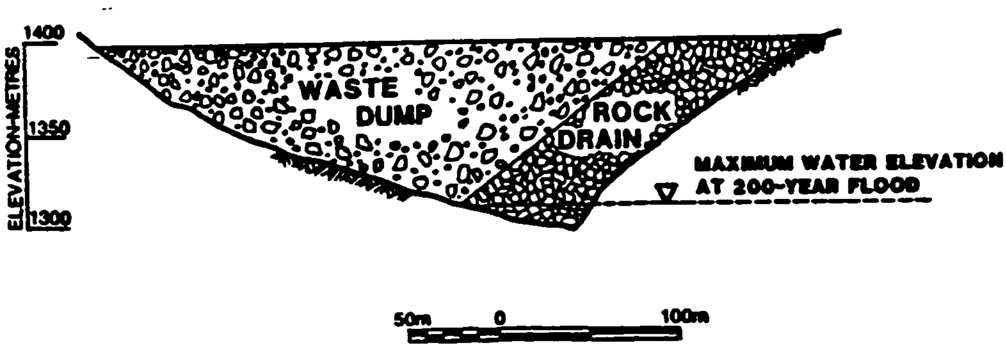


Figure 2-4. Flow-Through Rock Drain (from: Lighthall and Sellars, 1985)

In addition, the rock should be resistant to slaking and freeze/thaw activity. Das (1990) suggests that over 80 percent of the rock should grade larger than 100 mm. The requirement of coarse durable rock for rock drains can significantly alter a facility's mining plan (i.e., altering blasting methods to ensure proper material size or avoiding the mining of certain areas containing rock types that are not suitable for rock drains) (Lighthall, 1986). In the event that acceptable rock drains cannot be constructed utilizing waste rock from the site, a manufactured rock drain can be used (Claridge, 1986).

The rock drain should be capable of conveying the mean annual stream flow without buildup of water upstream of the pile. The inlet capacity and the outlet capacity are vital considerations in designing and operating a rock drain and ensuring the stability of a pile. While it may be necessary for the inlet to transmit the mean annual stream flow, the outlet is typically designed to discharge up to the 200-year flood flow without a reduction in pile stability (Das, 1990). Commonly, the rock drain is extended up the upstream slope, or inlet, of the waste pile providing for additional capacity in the event of blockages or increased flows. The outlet can be stabilized by constructing a flatter slope and/or utilizing larger, more angular, material (Lighthall, 1986). A bypass channel should be provided, in the event the inlet becomes blocked, to convey flood flows that cannot be passed through the rock drain without undesirable buildup of head on the upstream side of the pile (Piteau, 1991).

The use of a rock drain to convey surface water through a pile in place of upstream diversions creates a greater potential for environmental impacts downstream of the pile. As surface water flows through the pile the water may become contaminated: these contaminants then migrate downstream. In addition, ecological habitats downstream may be compromised due to decreased flows resulting from blockages in the pile (Das, 1990). However, it is not possible to divert surface water around all types of waste pile designs. As economically and environmentally favorable dumpsites become more and more scarce, it may become necessary to use "cross-valley" or "valley-fill" designs utilizing rock drains for stream conveyance and surface water control (Claridge, 1986).

2.5 Monitoring

Waste rock piles should be monitored on a regular basis to detect any environmental or structural changes. There are numerous reasons for (and benefits gained from) instituting a monitoring program at a waste rock pile. These include, but are not limited to: 1) complying with regulatory requirements, 2) lowering operating costs (comprehensive monitoring may allow a reduction in the factor of safety in the dump, and this is associated with lower dumping costs), 3) improving worker and equipment safety, 4) reducing the risk of damage to the environment (due to dump failure, acid rock drainage, etc.), 5) improving dump behavior predictions, and 6) improving future monitoring methods (HBT Agra Ltd., 1992). Two primary conditions are generally monitored: structural stability (e.g., movement and internal pressures) and environmental impacts (e.g., waste geochemistry, water quality) of the pile. Monitoring can be qualitative, quantitative, or both.

2.5.1 Structural Monitoring

Qualitative Structural Monitoring Methods

Qualitative monitoring is the visual observation of a pile for structural changes that could lead to stability problems. Typical changes that should be noted during visual monitoring include slumping, or movement within a section of a waste rock pile.

Quantitative Structural Monitoring Methods

Quantitative monitoring uses instruments and/or sampling and analysis procedures. There are numerous quantitative instruments available for monitoring water movement and pressure. Two reports published by the British Columbia Mine Waste Rock Pile Research Committee (Operating and Monitoring Manual prepared by Klohn Leonoff Ltd, 1991, and Mined Rock and Overburden Piles:

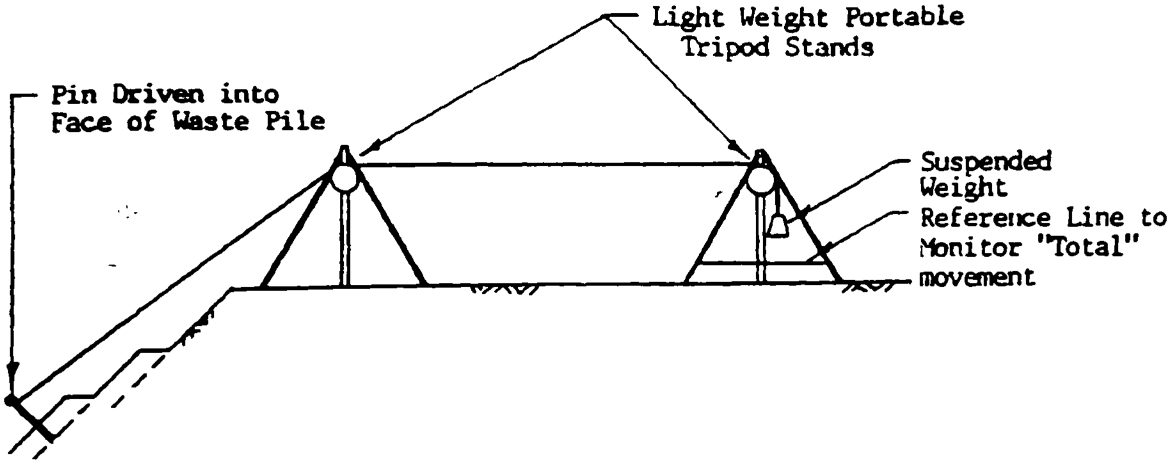
Methods of Monitoring prepared by HBT AGRA Ltd, 1992) provide detailed information on the quantitative monitoring of waste rock pile stability.

The most common equipment for quantitative monitoring of movement are wireline extensometers (also called tripod monitors or mechanical crest monitors) or buried extensometers (see Figure 2-5). Extensometers measure the change in distance between two points through the use of a wire attached between a stand installed on stable ground, which has low potential for movement, and an anchor in the pile surface (usually on a slope). The stand is the reference point from which the wire line may be read to determine the amount of movement occurring down the slope, parallel to the wire. Extensometers may be of the simple type with manual reading required at the stand, or a recorder unit may be used to plot movement over time. Extensometers are limited, however, by the fact that they are able to measure only the degree of movement that occurs parallel to the wire. In certain cases, this can significantly underestimate the actual movement that has occurred.

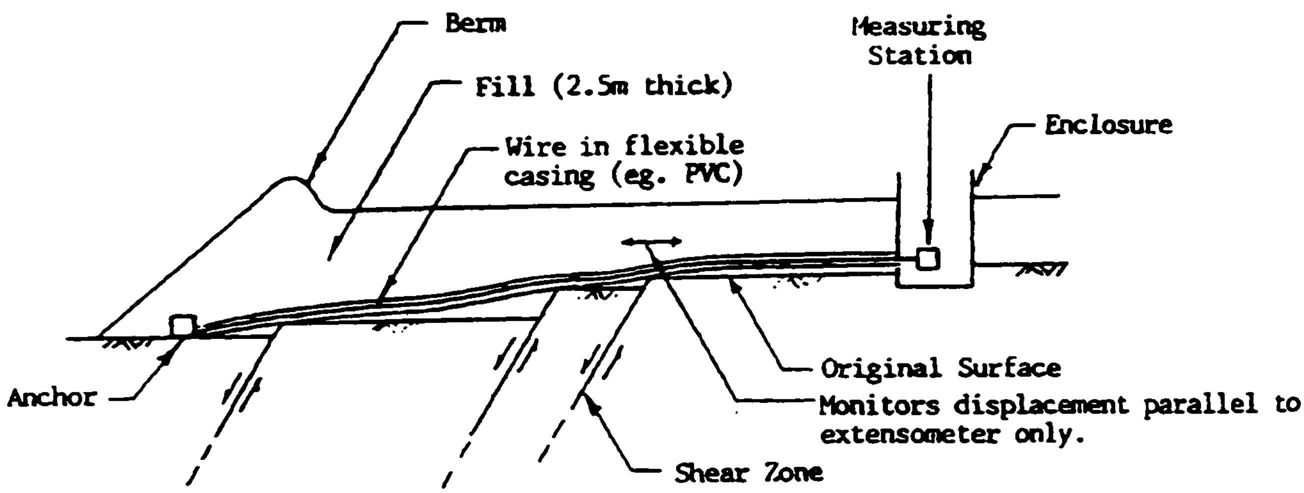
There are a number of movement-monitoring technologies designed to collect vertical settlement and total displacement data from waste piles. These include electronic distance measurement (EDM), settlement gauges, tiltmeters, and inclinometers. EDM is a technique based on traditional surveying techniques, whereby an electronically generated signal, controlled by a microcomputer, is aimed at reflected targets. After locating the position of the target, the EDM distance and new position of the target can be measured. Unlike extensometers, EDM technology is able to account for the full vector movement of the pile.

Settlement gauges are utilized to quantify the settling of the waste rock pile. Typical gauges consist of a measuring device on the surface of the pile and a probe that is inserted into the pile. The degree of settlement (movement between the surface and the probe) can then be measured and quantified. These data on vertical movements can supplement those gathered from extensometers. Inclinometers and tiltmeters are used to measure the horizontal or angular displacement within an embankment or across the foundation boundary and are most applicable in monitoring for rotational failure modes. Additional movement monitoring technologies currently are under development but are not yet available. These techniques include the Global Positioning System (GPS), acoustic emission techniques, electromagnetic monitoring (EM), videometry, and the use of laser cameras (HBT AGRA Ltd., 1992).

Pore pressure is one of the most critical measurements required to ensure pile and foundation stability. Pore pressure-monitoring instruments can be divided into two categories: 1) devices that are sealed into the pile and record pressures at that point (piezometers) and 2) open hole or well-type standpipes that record an average pressure over the length of the borehole. Piezometers are the most common pore pressure-monitoring devices employed in waste piles. Piezometers are available utilizing many different types of technologies: pneumatic, electrical resistance, electrical vibrating wire, standpipe, and multi-port or multi-level, as shown in Figure 2-6. Piezometers typically contain



a) Wireline Extensometer (Tripod Monitor)



b) Buried Extensometer

Figure 2-5. Wireline and Buried Extensometers
(from: HBT AGRA, Ltd., 1991)

a diaphragm that is deflected under pressure. The deflection in the diaphragm is measured utilizing numerous types of technologies, and quantified as a pressure reading. All of these piezometer types can be suitable and the decision on which type to use should be based on availability, prior experience, requirements for data acquisition, and cost (HBT AGRA Ltd., 1992).

Current Monitoring Methods Employed

In "Mined Rock and Overburden Piles: Methods of Monitoring," published by the British Columbia Mine Waste Rock Pile Research Committee, HBT AGRA Ltd. presents the results of a survey of mining companies, instrumentation companies, consultants, and other related companies concerning current monitoring methods employed. Over 170 companies were contacted. The results of the survey indicate that the most common monitoring practice is the use of simple mechanical devices (extensometers) to monitor surface movement. Use of piezometers to monitor pore water pressure in foundation materials is less common, but is used by some facilities. In nearly all cases, qualitative visual monitoring is performed (HBT AGRA Ltd., 1992).

Problems with Current Methods

There are a number of problems associated with current structural monitoring practices. For example, disturbances may occur in the location of surface monitoring stations. These reference points may be moved or disturbed due to rock falls/sloughs or activity on the pile. Data also may be incomplete due to infrequent or irregular data collection, thereby resulting in an incomplete picture of the pile's state. In addition, wireline extensometers (the most common movement-monitoring instruments) accurately measure only movements that occur in a direction parallel to the line made by the two reference points. Movements in other directions often are not recognized. Lastly, common movement-monitoring techniques (i.e., extensometers and visual observation) provide a picture of the performance of the surface of the pile, but do not provide data on the internal portion of the pile where critical instabilities may initiate. (HBT AGRA Ltd., 1992)

2.5.2 Environmental Impact Monitoring

Structural monitoring of the pile, while a useful tool for recording potential environmental conditions that could lead to stability problems, is not effective in monitoring for environmental (water quality) changes. Quantitative ground-water and surface water monitoring techniques based on chemical analyses are required to assess water quality impacts.

Quantitative Ground-Water and Surface Water Monitoring

Ground-water monitoring is generally not required by federal environmental programs, but is often required by States. In addition to satisfying regulatory requirements and aiding in the protection of the environment, a well- designed ground-water monitoring program is economically beneficial as it can reduce expenditures and liabilities associated with broad-scale remediation (Maxfield and Mair, 1995).

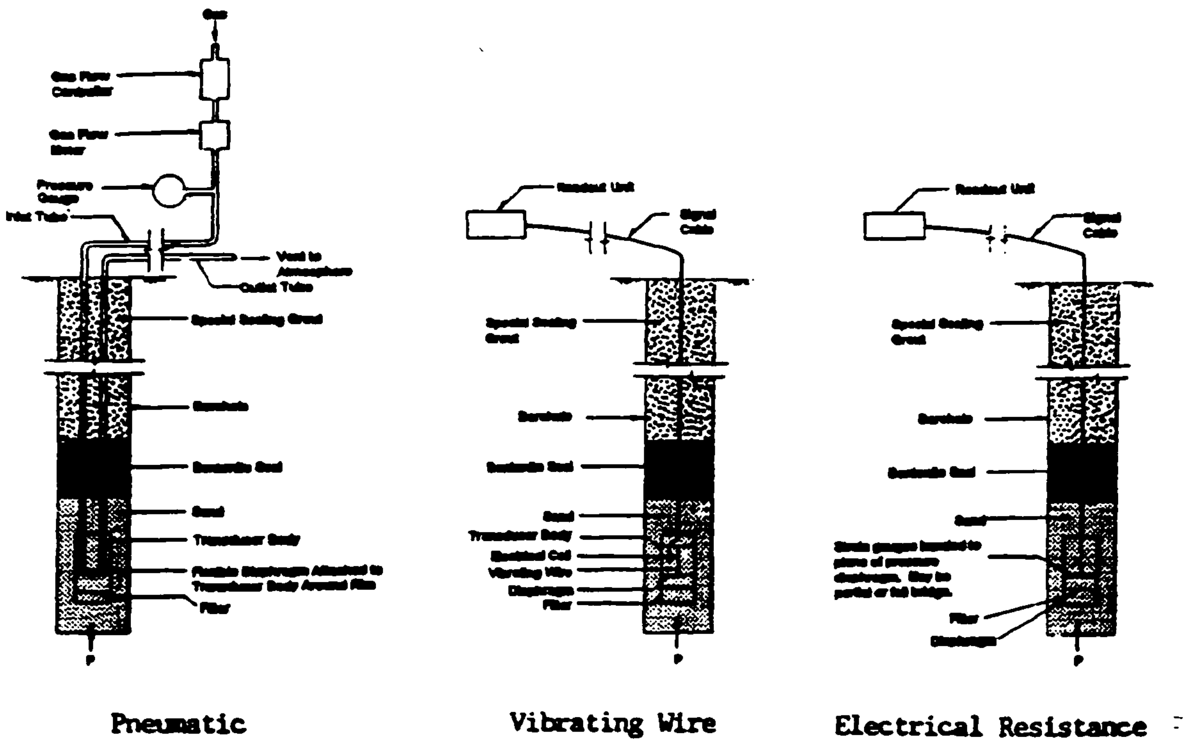


Figure 2-6. Typical Piezometer Types
(from: HBT AGRA, Ltd., 1991)

Sandra Maxfield and Alan Mair, in an article entitled "Strategic Design of Groundwater Monitoring Programs for Inorganics," (1995) outline the requirements for a well-designed ground-water monitoring system. A well-designed detection monitoring program contains several elements. The first element is the development of baseline ground-water quality data collected over a minimum of one year prior to foundation preparation and pile construction. A group of up-gradient monitoring wells should be used to establish baseline groundwater concentrations. These baseline data are then used as the comparison for future data collected. These wells are theoretically unaffected by the mining practices and are used to develop baseline data. On-site or down-gradient monitoring wells are needed to determine if a release has occurred. Data from these wells are compared to baseline data from up-gradient wells. Comparisons are made based on a set of targeted parameters. The next element of a monitoring program is the sampling schedule and procedures. The sampling schedule and procedures should be consistent and well-documented, preferably in the form of a Sampling and Analysis Plan (SAP). The final element crucial to a well-designed monitoring program is the development of an action level or concentration limit that should not be exceeded in on-site or down-gradient wells (Maxfield and Mair, 1995). The same procedure is applicable to the design of surface water monitoring programs.

Quantitative monitoring for ground water and surface water quality changes downgradient of a pile requires regular sampling and analysis of water samples (monthly, quarterly or another frequency correlated to site-specific conditions such as flow rates, that could affect pollutant release potential). Sufficient surface water sampling sites and ground water wells must be established immediately downgradient of the pile to address all potential water migration pathways. In addition, the parameters selected for sample analysis should reflect the geochemistry of the waste rock and any chemical agents that may be present as a result of the mining activities (e.g., acid drainage, heavy metals, nitrates from blasting compounds).

Any changes in water chemistry may signal developing water quality problems. For example, increasing concentrations of sulfate and total dissolved solids may signal the initial generation of acid rock drainage.

3.0 DESIGN AND OPERATION TO ADDRESS ACID ROCK DRAINAGE

One of the most serious environmental problems resulting from waste rock disposal at non-coal mines is the generation of acid rock drainage. Acid rock drainage from waste rock piles is responsible for the degradation of water quality in many streams in the western United States, as well as impacts to local ground waters. While much of the acid rock drainage is the result of historic mine waste disposal practices, discussions with federal and state mining regulators indicate that the same problems are seen at new waste rock piles where no definitive long-term designs or controls are implemented. Site-specific differences from one mine to another (e.g., rock type, climate variables, etc.) require the application of control techniques or designs that are customized to the site conditions.

In another report, EPA has described in some detail the process of acid generation and various predictive methods in use and under development (U.S. EPA, 1994). This section summarizes some of that information as it applies to waste rock piles.

3.1 Acid Generation in Waste Rock Piles

Acid generation and leaching from waste rock piles can severely impact potential uses for a receiving water. Acidic water enhances dissolution of metals, resulting in the discharge of acidic water containing high concentrations of toxic metals from the waste rock pile. Low pH waters may be corrosive to metal or concrete structures, toxic heavy metals may deplete or alter aquatic life, and higher oxygen demand lowers the concentration of oxygen that is available to sustain biotic organisms.

In extreme cases of acid drainage, receiving waters may exhibit a layer of brightly colored yellow orange-red iron precipitate known as "yellow-boy". The precipitate may also exhibit colors ranging from yellow-green to purple or black, depending on the presence and oxidation states of minerals and metals that are mobilized in the acid drainage. Other indicators of acid drainage include mineral salt blooms, irregular melting of snow over acid-generating materials, and accumulation of whitish gypsum slimes along drainage pathways from the waste rock pile. (BLM, 1992)

3.1.1 Acid Generation Chemistry

Acid drainage is generated from the chemical oxidation of sulfide compounds, particularly iron sulfides found in pyrites, to sulfuric acid. These acid generating reactions require the presence of the pyrite or other sulfide compounds, oxygen, and water. The pyrite may be oxidized either by oxygen or ferric iron. For the second reaction to proceed, ferrous iron must be oxidized to ferric iron. The oxidation reaction rate is increased in the presence of iron bacteria such as *Thiobacillus* *ferrooxidans*. Heat generated during reaction also accelerates the rate of oxidation (BLM, 1992, Doyle, 1990). The chemical reactions are as follows:

1) $FeS_2 + 7/2\ O_2 + H_2O <==> Fe^{2+} + 2SO_4^{2-} + 2H^+$

2a) $Fe^{2+} + H^+ + 1/4O_2 <==> Fe^{3+} + 1/2H_2O$

2b) $FeS_2 + 14Fe^{3+} + 8H_2O <==> 15Fe^{2+} + 2SO_4^{2-} + 16H^+$

The net result of these reactions is the production of sulfuric acid, which migrates with the water percolating through the pile.

Acid drainage can be mitigated or suppressed by the presence of basic carbonate minerals, such as calcite ($CaCO_3$), magnesite ($MgCO_3$), or dolomite ($CaMg(CO_3)_2$), in the pile. These minerals can dissolve in acidic solutions and neutralize the acid, according to the following equation:

3) $MCO_3 + H_2SO_4 ==> MSO_4 + H_2O + CO_2$ [M = Ca, Mg]

Some of the CO_2 generated by this reaction will remain dissolved in the aqueous solution and will act as a buffer to maintain the solution pH near neutrality until the neutralization capacity of the carbonate minerals is reached.

The *acid generating potential* (AGP) and *net neutralization potential* (NNP) of a rock sample can be measured by static and kinetic tests (*e.g.*, humidity cells) and by titration of a slurry of the sample. Minerals containing high levels of carbonates may exhibit higher NNPs, and thus be better able to suppress ARD. Waste rock with a ratio of NNP to AGP of 3.0 or more is unlikely to pose a threat of ARD. A NNP/AGP ratio of 1.0 or less will almost certainly result in ARD unless other mitigation measures are taken. NNP/AGP ratios between 1.0 and 3.0 may or may not produce significant amounts of ARD; such waste rock piles must be further evaluated individually.

The mere presence of ARD-neutralizing minerals in the waste rock or a high NNP is not sufficient to ensure that neutralization will occur. Carbonates may be concentrated in pockets inaccessible to the bulk of the ARD, or may be present beneath the rock surface. Even where such minerals are present at the surfaces of the rocks and accessible for intimate contact with the ARD, chemical reactions can eventually result in the deposition of slimes or scale deposits on the surface of the carbonates, preventing contact of the ARD with the bulk of the carbonate minerals and leading to depletion of the rock's neutralizing potential sooner than predicted.

3.1.2 Acid Generation Pathways

As shown in the reactions above, acid generation in waste rock piles requires the presence of both water and oxygen. Oxygen is transported within the waste rock pile by gaseous and aqueous advection and diffusion. Gaseous diffusion, described by Fick's First Law, is the migration of gaseous particles from a region of high concentration to one of lower concentration. Fick's First Law states that the gas flux or rate of diffusion is proportional to the difference in gas concentrations; the proportionality constant is referred to as the diffusion coefficient. Upon construction of a waste pile, the internal gas composition mimics the overall composition of the atmosphere without significant gradients between regions of the waste pile. As time passes, however, chemical reactions occurring within the waste pile alter compositions of localized gaseous space, and concentration gradients appear. (Northwest Geochem, 1991)

The rate of gas transport governed by these gradients generally explains random gas movement and is not likely to be as high as movement rates caused by advection, the predominant gas transport process. Gaseous advection is the bulk movement of gases through large pores or channels in the waste rock pile driven by pressure gradients. Although influenced by the permeability of the waste rock pile, advection allows for oxygen transport up to depths of 60 meters (Northwest Geochem, 1991, citing Wadsworth, 1981). Pressure gradients may be formed by gaseous transport resulting from localized increases in temperature from exothermic acid-generating reactions and decreases in surface temperature during winter months. Increased temperatures near acid-generating sites increase the local vapor pressure, which pushes the gases up toward the cooler surface of the waste pile. This phenomenon has been observed by localized snow melts on waste rock piles (Northwest Geochem, 1991). Other factors in forming pressure gradients include wind currents and atmospheric pressure changes; however, MEND indicates that gaseous advection induced by thermal gradients is considered to be the primary pathway for transporting the amount of oxygen necessary to create the large volume of acid products that is observed in waste rock piles.

Oxygen is also present in a dissolved state and transported through the waste rock via movement of water. The rate of water movement, which is governed primarily by aqueous advection, is dependent upon the hydraulic conductivity and hydraulic gradient. Where direct precipitation, which influences the hydraulic gradient, is the only source of oxygenated water to a waste rock pile and where permeability is low, the transport of oxygen via aqueous advection is expected to be much less than transport via gaseous advection (Northwest Geochem, 1991). In fact, research on tailings piles indicates that, due to their smaller particle sizes and presence as slurries, tailings do not permit aqueous or gaseous advection to any significant degree.

Water transport through a waste rock pile is complicated by variations in parameters such as hydraulic conductivity, which vary with the permeability of the rock and between layers of rock. As a result, certain sections of the waste pile may exhibit channeling or water flow across rock layers while other sections exhibit stratification or water flow within rock layers. Channeling is expected to be the primary method of water transport (MEND, 1991, citing Whiting, 1981); however, MEND indicates that monitoring of water movement through unsaturated rock is extremely difficult and that field observations are scarce. Hydraulic gradients in waste rock piles are dependent on a number of variables, including the rate of infiltration and runoff, surface topography, height and width of the pile, and distribution of hydraulic conductivity.

Solids transport within waste rock piles also affects the migration of water and oxygen needed for acid generation. For example, suspended solids may plug water channels, reducing the infiltration capacity of the channels. Particularly problematic is the plugging of water channels within large particle- size bases that are intended to drain excess water from the rock pile. Small particle-size rocks, fines, weathered clays, and mineral precipitants may be flushed to the base, causing a decrease in permeability over time and eventual geotechnical instability of the waste rock pile (MEND, 1991, citing Whiting, 1981).

In addition to serving as a key factor in the generation of acid drainage, water movement in and around waste rock piles constitutes the primary pathway for such contaminants as acids, acid byproducts, and metals, to migrate from a pile to the environment. MEND (1991) generalized the hydrogeological conditions surrounding the waste rock pile with three models. The three models describe waste rock piles that are located in 1) a groundwater recharge area, 2) a groundwater discharge area, and 3) between a recharge and discharge area on a sloping surface. MEND reports that the latter model is the most common scenario because mines often lie in sloping terrain. Many of the same factors influencing water movement within the waste rock pile also influence water movement around the pile. These factors include infiltration and runoff, evaporation, hydraulic conductivities and gradients, channeling and stratification, and mineral precipitation/dissolution.

3.1.3 Acid Generation Model

Robertson and Barton-Bridges (1990) present a model for visualizing acid generation in a waste rock pile (see Figure 3-1). Unfortunately, an understanding of the physical processes in a waste rock pile that lead to the chemical environment necessary for the development of acid drainage is not fully developed to support a waste rock pile design.

The model describes a waste rock pile as having "reactor sites" where optimum conditions for the development of ARD (sufficient oxygen, water and microbes) are available in the presence of sulfides. ARD develops at the "reactor sites" and is transported in water seepage down through the waste rock pile. As the acidic water flows contact basic materials along the flow path, the acidic seepage is buffered and the neutralization capacity of the rock decreases. As more and more

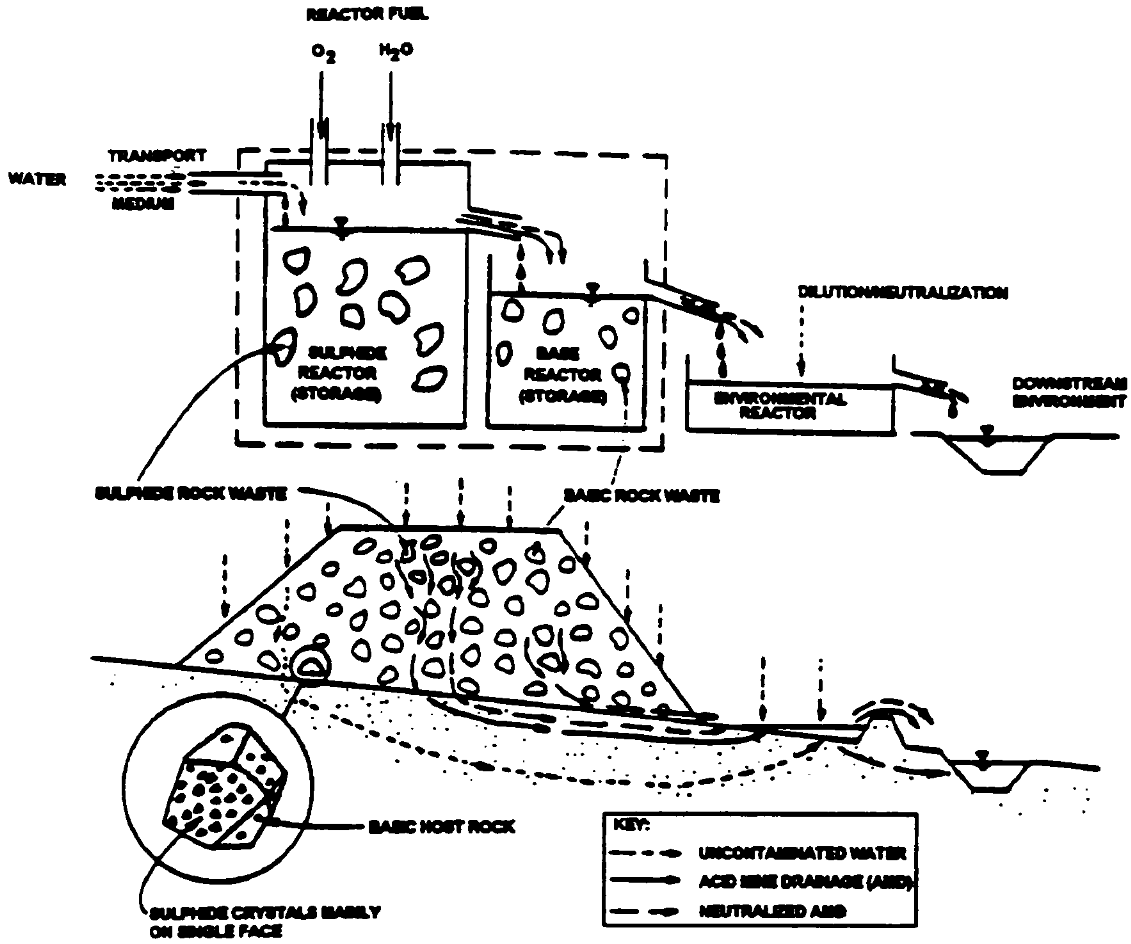


Figure 3-1. Model for the Visualization of Long Term ARD (from: Robertson and Barton-Bridges, 1990)

neutralization capacity is used, the pH of the acidic seepage is buffered less, resulting in lower pH solutions advancing along the flow path.

Over time, as the waste rock pile matures, the neutralization potential of the rock can approach zero. Thus, the acid seepage in the flow can no longer be buffered. This results in the acid front reaching the base of the waste rock pile. (The buffering capacity, as well as the acid-generating potential, for individual piles is highly site-specific.) The extent to which the entire pile becomes acidic is dependent upon the distribution of acid generation and neutralization capacities in the pile.

The acid product of acid generation is stored in the pile not only in solution, but also as solid-phase products. These are stored in zones where salts are precipitated as a result of evaporation within the pile. These stored acid products are flushed from the pile during periods of increased infiltration and flow (spring runoff and high precipitation events). Thus, high concentrations of acid products are found in the seepage water as flow rates increase. High loadings of contaminants occur at these times as toxic pollutant concentrations increase along with flows.

3.2 Design and Operating Factors Affecting ARD

Once the chemistry and pathways leading to acid generation are understood, and potentially acid-generating rock is determined to be present, specific design and operating procedures can be evaluated based on their effect on the generation and transport of acid drainage. For example, during construction of a waste pile, segregation of potentially acid-generating waste materials is increasingly being employed as an immediate measure to control acid generation. Examples of immediate measures that are discussed in this section include blending acid-neutralizing materials (e.g., limestone, lime, sodium carbonate, sodium hydroxide) with the acid-generating waste, prompt burial and compaction to minimize oxygen transport, and application of bactericides for short-term control of reaction rates.

When addressing acid-generating waste rock piles in the early stages of design, methods to prevent acid generation should first be considered, followed by methods to control acid drainage. As a final step, water diversion and treatment techniques are considered. This hierarchy of control selection attempts to prevent the ARD problem before acid control or treatment are necessary. In addition, the long-term effectiveness of collection and treatment systems is uncertain due to the potential for acidic groundwater to circumvent the collection ditches and the threat of a failure in the collection or treatment system (Robertson and Barton-Bridges, 1990).

3.2.1 Pile Operation

The method of piling, or material placement, greatly influences the compaction and particle size distribution within the waste pile. Compaction and particle size distribution have a profound impact on oxygen and water permeability and transport. These, in turn, affect the rate of acid generation and any resulting drainage from the waste rock pile. In addition, the method of waste rock pile construction affects the physical stability of the waste pile.

As stated earlier, materials may be end-dumped into their final resting place or bulldozers may be used to push the waste rock into or distribute it across a specific area of the waste rock pile. End-dumping, which is described by dumping the waste rock on the rock pile from a truck, results in the highest natural particle size distribution. The waste pile may partition into three zones of different particle sizes, with the coarsest particles on the bottom, and the finest particles on the top, or it may result in an evenly graded distribution throughout the height of the pile (Northwest Geochem, 1991). This method is most effective with frictional waste material such as blasted rock and permeable sand-gravel mixtures, so that a concentration of coarse material at the base of the pile forms an underdrain and prevents the development of hydrostatic pressure (CANMET, 1977).

Push-dumping is performed by dumping the waste rock near the crest of the pile with a truck or conveyor, and then pushing the rock over the crest with a bulldozer. Although large-sized particles still collect on the bottom of the pile, there is much less segregation of the finer particles with push-dumping.

With free-dumping, the waste pile is constructed by randomly depositing piles of waste rock, approximately 2 meters in height, across a level surface of the pile. Each layer, called a lift, is compacted prior to initiation of the subsequent lift, resulting in greater compaction but reduced segregation of particle sizes. As a result, there is less natural channeling and stratification than with end- or push-dumping and less potential for oxygen and water transport leading to acid generation. Greater compaction and less channeling also reduce pore water pressures, thus producing a more stable waste pile. For any method of construction, additional benefit is provided by the routine use of dump truck traffic which, when directed in a random manner, provides a uniform compaction across the working surface of a lift or waste pile.

3.2.2 Diversions/runoff control to address ARD

Whenever feasible, waste rock piles containing acid-generating sulfide materials should be located away from surface waters, springs, seeps, and wetlands (IMAC, 1992). In addition, with potentially acid-generating waste rock piles, water should be diverted around the waste pile with diversion channels. Diversion channels should lead to wastewater treatment systems that include acid neutralization with alkaline compounds such as lime, soda ash, or sodium hydroxide, followed by aeration and metals precipitation. These wastewater treatment systems typically generate a hydroxide and/or sulfate sludge requiring disposal. The selection of a disposal practice should consider that metals contained in the sludge may leach, especially at low pH.

Cross-valley, valley-fill, and other designs requiring the diversion of water through the waste pile, should be avoided when the potential exists for acid generation or leaching of toxic pollutants (e.g., nitrates from residual blasting compounds, heavy metals). In the event that diversion of water through the pile cannot be avoided, it is necessary to design the pile and rock drain to address several environmental impact issues. First, it is critical to determine the acid generation potential of waste rock that is to be disposed in designs that require rock drains (e.g., cross-valley or valley-fill designs). Second, allowing oxygenated water to pass through a pile via rock drains allows for the generation and transport of acid from the waste rock. Therefore, the drainage system should be designed to minimize the retention time of water in the pile, thereby reducing its contact with reactive sites. Lastly, sufficient flow must be ensured through the drain, otherwise ecological habitats downstream may be compromised due to decreased flows (Das, 1990).

Snow and ice should be kept off the surface of waste rock piles, and particularly acid-generating piles, to prevent water infiltration in the spring. Infiltration enhanced by snow and ice-melt may lead to acid generation if reactive rock is present. In addition, waste rock covered by snow and ice and associated infiltration leads to weak layers in the pile that are predisposed to failures. Section 2.4.3 of this report presents methods for preventing the accumulation of ice and snow on the pile.

3.2.3 Monitoring for ARD

As stated earlier, chemical analyses conducted as part of an environmental monitoring program that show increases in sulfate and total dissolved solids may signal the initial generation of acid drainage. In addition to chemical analysis, there are other methods that may indicate acid generation and assist in estimating the rates of reaction.

For example, since pyrite oxidation is exothermic, monitoring of temperature may be used to detect acid generation and determine reaction rates in waste rock piles. Temperature profiles, corrected for surface seasonal fluctuations, identify the depths and rates of acid generation. In order to develop the correction factors for atmospheric temperature changes, baseline temperatures for each season must initially be established. Heat generation models take into account the heat loss to the surface above a certain depth, and heat loss to the ground below that depth. Temperature profiles from several boreholes are then used as input to the model. Laval (1991) indicates that current models are one-dimensional, assuming linearity of reaction rates and heat flux with increased depth. Additional field data would allow for the development of more complex models that consider water infiltration and oxygen convection inside the waste pile. (Laval, 1991)

A second method for predicting acid generation rates is based on leachate concentrations, flow rates to collection ditches, and reaction stoichiometry. Given the average concentration of pyrite in the waste rock pile, the iron and sulfate concentration of the leachate, and the average flow rate, an estimated time period for potential acid generation may be calculated (Laval, 1991).

3.3 Predictive Testing

The ability to predict the long-term geochemical behavior of a waste rock pile is crucial during design and planning stages. If the long-term geological behavior of the pile can be accurately predicted through testing, measures can be taken to control acid rock drainage and metals leaching. The objectives of predictive testing are: 1) to determine if a discrete volume of waste rock will generate acid, and 2) to predict the quality of the drainage based on the rate of acid formation measured.

Two major types of characterization tests are currently used in predicting the behavior of waste rock piles: acid-generating potential (AGP) tests and leachate extraction tests. AGP tests are described either as static or kinetic and are used in determining a waste's potential for generating and neutralizing acid. Static AGP tests screen wastes for their net acid-generating potential. The most common static test, acid-base accounting, measures the acid-generating potential of a waste based on its sulfur content, using a stoichiometric conversion of iron sulfide to sulfuric acid. The neutralizing potential of the waste is quantified by measuring the amount of acid consumed by a small amount of finely ground waste.

If a significant acid-generating potential is identified in a waste by acid-base accounting or other static testing, it is generally tested further using a kinetic method. Kinetic methods are more complex techniques aimed at simulating the actual conditions of the waste pile over time. The most common kinetic test is a humidity cell test. The humidity cell test exposes a waste rock sample to alternating dry and moist air flows, leaching, and in some cases, natural bacteria, over a period of months (Lawrence, 1990).

Many manuals have been written on the use of static and kinetic testing, including sampling protocols. A review of these topics is found in EPA (1994) and in various reports published by MEND and the British Columbia Acid Mine Drainage Task Force.

Leachate extraction tests are employed to predict the mobility of heavy metals from the rock pile using an acidic leaching medium. Because the chemistry of waste rock piles changes considerably over time, traditional laboratory leaching tests (e.g., EPA's TCLP test) may not accurately predict the long-term geological behavior of waste rock piles (Lawrence, 1990). Some tests, however, are designed to mimic precipitation infiltration (e.g., EPA's Method 1312, the Synthetic Precipitation Leaching Procedure, and Nevada's Meteoric Water Mobility Test) and may be more appropriate for waste rock than the TCLP test. Laboratory leaching procedures are necessary in identifying hazardous characteristics as required by environmental regulations. However, waste rock pile design, operation, and remediation requires additional tests that are designed to identify leachate characteristics over the life of a waste pile. As a result, researchers have developed, and continue to develop, techniques for characterizing mining wastes and predicting their long-term behavior in waste rock piles. Examples of long-term leachability tests include lab column tests, pilot rock piles, and test pads in the field.

Results of predictive testing must be interpreted carefully. In addition, results from any one particular test may not be conclusive. Predictive characterization tests may fail to consider factors such as climate, hydrology, and the physical and geotechnical characteristics of the waste. Most cases require multiple techniques, or a technique designed to reflect site-specific geological and atmospheric conditions. (Lawrence, 1990)

3.4 ARD Modeling

The generation of acid in a waste rock pile is governed by a complex combination of physical, geochemical, and biological processes. With the increased power and speed of computers, researchers have attempted to simulate the formation and migration of acid rock drainage utilizing computerized mathematical models. Researchers at Ohio State University completed the first comprehensive ARD computer model in 1972 (Northwest Geochem, 1991).

ARD models based primarily on the stoichiometry of acid generation reactions and Fick's Law of gaseous diffusion have been available for many years (Northwest Geochem, 1991). Since the early 1970's, however, ARD models have been expanded to incorporate a number of additional factors that either contribute to or deter acid rock drainage.

These factors include, but are not limited to, gas and water transport in a waste pile, climatic conditions, particle size distribution in the pile, and the type of waste rock present. First, simple stoichiometric relationships have been expanded to incorporate waste from piles containing multiple or distinct types of geological material. Models now exist for piles that contain pyrite, chalcopyrite, chalocite, covelite, or mixtures of these materials. Contributions from bacteria present in waste rock piles can also be incorporated into ARD models. Second, modelling of oxygen transport through the pile has improved. Current models simulate the diffusion of oxygen into pore channels, advection (i.e., bulk gaseous transport resulting from pressure gradients that are induced primarily by heat generated during acid generation), and overall diffusion of air through the pile (i.e., random movement towards the bottom of the pile, which is the direction of lower oxygen concentration). Third, the particle size distribution of materials in the pile is incorporated in many models, enabling the model to determine more accurately the amount of geological material that is available for oxidation. Next, improvements have been made in the modelling of water movement through waste rock piles. Complex patterns of water migration resulting from saturated flows (heavy water flow), unsaturated flows (small "trickles" of water), and the migration of acid condensation all can be incorporated into ARD models. Finally, surficial and climatic processes that affect the overall pile dynamics can be addressed in ARD models (Northwest Geochem, 1991).

ARD models have improved greatly over the past several decades. Future modeling efforts will need to address the effectiveness of various control measures designed to alter acid generation and migration behaviors. Modeling of ARD will undoubtedly continue to improve in the future and will play an important role in the management and control of ARD.

3.5 Engineered Designs for the Prevention of Acid Generation in Waste Rock Piles

As more mines encounter sulfide waste rock during the excavation of ore grade rock, the need grows for proven engineered designs for disposal of these reactive wastes in waste rock piles. The internal reactions, or geochemical processes, occurring in a waste rock pile include the following: acid generation, acid neutralization, bacterial enhancement of reaction rates, and metals leaching. ARD preventive techniques target reductions in oxygen/water transport and bacterial count necessary for acid generation or increases in neutralization or buffering capacity. Examples of acid drainage preventive techniques include impermeable caps and liners, surface water diversions, and blending acid-consuming materials such as limestone with the waste rock. Several of these types of disposal designs/methods are currently in use or under study and are discussed below. All of these techniques are of recent origin. They appear conceptually sound, but their long-term effectiveness is unproven. As a result, long-term vigilance is necessary.

In addition, researchers are investigating novel acid generation control methods aimed at inhibiting the generation of acid in the waste pile instead of controlling or treating the acid after it has been generated. Two such methods are phosphate addition and electrolytic control, which also are presented in this section.

Encapsulation

Encapsulation (or segregation) of sulfide-bearing waste rock within a waste pile is an increasingly common design for the prevention of acid generation in waste rock piles. There are several versions of the encapsulation design, which generally involves the disposal of reactive waste within one area of a waste rock pile, surrounded by non-acid-generating waste. Figure 4-3 illustrates a generalized cross-sectional view of a waste rock pile incorporating the encapsulation method to isolate reactive waste from oxygen and water. Variations on the general design may be incorporated when required by site-specific conditions. For example, in some climates it may be necessary to surround the reactive waste with low permeability materials to prevent moisture from infiltrating the isolated waste. In addition, an underlying capillary barrier may not be necessary in an area of deep groundwater and limited precipitation (i.e., most areas of Nevada).

The effectiveness of encapsulation remains open to debate. Harris and Ritchie (1990) report on a completed 600 m long, 400 m wide and 15 m high waste rock pile at the Woodcutters Mine in Australia. This pile was constructed to contain the most reactive waste rock (5 percent pyrite) in the middle of the pile. Indications suggest that the pyritic material in the pile is oxidizing and a monitoring program has been established to determine the extent and rate of oxidation. The report did not provide information on the indicators used to determine that acid generation was occurring in the pile.

The McLaughlin Mine in California has employed an encapsulation method for the disposal of reactive waste. To date, monitoring of the waste rock pile underdrains indicates that the method has been effective (see Section 4.0). Similarly, the Rain mine in Nevada began encapsulating sulfide waste rock within the larger pile by placing compacted neutral materials over, under, and around the sulfide material.

Layering and Blending of Acid and Alkaline Materials

The addition of alkaline materials to acid-generating materials can provide pH control in waste rock piles. MEND cites several methods that have been suggested and/or investigated for their effectiveness. Neutralization methods cited by MEND include blending acid-consuming and acid-producing wastes to effect neutralization within the waste pile; placing alkaline materials such as limestone upgradient of the acid-generating waste rock, and placing alkaline materials in a collection trench downstream of the acid source. Because these control techniques rely on the flow of water through both the acid-consuming and acid-generating material, the success of the techniques is highly dependent on site hydrology and the ability to predict and manipulate water flow through the system. MEND suggests that the volume of material required to neutralize highly acidic waste rock could be prohibitive (Northwest Geochem, 1991). In addition, while pyrite oxidation is nearly complete within the first year and a half of weathering, the acid drainage may leach from the rock over a period of many decades, imposing long-term treatment requirements on mining companies (Ziemkiewicz, et.al., 1990).

Engineered Soil Covers

Waste piles located in areas with fine-grained soil, or till, mixed with clay may be candidates for closure using engineered soil covers. Fine-grained soils, when compacted and applied at near-saturated conditions, can offer low hydraulic conductivities, which reduces the transport of dissolved oxygen via advection. In addition, at near-saturated conditions, few of the pores remain filled with air, leading to low oxygen diffusion rates. A single saturated soil layer used as a waste pile cap would eventually desaturate due to drainage and water loss from evaporation. Use of a thick layer may address this problem in some climates. In addition, single layer caps do not protect the pile from wind and water erosion without vegetation. (Northwest Geochem, 1991)

In order to maintain erosion protection, an impermeable barrier, and long-term stability to the cap, multiple layered caps are advisable. A top layer of vegetation or coarse gravel prevents erosion from weathering. A second layer of medium to fine textured soils serves to retain moisture for vegetation and reduce oxygen diffusion to the waste pile. In addition, the moisture retention layer prevents the underlying layers from cracking due to excessive dryness. A drainage layer prevents ponding above the lower, impervious layer and prevents moisture loss from the lower layer, which may be designed to remain moist. The infiltration barrier is comprised of fine-grained soil, impermeable clay, compacted till, and/or synthetic materials. For drainage to be effective, it must maintain a slope of 1 percent or greater (Brodie, et.al., 1992). Once installed, the greatest advantage of engineered soil covers is low maintenance (MEND, 1992).

Case Study for Engineered Soil Covers

In the 1950's, the Chamber of Mines of South Africa investigated several options for stabilizing slime deposits from gold mines against wind and rain. The research team determined that a vegetation layer would provide the needed stabilization if suitable plant species were identified. After testing hundreds of species, the representatives from the Chamber of Mines concluded that common plant species were required in order to maintain an adequate supply of seed, and that modifications of the soil with lime and fertilizer would sustain the growth of common plants.

In vegetating the inactive waste piles, the research team encountered, in 1961, slime deposits of high acidity that would not sustain the growth of vegetation. After experimenting with rotavation and lime addition, the research team realized that the acid was rising from below the upper layers of the slime deposit, probably due to upward movement of soil moisture replacing near-surface moisture that had evaporated. In addition, the research team determined that the acidic layer moved downwards after rain, and was confined the first 2 meters of depth. The situation was resolved by installing water sprinkler systems on top of the slime deposit to maintain moisture in the upper layers and induce a downward movement of water to the lower alkaline regions of the deposit. As a result, the pH of deposit surface was maintained at the level required to sustain plant growth. The sprinklers provided an intermittent mist so that pooling and soil consolidation did not present additional barriers to plant growth. Long-term monitoring of the slime deposit also was required in order to maintain the balance between optimum pH and moisture content. (Marsden, 1987)

Chemical Treatment

Chemical additives used to control the bacterial population or coat particle surfaces to reduce acid generation from the waste rock have been researched to a limited extent. MEND provides references for the application of anionic surfactants to limit bacterial growth in waste rock piles at coal mines, and the use of organic and inorganic chemical treatment to control bacterial growth and coat particle surfaces. MEND suggests that chemical treatment may be more appropriate for short-term rather than long-term treatment because the chemicals tend to solubilize in water and require repeated applications. In addition, chemicals applied to the surface of the rock pile are unlikely to reach acid-generating reactions that occur at greater depths within the rock pile. (MEND, 1992)

Underwater Disposal

Disposal of waste rock underwater reduces the influx of oxygen to essentially zero due to elimination of air transport underwater, and the low aqueous diffusivity of oxygen. Concerns with this technique include impacts on the benthic ecosystem of potential metals leaching from the waste rock, and the long-term potential for the low oxygen levels present in the water to generate acid. Robertson (1990) recommends a thin sand layer over the waste rock pile to penetrate pores and reduce direct contact with the water. Robertson also recommends consideration of man-made water bodies using non-acid generation waste rock for impoundment construction. However, the proximity of a suitable water body, site, and/or construction materials may eliminate underwater disposal as a viable option. In addition, the waste rock material must be kept beneath the water surface at all times.

Underwater disposal of old waste rock is not recommended because oxidation at acid-generating sites has already occurred. When placed underwater, large amounts of acid could become mobilized. Closely controlled neutralization operations are possible, however, the environmental impact of large volumes of sludge (e.g., from lime treatment) containing metal precipitates may be significant. (Robertson, 1990)

Phosphate Addition

The addition of small quantities of rock phosphate (approximately 5%) to a waste rock pile creates a chemical and physical environment that inhibits the formation of acid. Iron ions are consumed in rapid reactions with phosphate ions to produce an insoluble ferric or ferrous phosphate and are thus prevented from reacting with oxygen and water to produce acid. In addition, the resulting phosphate salts precipitate and occupy reactive sites in the waste rock, further inhibiting acid generation. (Ziemkiewicz, et.al., 1990, MEND, 1993)

Electrolytic Control

Utilizing the principle of electrolysis, iron ions and other cations are oxidized at the cathode and precipitate insoluble hydroxide flocs, as hydrogen ions (H^+) are reduced at the anode to release hydrogen gas (H_2). This process has a secondary benefit of removing hydrogen ions which reduces the acidity of the pile, and consequently, the potential for metals leaching (Ziemkiewicz, et.al., 1990).

3.6 Comparison of Engineered Designs

A study was recently conducted under the Mine Environment Neutral Drainage Program (MEND) to compare selected ARD preventive techniques (Yanful and Payant, 1993). Samples of waste rock came from the Stratmat site, Heath Steele Mines, near Newcastle, New Brunswick, and from Les Mines Selbaie, located near Joutel, Québec. Outdoor lysimeter tests and indoor laboratory column experiments were performed on the waste rock samples with covers of water, soil, and wood bark, as well as on samples amended with varying levels of either limestone or phosphate rock. Results of triplicate runs were compared to controls which did not receive covers or amendments.

The Stratmat waste rock was derived from the footwall of the ore zone, which contains disseminated and massive sulfides (sphalerite-galena-pyrite and chalcopyrite); the waste rock sample was characterized as a sericitized and pyritized meta-rhyolite consisting of approximately 20% pyrite (9% - 10% total sulfur). The Selbaie waste rock sample came from a region dominated by massive pyrite infilled with quartz; the sample contained approximately 75% pyrite (almost 50% total sulfur).

The outdoor tests used 170 kg of each type of waste rock in each experiment. The crushed (1-2 inch) waste rock and covers or amendments were placed in 160-L plastic containers, with bottom drains for withdrawal of analytical samples, and exposed to ambient weather conditions. The indoor tests each used 20 kg of waste rock sample in a 6-inch PVC column with bottom drain; the columns were subjected to cycles of wet and dry conditions. The following covers and amendments were tested with each rock type:

- water (1 m deep);
- soil: 15 cm of compacted clay sandwiched between 7.5-cm layers of sand;
- wood bark (15 cm thick, uncompacted);
- crushed phosphate rock, added at levels of 1% and 3% by weight, mixed with the waste rock;
- crushed limestone, added at levels of 1% and 3% by weight, mixed with the waste rock.

Leachate samples were collected periodically through the bottom drains and were analyzed for pH, metals, anions, and acidity (as mg $CaCO_3$). Effluent water quality had been monitored for approximately 14 months as of the date of publication, and was scheduled to continue for another two years.

The control samples (without covers or amendments) began producing acid within 5 weeks of the start of the tests. The Stratmat samples generated acid at a higher rate than the Selbaie samples, despite their lower sulfur content; the reason for the difference was not determined, but could be due to different pore structures in the rocks. Higher acid production rates were observed in the laboratory samples, and were attributed to higher indoor temperatures.

The experiments using a wood bark cover were designed to test the hypothesis that the presence of organic material could promote the growth of sulfate-reducing bacteria in the waste rock; however, the organic material apparently promoted the growth of iron-oxidizing microorganisms more than that of sulfate-reducing bacteria. As a result, the drainage from the experiments with the wood bark covers contained ***higher*** levels of acidity than the controls. Effluent from a separate control experiment (wood bark without waste rock) exhibited little acidity and near-neutral pH, showing that acid production was due to bacterial oxidation of the sulfide rock and not decomposition of the wood bark cover.

The effectiveness of the control measures was determined as the percentage reduction in acid production, compared to the controls. The phosphate rock treatment lost effectiveness after initially suppressing acid production; the initial suppression was attributed to the presence of low levels of carbonate mineral (calcite) in the amendment which delayed acid production for some time. The soil cover was more effective in the indoor tests than in the outdoor tests; this was attributed to infiltration of air and water around the edges of the soil cover, and to the effects of adverse natural climatic conditions (freezing and thawing) which were not present in the laboratory.

The most effective control for both types of rock in both the indoor and outdoor tests was the water cover, which suppressed 99% of the acid production. Limestone amendment, soil cover, and phosphate rock amendment (in decreasing order of effectiveness) were all less effective than the water cover in controlling acid production; this order of effectiveness held for all test conditions.

4.0 CASE STUDY

Exemplary practices with respect to the environmental management of waste rock piles are briefly presented in the following case study. This case study and other similar operations provide an opportunity to demonstrate the effectiveness and feasibility of environmentally sound design and operation practices currently in use. Further, the study can provide insight into the geotechnical and geochemical behavior of waste rock piles.

4.1 McLaughlin Mine

The innovative waste rock disposal system and general environmental management practiced at the McLaughlin Mine have been presented by the mining industry as excellent examples of the ongoing efforts by the industry to mitigate the impacts of mining. In addition, the McLaughlin Mine has been honored for their environmental management programs through numerous awards and commendations, including the 1991 BLM "Partner in the Public Spirit" award, and a 1984 Sierra Club Commendation.

The environmental manager at the mine, Mr. Ray Krauss, was the recipient of the 1993 Earle A. Chiles award for "the application of environmentally sound management principles to the mining and extraction of mineral resources in the Intermountain West." The U.S. EPA appreciates Mr. Krauss' assistance (through telephone conversations and providing documentation of McLaughlin's waste rock disposal and environmental management practices) in the development of this case study. The following case study was developed from the materials provided by Mr. Krauss: Homestake (undated), Krauss (1993), and Krauss (1994).

4.1.1 Mine Background

The McLaughlin Mine is a gold mining and milling facility located in the Coast Range approximately 70 air miles north of San Francisco, California. The components of the mine (open pit, freshwater reservoir, waste rock pile, and mill and mine buildings) are distributed over private and public lands (BLM) in three counties (see Figure 4-1).

The mine was developed in an historic mercury mining district in the early 1980s following an extensive exploration program that defined a gold ore body grading 0.113 ounces of gold per ton. The ore body is mined using open pit surface mining methods. For every ton of ore removed from the pit, five tons of waste rock must be removed. The estimated total ore to be mined at the McLaughlin mine is 30 million tons. Therefore, 150 million tons of waste rock will need to be excavated and disposed of during mining. The mined ore is transported to a crushing and grinding circuit where the ore is reduced

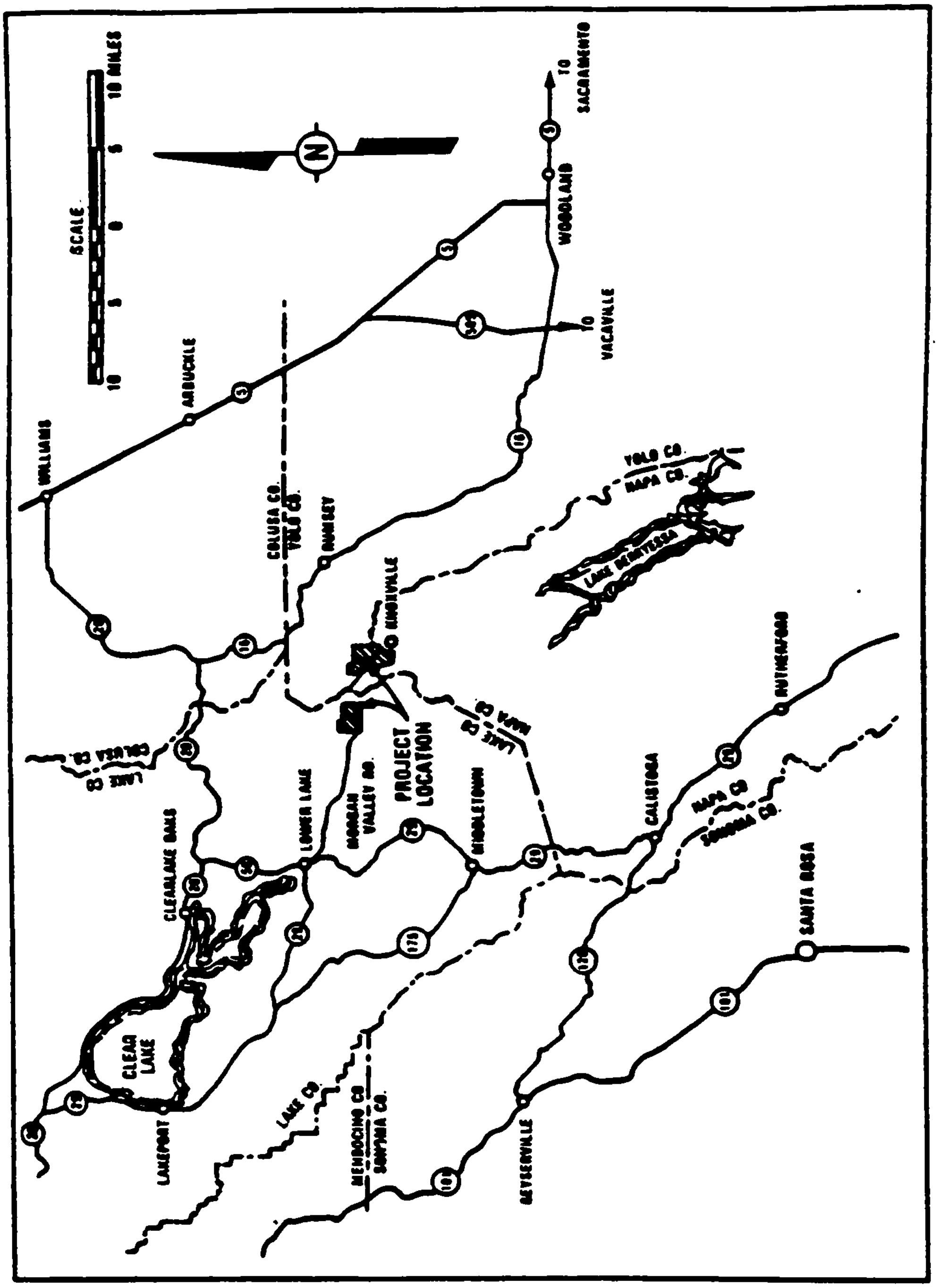


Figure 4-1. McLaughlin Mine Location Map
(Source: Homestake Mining Company)

to a muddy slurry. The slurry is then transported via a pipeline to a process facility where the gold is extracted from the rock. The barren slurry is then disposed in a tailings impoundment.

4.1.2 Waste Rock Piles

Waste rock from the pit has occurred/is planned in three areas: the East waste rock pile, the Site Five waste rock pile and the north pit backfill (see Figure 4-2). The East waste rock pile, now closed and reclaimed, covers 65 acres and the Site Five waste rock pile, which currently receives waste rock, covers 385 acres. The areal extent of the north backfill pit is not known since this area is not yet actively receiving waste rock.

The waste rock piles, with a combined total disposal capacity of 150 million tons, are constructed using the ascending construction sequence. The waste rock was initially end-piled in lifts 50 to 100 feet in height; currently the waste rock is being piled in lifts 50 feet in height. The construction of flat benches between lifts results in an overall slope angle not exceeding 18 degrees (3 horizontal to 1 vertical). The waste rock pile slope between the benches is graded to an angle not to exceed 22 degrees (2.5 horizontal to 1 vertical). These final slope angles facilitate reclamation and assure seismic stability.

Serpentine soils (relatively low strength) underlie the East and Site Five waste rock piles. Foundation preparation required the installation of underdrains in areas of ground-water discharge. Those areas were bladed to subsoils by bulldozers and filled with non-acid-generating rock sized 8 to 10 inches. A filter fabric encloses the rock-filled drains and prevents the migration of fine sediment into the drain. Water from the underdrainage system is conveyed to a sump for use in the process circuit. An overflow pond near the sump would receive any overflow in the event significant flows from the underdrains exceed the capacity of the sump. Underflow from the East waste rock pile underdrains is about 1 gpm. The rate of flow from the underdrains at the Site Five waste rock pile was not obtained.

Surface water is intercepted upstream of the waste rock piles and diverted around the piles through ditches. This water and the runoff from the reclaimed benches at the Site Five and the East waste rock piles are directed to the stream diversion system. This water does not come into contact with wastes or disturbed ground. Runoff from the active surfaces of the Site Five pile flows to sediment ponds. Water from these sediment ponds is discharged after settling or pumped to the grinding circuit for reuse. The discharge from these ponds is permitted.

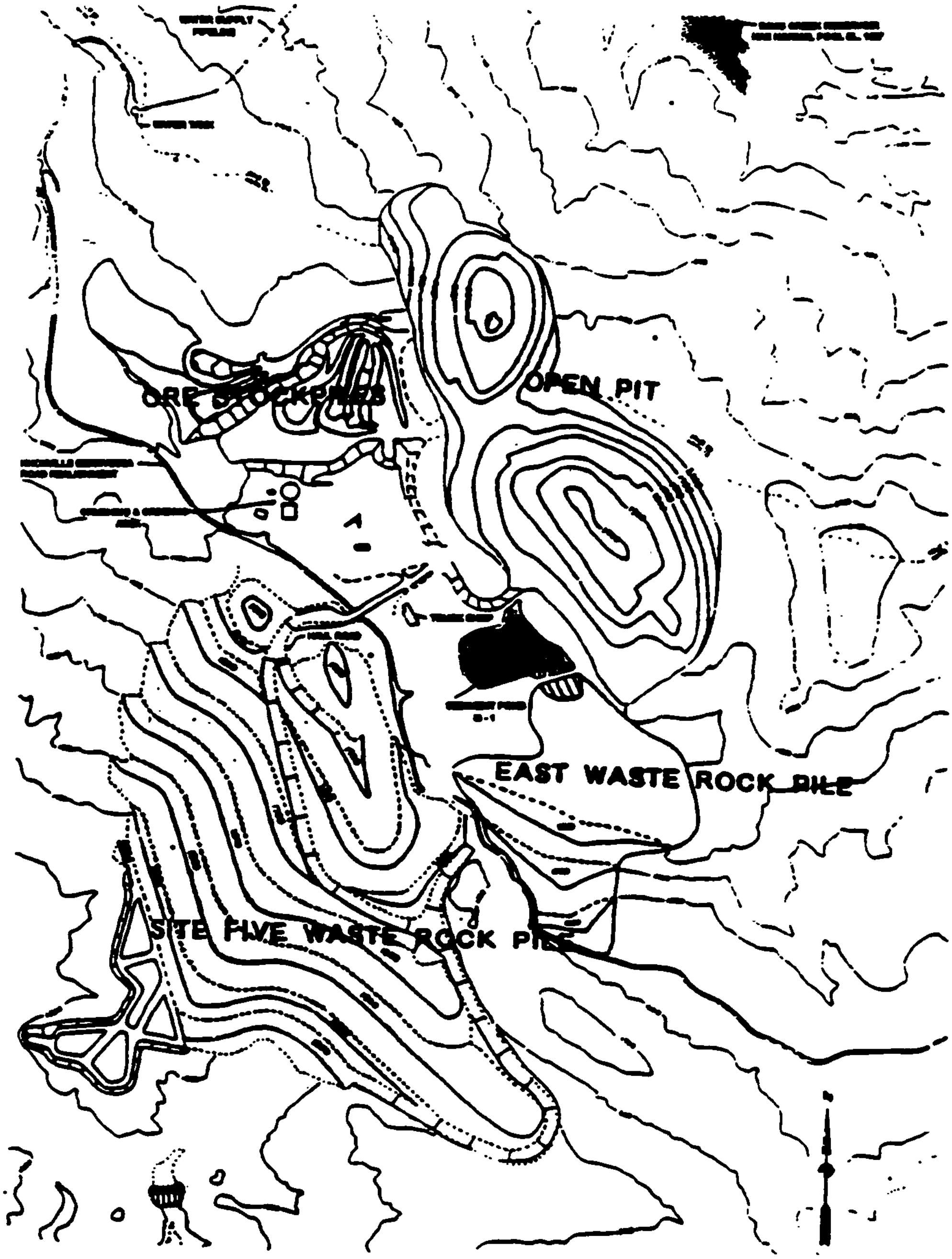


Figure 4-2. McLaughlin Mine Layout
(Source: Homestake Mining Company)

4.1.3 Waste Rock Disposal Planning, Monitoring, Reevaluation and Plan Modification

When the McLauglin Mine was in the planning stages in 1981 and 1982, representative waste rock samples were characterized, using static testing (considered state-of-the-art at that time), for the potential to generate acid rock drainage. Based on these tests, it was calculated that only eight percent of the waste rock would have a net acid-generating potential. Therefore, the determination was made that random dumping of waste rock into the waste rock pile would not lead to the formation of acid drainage. McLaughlin monitored the effluent from the waste rock pile underdrains from the startup date. The early results (analyzed using statistical and trend analysis) of this monitoring indicated that sulfate production was exceeding predicted rates. Calcium concentrations were also increasing, indicating some neutralization was occurring, however, it was insufficient to match the rate of acid formation.

At that time, McLaughlin Mine staff reevaluated the acid generation potential of the waste rock. This reevaluation determined that up to 40 percent of the waste material had a net acid-generation potential. Based on this new information, the McLaughlin staff implemented a new waste rock management program requiring on-the-ground differentiation of waste types in the pit and a change from the random disposal method used at the waste rock piles.

Waste rock was classified as type 1 or type 2. Type 1 waste rock is non-acid-generating and is further divided by physical characteristics into clays and other larger-sized material. All type 2 waste is acid-generating. An experienced mine geologist is responsible for "flagging" waste materials after visually examining drill cores for ore and waste type. The visual observation method used to differentiate wastes in the pit prior to excavation was developed based upon the results of the extensive testing of waste rock types for acid generation potential (conducted during the reevaluation of waste rock at the mine). Both types of flagged waste are excavated and trucked to the waste rock piles for disposal based on a selective waste rock disposal management plan.

The earlier random waste rock disposal method was changed to a waste selective program that encapsulates reactive waste rock (type 2 waste) using type 1 non-acid generating clays. These non-acid generating clays are used in an approximately 5-foot-thick layer at the base of the waste rock pile. The pile is constructed by placing type 2 waste on top of the clay in 50-foot-high lifts. This low lift height enhances dump compaction. During the construction of the pile, the gradient of the lift surface is carefully controlled to ensure that precipitation flows rapidly off the lift surface. In the event the dump surface does not tightly compact, clay is placed on the working surface. After the type 2 waste lift is placed and compacted, the exterior slope is reduced to 2.5:1 (H:V). Type 1 waste is then dumped over the exterior slope to provide a 10-foot-thick layer when compacted. The surface of the lift is covered with type 1 waste and dozer spread to 5 ft thickness. When possible, truck traffic is routed over the clay surface to provide compaction.

A second 50-foot-thick layer of type 2 waste is dumped and compacted on top of the clay, capping the first lift of type 2 waste. This second lift receives the same clay layer as the first lift. In addition, the outer 150 feet of the top surface are left as a bench to provide the overall waste rock pile slope of 4:1 (H:V). An additional 5-foot-thick layer of clay is placed on top of the clay bench to increase the thickness to 10 feet. The mine personnel ensure that the clay layers on the slope and surface of the dump are tied together to form a continuous cap over the type 2 waste. Figure 4-3 illustrates this method of construction for the McLaughlin waste rock piles. Final closure criteria for the waste piles require a 20-foot-thick cover between the reactive waste rock and the surface of the pile. This twenty foot layer consists of: 1) 15 feet of non-acid generating, low permeability clay directly above the reactive rock, 2) three-and-one-half feet of weathered oxidized rock above the clay, and; 3) one-and-one-half feet of top soil. The closure of each lift occurs at the earliest opportunity, followed by reclamation.

4.1.4 What Went Wrong?

The initial testing for acid generation potential in the waste rock was based on static testing of composite samples. Although this method was state-of-the-art in the early 1980s (during the development of the McLaughlin Mine), its limitations became apparent as the operation of the waste rock piles began. McLaughlin staff have identified several errors in the initial testing of waste rock with respect to the management of waste at the mine.

- The testing of composite samples of the various geologic rock types at the mine was found to mask or minimize the acid-generating potential of specific waste types.

- The samples were subjected to a static acid/base accounting procedure that involved grinding the materials to minus 200 mesh. This procedure compares the total acid potential to the total alkalinity of the sample. This testing was determined not to be representative of the behavior of the waste rock as found in the pile where the run of mine waste rock rarely approaches the size 200 mesh used in the static testing. In addition, the waste rock excavated and disposed in the pile displays fracture patterns that are more likely to selectively expose sulfides than carbonates.

- Reaction kinetics are likely to favor acid-forming reactions over neutralization reactions and the neutralization products tend to form a scale on the carbonate rock, preventing further reaction.

4.1.5 Waste Rock Disposal Management and Cost

Mine planning at McLaughlin now integrates waste management with ore development. McLaughlin has developed a life of mine inventory for waste rock and the waste management plan reflects the proportions of the various waste types. The need for double handling of the acid and non-acid forming material has been avoided through careful design and operation of the waste rock pile lifts, providing sufficient area for disposal of each waste type. The implementation of the McLaughlin waste rock management system has resulted in the protection of pre-mining water quality and aquatic ecology downstream of the mine. The cost of implementing a reactive waste rock management system as operated at the McLaughlin mine may, at first glance, be considered excessive by mine planners. Mr. Krauss indicated that the McLaughlin approach to waste rock disposal has been criticized by those in the mining industry that believe the system is overly conservative and costly. He refutes this opinion, as follows:

> *The cost of implementing the acid rock drainage management system is nominal at approximately two cents per ton of ore placed in the pile. The cost is minimized by careful planning to avoid the need to double handle any waste rock and to utilize only waste required to be moved by the mine plan, and not mine other materials to effect closure. This cost is relatively insignificant when compared to what the cost might be to construct and operate a water treatment plant to treat the discharge from an unmanaged waste rock pile.*

Looking toward the future, Mr. Krauss notes that Homestake now incorporates, from the exploration stage forward, consideration of acid rock drainage potential into the evaluation and planning for new mines.

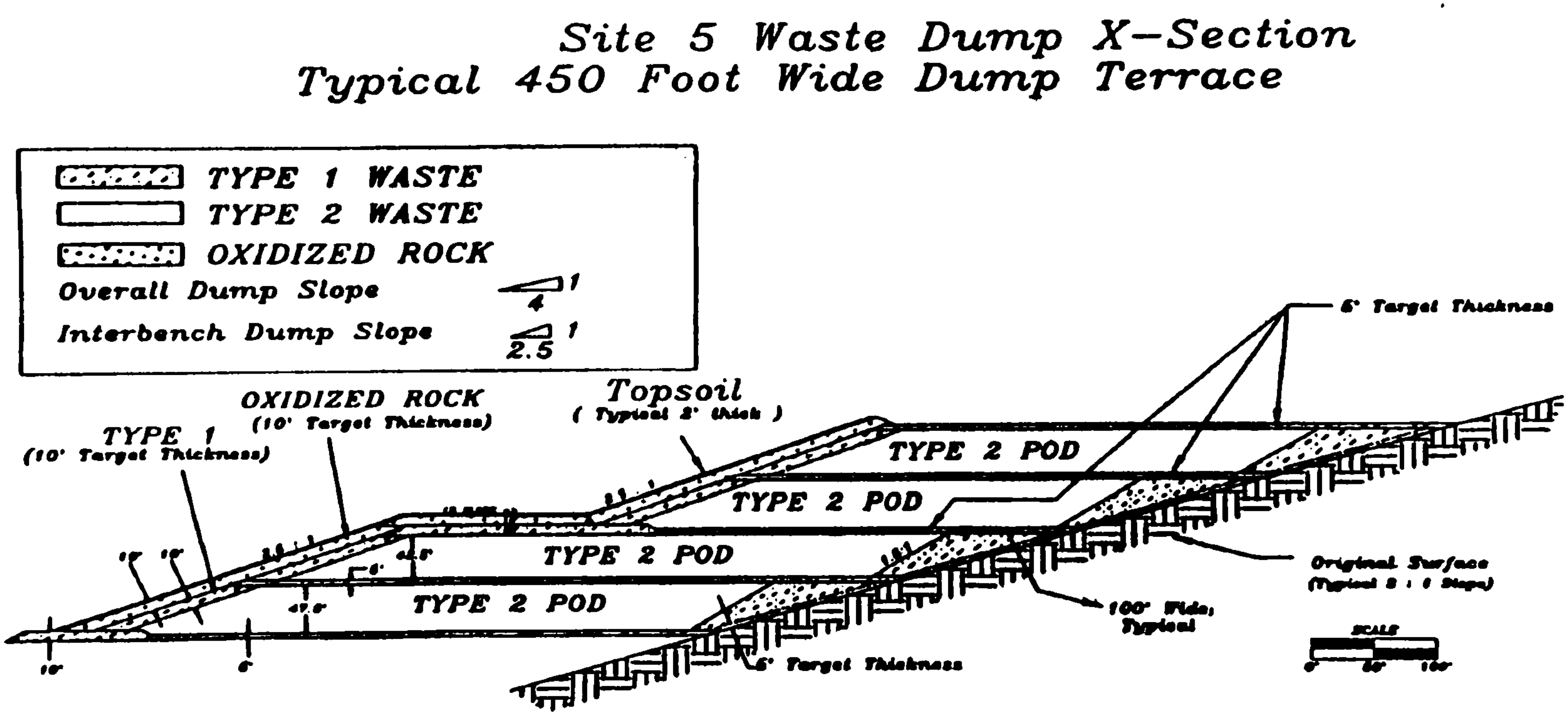


Figure 4-3. Inter Barrier Construction at the McLaughlin Mine Waste Rock Piles

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