N A T U R A L   R E S O U R C E S

CYANIDE HEAP LEACHING

A Report to the Legislature

by David K. Norman and
Robert L. Raforth

December 1994

Prepared in response to
Engrossed Substitute House Bill 2521,
The Metal Mining and Milling Act
(Chapter 232, Laws of 1994)
for
The House Committee on
Natural Resources and Parks

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Jennifer M. Belcher - Commissioner of Public Lands
Kaleen Cottingham - Supervisor

Acknowledgments

Washington Department of Natural Resources
Division of Geology and Earth Resources
P.O. Box 47007, Olympia, WA 98504-7007

Washington Department of Ecology
Central Region Water Quality Program
106 S. 6th Avenue, Yakima, WA 98902-3387

Reviewers

Bill Lingley, *Washington Department of Natural Resources*
Ray Lasmanis, *Washington Department of Natural Resources*
Bob Barwin, *Washington Department of Ecology*
Rod Lentz, *U.S. Forest Service, Okanogan National Forest*
Allen Throop, *Oregon Department of Geology and Mineral Industries*
Bruce Schuld, *Idaho Department of Environmental Quality*
Beth Norman, *South Puget Sound Community College*

Contributors

Jari Roloff, *Washington Department of Natural Resources*
Keith Ikerd, *Washington Department of Natural Resources*
Polly Zehm, *Washington Department of Ecology*
Doug Clausing, *Washington Department of Ecology*
Bob Swackhamer, *Washington Department of Ecology*

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Printed in the United States of America

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Contents

Cyanide Heap Leaching

Introduction

Cyanide heap leaching is a process for recovering gold and silver by trickling cyanide solutions through low-grade ore that has been stacked on open-air pads (Fig. 1). Cyanide heap-leach methods are viewed by industry as offering a low-cost means of producing precious metals. The natural oxidizing conditions of the arid western states are optimal for this process. (Abundant flat ground helps too.) Heap-leach operations must be properly designed, managed, neutralized, and reclaimed to avoid adverse environmental impacts.

As part of the Metal Mining and Milling Act (Chapter 232, Laws of 1994), the Legislature directed the Departments of Natural Resources and Ecology to undertake a study of cyanide heap leaching and the adequacy of Washington's laws to regulate this industry. This report summarizes the Departments' findings.

Cyanide and the Mining Industry

The cyanide anion is a simple compound consisting only of carbon and nitrogen (CN^-). Cyanide has many uses, particularly in the chemical and mining industries because of its strong tendency to form 'complexes' with gold, silver, iron, copper, and many other metals. Even weak cyanide solutions can be used to extract metals from oxidized ore.

Cyanide is a potent asphyxiant (a chemical that stops respiratory functions or displaces oxygen) that acts rapidly in an aquatic environment. Though cyanide is not a cumulative poison, some metal/cyanide complexes release toxic forms of cyanide within hours to days after ingestion.

Inadequately regulated cyanide use at mines has caused significant wildlife mortality, especially in migratory birds. Studies show that between 1980 and 1989, almost 7,000 birds were found dead at cyanide leach ponds at gold mines in California, Nevada, and Arizona. Covering the ponds and neutralizing the cyanide solutions are effective means of stopping wildlife deaths at these mines.

There have been three heap-leach operations (all less than 2 acres) in Washington. Two of these operations, the Silver Mountain mine and the Minnie mine in north-central Washington, were improperly abandoned, and the heaps will be neutralized and reclaimed at the expense of the taxpayer. The Gold Dike mine in Ferry County did not achieve full-scale production. No commercial heap leaching has occurred in Washington during the past decade.

Cyanide Heap-Leach Regulation

No single body of Washington law deals solely with the cyanide heap-leach mining process. However, portions of existing laws are applicable to cyanide processes. A few specific restrictions prevent agencies from regulating aspects of heap-leach operations. For example, an exemption for underground mines prevents the Department of Natural Resources from assuring reclamation of heap-leach sites. Instead, portions of other laws are invoked by state and federal agencies to cover the gaps.

The most important state laws generally applicable to mining are the State Environmental Policy Act (SEPA) (RCW 43.21C), the Metal Mining and Milling Act (Chapter 232, Laws of 1994), the Surface Mine Reclamation Act (RCW 78.44), the Water Pollution Control Act (RCW 90.48), and the Clean Air Act (RCW 70.94).

The key aspect of cyanide heap-leach regulation lies in site-specific analysis under SEPA. As is the case elsewhere, in Washington each mine deals with unique ore, water chemistry, and climatic characteristics that defy blanket or rigid regulation.

The Metal Mining and Milling Act of 1994 adds detail to more general language in existing regulations. This Act stipulates that all mining and milling operations using chemical processing are regulated and that every proposed operation covered under the Act must first prepare an Environmental Impact Statement.

Any amendments to existing law should provide ample opportunity to impose site-specific requirements. The Legislature should bring under the reclamation requirements of RCW 78.44 those new underground mines as well as surface metal mines that are below the 3-acre threshold.

Recommendations

The Departments of Natural Resources and Ecology do not recommend passage of new legislation specific to cyanide heap leaching. The Departments do recommend the following:

- Use the Metal Mining and Milling Act to regulate heap-leach operations.
- Give legislative intent but not detailed descriptions of procedures or standards.
- Develop heap-leach performance standards and guidelines.
- Regulate reclamation of new underground mines and their related surface disturbance under RCW 78.44.
- Eliminate size threshold for reclamation of metal mines.
- Establish an adequate funding source.

by
David K. Norman, *Washington Department of Natural Resources*, and
Robert L. Raforth, *Washington Department of Ecology*

December 1994

Cyanide Heap Leaching

David K. Norman
Washington Department of Natural Resources
Division of Geology and Earth Resources
P.O. Box 47007, Olympia, WA 98504-7007

and

Robert L. Raforth
Washington Department of Ecology
Central Region Water Quality Program
106 S. 6th Avenue, Yakima, WA 98902-3387

INTRODUCTION

In its 1994 session, the Washington State Legislature passed a moratorium on cyanide heap-leach operations until June 30, 1996, and directed the Departments of Natural Resources and Ecology to review the adequacy of laws pertaining to heap-leach operations and to submit their findings by December 30, 1994. This document is submitted to fulfill this legislative mandate. It contains a description of cyanide chemistry and cyanide heap-leach technology, a review of state and federal regulations, and the Departments' recommendations for minor amendments that might strengthen Washington laws.

Heap leaching is a metallurgical process for extracting metals by trickling cyanide solutions through crushed ore that has been stacked on the ground (Fig. 1). The process is used primarily for extracting gold and silver from low-grade oxidized ores where large flat areas are available for outdoor pads. Cyanide heap-leach operations are currently used primarily in the arid western states, particularly at gold mines in Nevada (Fig. 2, p. 7).

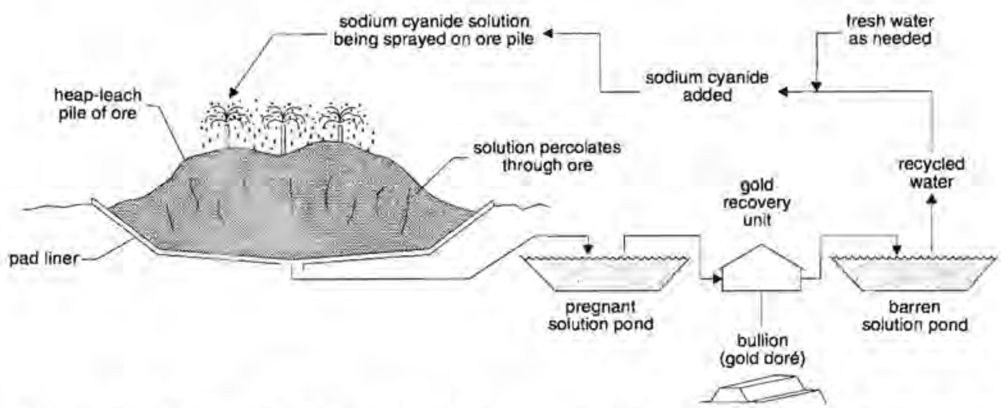

Figure 1. Main steps of a heap-leach operation that produces gold doré or bullion (semirefined gold and silver with some impurities). (Redrawn from an illustration provided courtesy of Alan Czarnowsky, TerraMatrix.)

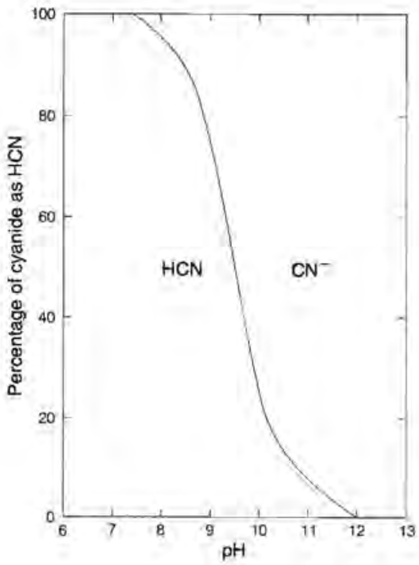

Figure 3. Relation of HCN and CN^- to pH.

While the concept of extracting metals using cyanide is fairly old, cyanide heap-leach technology has developed significantly over the past 15 years. Use of cyanide heap leaching has steadily increased due to its low cost for recovering gold and silver.

Northern Nevada was the site of the first small-scale commercial cyanide heap-leach operation by the Carlin Gold Mining Company in the late 1960s (Hiskey, 1985). The first large-scale operation, in the early 1970s, was also in Nevada (Dorey and others, 1988). Only three cyanide heap leaches have operated in Washington. None is currently active, and all were less than 2 acres. However, the impact of these operations has been greater than their size would indicate. A brief case study of each of these operations begins on p. 15. Large-scale cyanide heap-leach operations have not been attempted in Washington.

CYANIDE AND THE MINING INDUSTRY

Cyanide Chemistry

The cyanide anion is a simple compound consisting only of carbon and nitrogen (CN^-). It is a fundamental building block of many organic compounds.

Many industrial uses for cyanide have been discovered, principally in the chemical, metal, and mining industries. It is an important ingredient in processes for electroplating, case hardening of steel, metal cleaning, metals leaching, and ore flotation. A host of diverse products, such as pesticides, fertilizers, drugs, plastics, dyes, and pigments, require cyanide in their manufacture (Stanton and others, 1986).

Cyanide is usually transported as a solid to the mine site, where it is dissolved for use in processing. Cyanide readily forms stable salts composed of cyanide, sodium, calcium, and potassium. Sodium cyanide (NaCN) is the most common salt used in mineral processing. Sodium cyanide is a white crystalline compound that is highly soluble in water. In solution, sodium cyanide dissociates to sodium (Na^+) and cyanide (CN^-). When cyanide reacts with water, it forms hydrocyanic acid (HCN). The liquid forms are employed in the cyanidation process used by the mineral industry.

Hydrocyanic acid readily evaporates and has an odor similar to that of almond oil. Hydrocyanic acid gas is less dense than air, flammable, and toxic. Cyanide may be kept in the liquid state by controlling the concentration, temperature, and pH of the solution. In general, higher temperature, higher solution concentration, and lower pH (more acidic) promote the generation of gaseous hydrocyanic acid (Fig. 3).

Removal of Metals with Cyanide

Cyanide is able to complex (bond) with gold and silver, a characteristic that makes possible the dissolution and removal of these metals from ore. However, cyanide can also form complexes with mercury, zinc, copper, iron, nickel, and lead. If ores also contain these metals, extracting gold requires more concentrated cyanide, which in turn creates waste waters that are difficult to treat (Smith and Mudder, 1991).

Chemists believe that gold (Au), as well as silver (Ag), is dissolved by cyanide in a two-step process:

$$2Au + 4NaCN + 2H_2O + O_2 \rightarrow 2NaAu(CN)_2 + 2NaOH + H_2O_2$$

$$2Au + 4NaCN + H_2O_2 \rightarrow 2NaAu(CN)_2 + NaOH$$

The overall reaction is:

$$4Au + 8NaCN + O_2 + 2H_2O \rightarrow 4NaAu(CN)_2 + 4NaOH$$

In general, fairly weak cyanide solutions can be used to extract gold and silver because the chemical tendency to complex with these metals is strong. In the absence of other metals, a 100 milligrams/liter (mg/l) solution of NaCN (that is, about 50 mg/l free cyanide) can provide the maximum rate and extent of dissolution (Smith and Mudder, 1991). Free cyanide is defined as the sum of molecular hydrogen cyanide (HCN) and cyanide anion (CN^-).

The solution of gold complexed with cyanide is called a 'pregnant' solution. Gold is recovered from this solution by either the zinc precipitation process or the activated carbon adsorption process.

The *zinc precipitation process* is an electrochemical reaction in which electrons are released as the metallic zinc powder reacts with free cyanide ions in the absence of oxygen, converting the gold ions that are complexed with cyanide to elemental gold.

The *activated carbon adsorption process* introduces no additional metals into the gold recovery process. Stripping the adsorbed gold from carbon is typically accomplished using a solution containing 0.1% NaCN (sodium cyanide) and 1% NaOH (sodium hydroxide) at elevated temperatures. The gold is generally recovered from the sodium cyanide/sodium hydroxide solution by electro-winning (the recovery of metals from solution by electrolysis), allowing a portion of the cyanide to be recycled (Muhtadi, 1988). The use of activated carbon can decrease the concentrations of undesirable metals (particularly mercury) in solution, making wastewater treatment more efficient (Smith and Mudder, 1991). As a consequence, many mine operations have begun using the activated carbon adsorption process.

Cyanide Extraction Methods

Heap leach and tank cyanidation are the two most common methods of gold extraction using cyanide that are currently employed by the mining industry. This report deals only with the heap-leach process, but there are similarities between the two methods.

Heap-leach extraction is used for lower grade ore. The ore is stacked in the open on an impervious pad, and a cyanide solution is trickled through the pile. Prior to being stacked on the pad, the ore must be prepared. Ore preparation can range from no treatment, to crushing only, to crushing and agglomeration (combining smaller particles of ore into groups of particles). Agglomeration is accomplished with lime or cement to form pellets that increase the permeability of the heap.

Oxidized ores are most amenable to heap leaching. Most oxidized ore has been subjected to the action of surface waters carrying oxygen, carbon dioxide, etc..

that have altered the original sulfide minerals to form oxides. (An oxide is a metal bonded to oxygen; a sulfide is a metal bonded to sulfur.) For ores that are not oxidized, one strategy for oxidizing the ore is autoclaving (pressure cooking) the sulfides.

Tank cyanidation is used for higher grade ores. For tank cyanidation, the ore must be milled (finely ground) prior to treatment. The efficiency of gold recovery from fine ore is much higher. Cyanidation takes place in an enclosed tank (indoors or outdoors). It is widely used in the mining industry—both the Echo Bay Mining and Hecla Mining Co. operations at Republic, Washington, use tank cyanidation to recover gold and silver.

THE HEAP-LEACH PROCESS

For a cyanide heap leach, the ore is piled in truncated pyramids, typically in 20- to 30-foot high lifts (layers) (Fig. 4, p. 7) that may cover as much as several hundred acres. A dilute sodium cyanide solution is then applied to the top of the ore pile by drip or spray-irrigation techniques (Fig. 5, p. 7). Typical application rates range from 5 to 75 gallons per square foot of surface per day. Solution strengths are approximately 400–800 mg/l sodium cyanide, which has a pH of about 10.3. As the sodium cyanide solution passes through the stockpiled ore, gold is leached from the rock.

The pregnant solution containing the gold flows out from under the pile onto an impervious pad or liner (Fig. 6, p. 8) and into a lined pregnant solution pond (Fig. 7, p. 8). The pregnant solution is then pumped to a gold recovery plant, where either the activated carbon adsorption or the zinc precipitation method extracts gold.

Once the gold is stripped from the liquid, the barren cyanide solution is recycled to the leach piles. Depending on the chemistry of the barren solution, more cyanide may be added and the pH may be adjusted. The piles are leached until all of the gold that can be economically extracted by the method is removed. Heap leaching typically recovers only 60 to 80 percent of the gold and silver in the ore.

In well-operated mines, the heaps and solution ponds are then neutralized by natural processes, washing with water, or treating with chemicals that destroy cyanide. The neutralization process can generate nitrites, nitrates, and inorganic carbon. An overview of cyanide neutralization is given in the Appendix (p. 25).

The heaps are either reclaimed in place or the neutralized spent ore is placed back in the pit (if suitable conditions are present and the pad can be unloaded without damage) (Fig. 8, p. 8).

Heap-Leach Components

The main components of a heap-leach operation (Fig. 1) are the:

- mine or source of ore,
- ore preparation,
- heap pile (ore),
- pad,
- liner,
- cyanide solution application system (sprinklers or drip irrigation),

- pregnant solution pond,
- gold recovery circuit, and
- barren solution pond.

The three main components of a heap-leach operation that have the potential to create significant adverse environmental impacts are the:

- mine area (not unique to the heap-leach process),
- waste-rock dumps, where overburden is placed during mining (also not unique to the heap-leach process), and
- ore-processing area with a leach pad and pond system (unique to the heap-leach process).

Heap and Pad Construction

Three basic methods of heap and pad construction are used:

- *Permanent multiple-lift expanding heap.* Spent ore remains on the pad after leaching is completed. New layers, referred to as lifts, are continually built on top of the spent ore (Figs. 2, 9; p. 7, 9), resulting in a truncated pyramid appearance.
- *Reusable pads.* Spent ore is removed from the pad and disposed of. More ore is then placed on the pad, and the process is repeated (Figs. 4, 10; p. 7, 9).
- *Valley leach.* A valley is used as the leaching area. An earthen dam built at the lower end of the valley provides containment. The heap and the pad are designed to be stable structures that contain both the ore and the leachate (Dorey and others, 1988). This method is most commonly used in mountainous terrain (Fig. 11, p. 9). Ore is continuously placed on the heap as in the permanent multiple-lift expanding heap method.

Choices of heap locations are generally constrained by haul distance, land availability, and topography. The foundation for the heap must be engineered to withstand loading—it must be stable and not settle. Where valley heaps are used, the liner must resist the tendency to creep down the valley (Dorey and others, 1992).

Liners

The pad liner is a critical component for a safe heap-leach operation. The purpose of the liner is to collect and contain the leach solutions (Fig. 12). The liner also acts as a platform on which the heap is built. Historically, liners (soils, clays, and geomembranes) have failed and leaked, but recent advances have made liners more reliable. However, design criteria must be based on the assumption that leaks will occur and that leak detection and recovery systems are necessary.

Soil for liners can consist of onsite or local borrow materials (if they have the correct clay content), bentonite, or mixtures of both. Important considerations in choosing soil for liners are its availability and composition. Imperfections such as roots must be removed during pad construction. The soil must have a appropriate clay content, low permeability, plasticity, and chemical stability when in contact with a cyanide solution.

The thickness and method of liner compaction at the site are also important engineering considerations. Most clay liners are designed to achieve a hydraulic conductivity (permeability) in the range of 10^{-6} to 10^{-7} centimeters/second

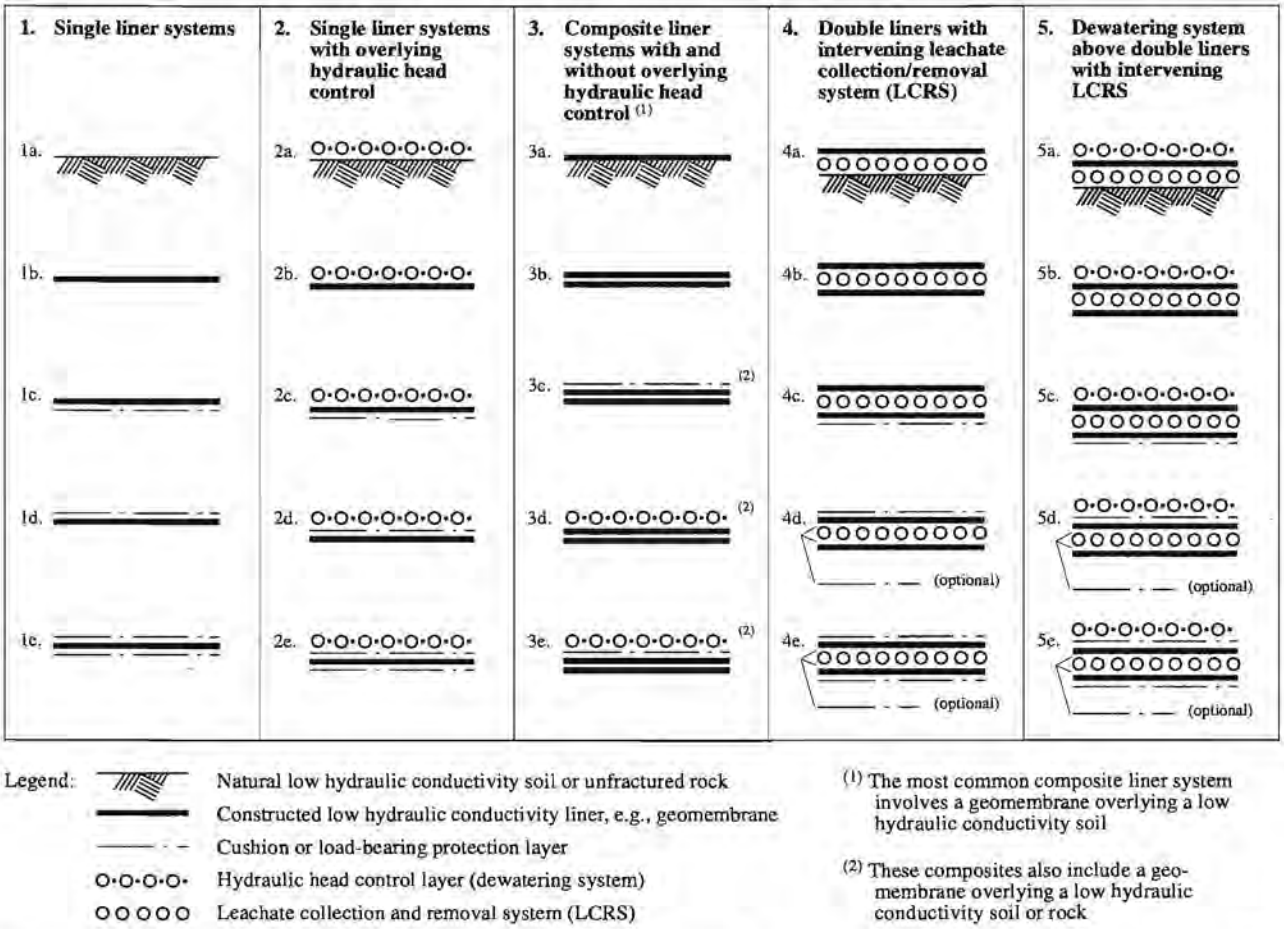

Figure 12. Various combinations of liner systems. (Redrawn from Ellison and others, 1992, fig. 7.1, p. 335. Used by permission of Lewis Publishers, an imprint of CRC Press, Boca Raton, Florida.)

(1.0–0.1 foot/year). To attain low-permeability containment, clay liners must be properly compacted with appropriate equipment, while protecting against damage due to cracking from drying and (or) shrinkage (Hutchinson and Ellison, 1992). In general, increasing the clay content of soil decreases the permeability. However, clay mineralogy can also affect permeability. Expandable clays (smectite and illite-smectite group clays) are less permeable than other clays (kaolinite or illite). If the clay is not thoroughly mixed, conditioned, and carefully placed, the liner permeability is unlikely to be uniformly low. Careful review of construction quality assurance/quality control (QA/QC) should be carried out for any liner installation.

Mine location can influence the choice of liners. Some sites lack adequate natural materials such as clay, sand, and gravel to construct liner components. If natural material is not available, a synthetic liner system must be used. Typically, multiple liners are required, with the bottom layer consisting of clay.

Technological advances in the manufacture of synthetic materials during the past decade have resulted in the use of geomembranes for all components of the liner system (Ellison and others, 1992). Geomembranes are made of polyvinyl chloride (PVC), hypalon, high-density polyethylene (HDPE), very low density polyethylene (VLDPE), Chevron Industrial Membrane (CIM), chlorinated polyethylene (CPE), and asphalt/hydraulic asphaltic concrete (HAC) (Dorey and others, 1988). The most commonly used geomembrane is HDPE. It is important that geomembranes do not react with the reagents used in heap-leach processing. Other important considerations in choosing geomembranes are

Figure 2. The Gold Bar mine in Nevada owned by Atlas Gold Mining, Inc. Shown in the photo are:
(1) the open-pit mine,
(2) heap-leach pads and pad area,
(3) barren ponds and pregnant ponds,
(4) cyanide neutralization facilities,
(5) building facilities and crushers, and
(6) waste rock.

Figure 4. Heap-leach pads at Minven's Stibnite mine in central Idaho. Fence posts in foreground are about 6 feet high. Sprinklers apply cyanide solution to the ore. After trickling through the heap, solutions are collected in ditches at the perimeter of the heap and directed toward the pregnant solution pond. (Photo by Allen Throop, Oregon Department of Geology and Mineral Industries.)

Figure 5. Sprinkler system applying cyanide solution to a heap-leach pad at the Gold Bar mine in Nevada. In contrast to drip irrigation systems, sprinklers oxygenate the cyanide solutions. Drip systems have less evaporative loss. (Photo courtesy of Atlas Gold Mining, Inc.) Photo courtesy of Atlas Gold Mining, Inc.)

Figure 6. Preparation of a heap-leach pad and liner at the Coeur Thunder mine in central Idaho in 1985. A sheet of impermeable geomembrane is laid down on a slightly inclined surface of compacted low-permeability glacial till, and the ore is then stacked on top of the sheet. Lined ditches contain and collect solutions. (Photo courtesy of Bruce Schuld, Idaho Department of Environmental Quality.)

Figure 7. Pregnant solution pond during operation at the Coeur Thunder mine in 1985. Posts in foreground are about 5 feet high. (Photo courtesy of Bruce Schuld, Idaho Department of Environmental Quality.)

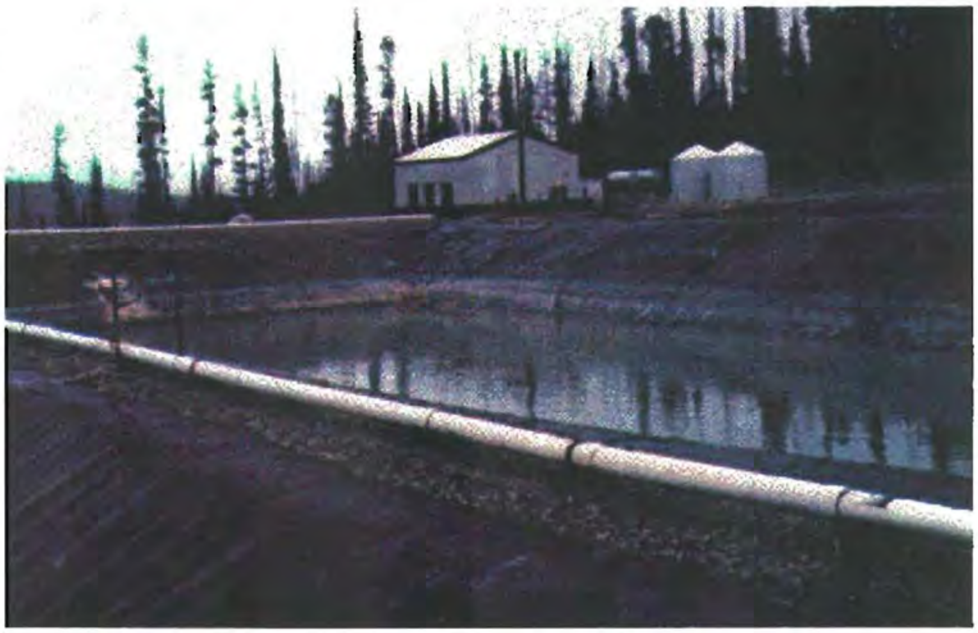

Figure 8. Reclaimed heap-leach pad in 1993 at the Coeur Thunder mine, approximately 2 years after mining was completed. Spent ore was unloaded from pads and placed in mined-out pits. Photo shows approximately the same location as that in Figure 6. The recent drought has limited growth at this site. However, grass and pine trees have begun to spread as conditions become more favorable.

Figure 9. Hecla Mining Company's Yellow Pine, Idaho, heap-leach facility. Lifts are approximately 20 feet high, resulting in an 80-foot high heap. After each layer of the heap is leached, a new layer is placed on top and leaching continues.

Figure 10. Aerial view of the construction of the West End project heap-leach pads and ponds at the Stibnite mine, Idaho, in 1982. Pads consist of asphalt set on glacial sediments. These asphalt-lined pads are unloaded after heap neutralization and then reused. (Photo provided by Ray Lasmanis, Washington Department of Natural Resources.)

Figure 11. The Zortman-Landusky mine in northern Montana was the first to use the valley fill method. Ore is layered in approximately 30-foot lifts. Cold weather at the site requires that pipes delivering the cyanide solutions be buried beneath ore layers. Ore is not crushed at this mine, simply reduced in size by blasting and loaded on the pad. (Photo by Bob Derkey, Washington Department of Natural Resources.)

Figure 13. Installing liner systems and welding seams to prevent leaks, circa 1985. Seams have been one of the weak links in the liner process and have been a source of leaks at many sites. Improvements in welding seams have reduced the number of seam failures. (Photo courtesy of Bruce Schuld, Idaho Department of Environmental Quality.)

Figure 15a. Initial construction of a heap-leach pad and pregnant and barren solution ponds in 1984 at the Minnie mine (Fig. 14). Each pond could hold about 80,000 gallons. Ponds used a double geomembrane liner system with leak detection placed on a compacted soil base. (Photo by Rod Lentz, U.S. Forest Service, Okanogan National Forest.)

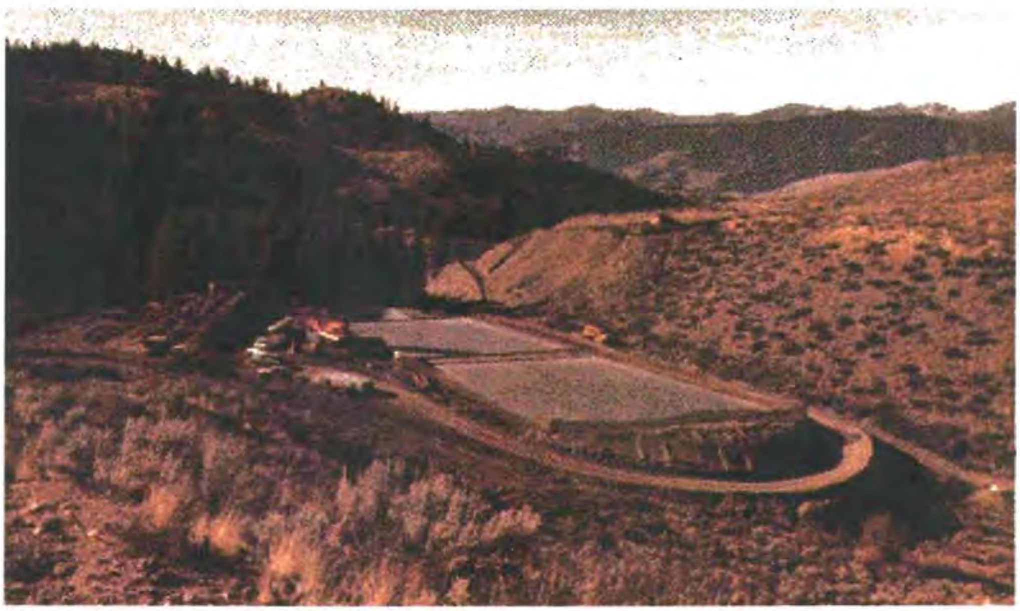

Figure 15b. Heap-leach pad at the Minnie mine prior to the placement of ore heaps. Pad liners consisted of single layer geomembrane placed on a compacted soil base. Pads are 120 ft x 120 ft. (Photo by Rod Lentz, U.S. Forest Service, Okanogan National Forest.)

Figure 15c. Ore stacked 16 feet high on the only pad that was actually used at the Minnie mine. Ore was crushed and agglomerated with cement prior to stacking. Sprinklers delivered cyanide solutions. Spent ore was washed with water and also neutralized using alkaline chlorination. During reclamation, stripping neutralized layers off the pad assisted neutralization by exposing lower material to air, light, and treatment solutions. (Photo by Rod Lentz, U.S. Forest Service, Okanogan National Forest.)

thickness, strength, durability, cost, cover material needed for cushioning, the method of placement, and the method and quality of seams between the sections of the liner (Fig. 13).

There is a wide variety of liner designs that must be chosen on a site-specific basis. In Colorado, for example, the most common liner systems consist of:

- Two layers of synthetic material separated by a permeable leak-detection layer (sand or a permeable synthetic net);
- A lower layer of clay or clay-amended soil, a middle leak-detection layer of sand, and a capping synthetic layer;
- A composite liner composed of a synthetic layer immediately overlying a clay or clay-amended soil layer; and
- A reusable pad (Doerfer, 1992).

The term 'triple liner' (double composite liners of the U.S. Environmental Protection Agency; Strachan and van Zyl, 1988) generally means two geomembranes separated by a drainage layer and underlain by a clay liner.

Past failures of geomembrane liners have been attributed to poor welding of the seams or joints in the geomembrane or to puncturing. Puncturing can be avoided by properly cushioning the geomembrane. New techniques for welding seams have improved seam reliability. Installing a cover layer to cushion and protect the geomembrane has also been key in successful operations. Most failures can be prevented by strict adherence to QA/QC during pad construction.

Solution Application and Collection Systems

At most facilities, cyanide solutions are pumped onto the heap through a sprinkler or drip system. The chemical reaction that dissolves the metals with cyanide requires oxygen. Sprinklers can make more oxygen available by mixing the solution with air. In most instances, however, sufficient oxygen is available in the heap itself. The pregnant solution is collected by a system of perforated drain pipes and trenches that divert the liquid to the pregnant solution pond.

Solution Storage Ponds

The pregnant solution pond holds highly toxic solutions that contain the dissolved gold. The barren solution pond holds the solutions that have been stripped of gold. Impermeable pond liners must be used to ensure that no leakage occurs. Commonly, the barren solution pond and pregnant solution pond are placed side by side to confine large volumes of solutions to one area and to reduce costs of pumping (Fig. 1). The volumes of both storage ponds must be designed to contain the heap-leach solutions as well as precipitation from storm events. Pond size, geometry, and depth reflect the size of the site, the volume of leach solutions, and amount of precipitation expected at the mine site.

Water Balance

Every mine operator and regulator must be concerned about the water balance, or the volume of water for processing ore together with precipitation and evaporative loss. Water balance is a critical design element for heap-leach operations because processing occurs outdoors and pads and ponds may cover many acres.

Because of water balance, climate becomes an important consideration when designing a heap-leach facility. For example, many potential sites for a heap-leach process in Washington are extremely wet. Failure to properly account for water balance could result in the heap becoming overly expensive to operate or failing to function as excess water dilutes the cyanide solution. Pads and ponds must be designed to contain all solutions from the heap-leach process and all precipitation that falls on the heap. Overtopping of ponds could release toxic metallocyanide solutions to surface and ground water.

ENVIRONMENTAL ISSUES

Cyanide Toxicity

Cyanide is a potent asphyxiant (chemical that stops the respiratory function or displaces oxygen) that acts rapidly in an aquatic environment. Cyanide enters the body by inhalation, ingestion, or absorption through the skin. It spreads throughout the body in the bloodstream. Since the central nervous system of higher animals has the greatest oxygen requirement, it is the most strongly affected by cyanide. Central nervous system suppression leads to suspension of all vital functions and death (Smith and Mudder, 1991). However, sublethal doses of cyanide may be ingested without bio-accumulating due to cyanide's high biological reactivity and the body's detoxification mechanisms.

In an aquatic environment, the primary toxic agent is free cyanide, which was defined as the sum of molecular hydrogen cyanide (HCN) and cyanide anion (CN^-). HCN is the most toxic cyanide species. As previously noted, HCN is extremely water soluble. For solutions with pH greater than 10, nearly 90 percent of the free cyanide is in the form of CN^-. Below pH about 8.5, nearly 90 percent of the free cyanide occurs as HCN (Fig. 3). Thus, small pH differences significantly change the toxicity of process solutions.

Factors other than pH also affect cyanide toxicity. Among these are temperature and oxygen content of the aquatic environment, acclimation of the organism to cyanide (which activates defense mechanisms), life stage, stress factors, size and species of organism exposed, presence of other chemicals (such as ammonia) in the environment, concentrations, or time-dependent tolerance increases.

Toxicity of Cyanide-Metal Complexes

Cyanide is used for processing ores because, when present in excess, it readily complexes with and dissolves metals. The toxicity of solutions containing cyanide complexed with metals depends on the concentration of free cyanide formed by dissociation or hydrolysis. Metallocyanides are classified as weak acid dissociable (WAD) if they dissociate at pH 4.5. The WAD method of cyanide analysis uses acids with pH 4.5. It will recover all the cyanide from zinc and nickel cyanide complexes, about 70 percent from copper complexes, and 30 percent from cadmium cyanide complexes. It does not recover any cyanide from iron- (ferro- and ferri-) or cobalt-cyanide complexes (Smith and Mudder, 1992). Upon dissociation in acidic aqueous solution, WAD cyanide complexes liberate free cyanide, thus increasing the toxicity of the solution.

Cyanide complexes with gold, silver, iron, and cobalt are considered stable, although photolysis (chemical decomposition induced by light) will cause iron cyanide complexes to release free cyanide. Turbidity, shading, and depth of the solution will affect photolysis.

Cyanide Persistence in Surface Water, Ground Water, and Soils

Cyanide is seldom biologically available in aquatic environments or soils owing to its reactivity—it rapidly complexes with metals to form insoluble compounds. Some free cyanide is lost to the atmosphere through volatilization. Under aerobic conditions, soil microbes metabolize cyanide, producing carbon dioxide and ammonia. Under anaerobic conditions in nonsterile soils, bacteria convert cyanide, through denitrification, to gaseous nitrogen compounds that escape to the atmosphere. However, significant amounts of cyanide are neither absorbed nor adsorbed by soils and can leach into the surrounding ground water.

Cyanide has relatively short persistence in surface water under normal conditions because it degrades quickly. It may be present for extended periods in ground water where it cannot readily volatilize. Volatilization is the dominant mechanism for removing free cyanide from concentrated solutions and is most effective at high summer temperatures and in solutions with high dissolved oxygen levels or high carbon dioxide concentrations. All of these conditions may be lacking in ground water.

Cyanide Impacts on Wildlife

Eisler (1991) determined that between 1980 and 1989, nearly 7,000 birds, including many species of waterfowl and songbirds, were found dead at cyanide-extraction leach ponds at gold mines in California, Nevada, and Arizona. Also killed were about 520 mammals, mostly rodents and bats, but the list included coyotes, foxes, skunks, badgers, weasels, rabbits, deer, and beavers. Also found dead at these same leach ponds were 38 reptiles and 55 amphibians.

Studies of birds indicate that species sensitivity to cyanide is not related to body size; rather, it seems to be associated with diet. Birds that feed predominantly on flesh, such as vultures, kestrels, and owls, are more sensitive to cyanide than species that feed mainly on plants—with the possible exception of mallards.

The situation is complicated by the condition of birds arriving at the mine ponds. Some consume relatively little fluid, while others, if dehydrated, may consume much larger volumes of the pond waters. Other pond factors such as location, size, visibility, and proximity to other water bodies and migration routes may be important in influencing mortality rates (Hallock, 1990).

Some birds may die after drinking solutions containing theoretically sublethal concentrations of cyanide. A mechanism that could account for this phenomenon involves WAD cyanide compounds. Cyanide bound to certain metals, particularly copper, is dissociable in weak acids such as those in the stomach. Clark and Hothem (1991) suggest that animals that drink sublethal cyanide solutions may die at a later time when additional cyanide is liberated by stomach acid.

Case histories show that migratory birds constitute the majority of documented wildlife deaths attributed to cyanide at mine sites. According to Hallock (1990) of the U.S. Fish and Wildlife Service, "the Migratory Bird Treaty Act makes no provisions for migratory birds killed at ponds containing cyanide. The federal agency's [U.S. Fish and Wildlife Service] position is that killing migratory birds with cyanide at mine ponds is illegal."

For mammals, studies show that cyanide is not bio-accumulative or biomagnified in the food chain, possibly because most animals rapidly detoxify sublethal doses or die after higher doses. In sublethal doses, cyanide exposure does not result in cumulative adverse effects, and sublethal intermittent doses can be tolerated by many terrestrial species for long periods, perhaps indefinitely.

Eisler (1991) reported that fish were the most sensitive animals included in his survey. Adverse impacts on fish included impaired swimming ability, increased vulnerability to predation, disrupted respiration, and altered growth patterns. For example, with salmonids, swimming ability is irreversibly impaired in well-aerated water with free cyanide concentrations as low as 10 micrograms/liter (μg/l). Of all animals studied, aquatic invertebrates were most sensitive to HCN at elevated water temperatures, regardless of dose.

Bird control at containment ponds in the past has used two primary techniques: hazing with sound/visual systems and stretch wire. These approaches are not completely effective (Martin, 1992). Netting can be effective in keeping birds away from smaller regularly shaped ponds such as those constructed to contain pregnant solutions (Hallock, 1990). Entanglement in nets can be a problem for some birds. The most important method of reducing wildlife mortalities is to properly neutralize cyanide solutions.

FACTORS THAT LEAD TO ENVIRONMENTAL PROBLEMS

Some of the problems that have occurred in the past at sites throughout the western United States can be attributed to:

- *Leach solution overflow.* During heavy rains or rapid snowmelt, some leach solution ponds have proven to be too small to contain the precipitation. The cyanide solution overflows onto the ground or into streams.
- *Leaks in liners.* Liner failures allowed the leach solution to leak through to the ground under the pad or ponds.
- *Improper closure.* The cyanide leach solution is not neutralized to subtoxic levels at time of mine closure. Improper management of leach solutions containing concentrated metals or operator bankruptcy have resulted in abandonment of unreclaimed sites.
- *Poor site selection.* The selection of a mine site can be affected by many variables such as climate, topography, and the geology and geochemistry of the site. Poor selection can bankrupt the mine operator and create environmental problems.

In the now infamous case at Summitville, Colorado, all of these factors contributed to some extent to the failure of the operation and subsequent adverse environmental impacts (Knight Piésold and Co., 1993; Lyon and others, 1993).

RECLAMATION

In Washington, after a heap has been neutralized (discussed in the Appendix), the site must be thoroughly reclaimed (Revised Code of Washington (RCW) 78.44). Reclamation of mines has been discussed in Norman and Lingley (1992)

Figure 14. Locations (x) of the three cyanide heap-leach operations in Washington.

and Norman (1992). The same basic principles and strategies apply to reclamation of heap-leach operations. The important activities in planning and executing reclamation are saving and replacing topsoil, creating natural and stable landforms, and establishing vegetation.

In the past, industry practice was to use spent ore from the pad for backfill in a mined-out pit or to reclaim the heap in place. Dumping spent ore into a pit seldom results in landforms that are stable or properly shaped. Norman (1993) describes use of spent ore to create stable landforms that appear natural at the Coeur d'Alene Mining Co. Coeur Thunder mine in Idaho.

If the heap leach is to be reclaimed in place, the slopes of the heap must be pushed down to a stable, natural appearing configuration. Experience has shown that slopes no steeper than 3 horizontal to 1 vertical on which topsoil is replaced offer the best environment for revegetation.

CYANIDE HEAP-LEACH OPERATIONS IN WASHINGTON

There have been three heap-leach operations in Washington (Fig. 14). Two of these heap-leach mining sites, the Silver Mountain mine and the Minnie mine (Fig. 15) in north-central Washington, were abandoned and are, or will be, undergoing cleanup at the expense of the taxpayer.

The Silver Mountain operation was an underground mine located on private land that used heap-leach processing from 1980 to 1981. A 20-mil plastic liner was placed on the ground and covered with an ore heap measuring 100 ft x 105 ft x 14 ft and containing approximately 5,300 tons of ore. Over the life of the mine, an estimated 4,400 pounds of NaCN was mixed with water and sprayed over the heap. Overflow from the leachate collection pond contaminated the soils adjacent to the heap; liner failure was also suspected. Cyanide and other contaminants from the leach pile were found in ground-water monitoring wells installed by U.S. Environmental Protection Agency. The site was added to the National Priority List of Superfund Sites in 1984.

The Minnie mine operated from 1984 to 1985 and was located on federal land. The pad consisted of a 30-mil geomembrane placed on a compacted soil base. The operators were issued a temporary state Waste Discharge Permit by the Department of Ecology before operations commenced. Approximately 6,000 tons of ore were placed on the 120 ft x 120 ft x 16 ft pad. The operators failed to neutralize either the ponds or the heap and declared bankruptcy. The U.S. Forest Service collected a bond of $7,200 and an additional $8,000 in compensation and began site cleanup and neutralization in 1991. Final closure/cleanup costs will be in excess of $225,000. This greatly exceeds the original bond estimate because of requirements not envisioned by the U.S. Forest Service. The remediation costs not foreseen involved mainly the offsite disposal of treated pond fluids and sludges and the associated studies, reports, and engineering designs required under both the Model Toxic Control Act (MTCA) and the federal Comprehensive Environmental Response and Compensation Act (CERCLA). The site will be capped in 1995, and long-term monitoring will commence (Rod Lentz, U.S. Forest Service, written communication, 1994).

The Gold Dike mine operated by N. A. Degerstrom, Inc., is located on private and federal land in Ferry County. Degerstrom performed a pilot project in 1989 but subsequently suspended operations. However, Degerstrom still has a valid

Reclamation Permit for the site. The performance security for the site is \$215,000 and is held by the Department of Natural Resources. The likelihood of the project proceeding is low because of the poor economics of the deposit. Termination of the Reclamation Permit has been discussed with the operator.

MINING REGULATIONS

In Washington, there is no one body of law that deals solely with the cyanide heap-leach mining process. Rather, portions of existing laws are interpreted by agencies to apply to cyanide mine processes. Regulation of mining begins with identification and mitigation of adverse environmental impacts during the preparation of an Environmental Impact Statement (EIS) pursuant to the State Environmental Policy Act (SEPA) (RCW 43.21C). The Department of Ecology is designated as the SEPA lead agency for metal mining and milling (Chapter 232, Laws of 1994). No permits may be issued until the EIS is accepted by the SEPA Responsible Official. Permit requirements are based on criteria and process set forth in law, rule, or ordinance. SEPA substantive authority may be applied on a site-specific basis.

The most important state laws generally applicable to mining are SEPA, the Metal Mining and Milling Act (Chapter 232, Laws of 1994), the Surface Mine Reclamation Act (RCW 78.44) (although underground mining and its surface effects are currently excluded from regulation), the Water Pollution Control Act (RCW 90.48), and the Clean Air Act (RCW 70.94).

Virtually all mitigation requirements must be applied on a site-specific basis because cyanide heap leaching is only one of many metallurgical methods for processing ore. The geology and hydrology of each site is markedly different, and consequently generic review standards cannot be applied.

Historically, heap-leach processing in Washington has escaped thorough regulation under waste-management law. Operators of heap-leach projects have asserted that all their leach solutions are continuously collected and recirculated into the ore. In this scenario, the leach solution does not meet the definition of 'waste'. Therefore, regulations for dangerous waste do not apply until the end of the project when the leach solution is collected for final disposal.

Any heap-leach operation that occupies federal land must also meet the requirements of the National Environmental Policy Act (NEPA) (42 United States Code section 4321). NEPA sets forth both environmental policies and the means for carrying out these policies. All federal agencies making decisions about permits or licenses are required to comply with the NEPA. NEPA requirements are similar to those of SEPA. The SEPA/NEPA lead agency and review processes have been shared cooperatively with a federal agency and Department of Ecology. Regulatory responsibilities of federal, state, and local agencies are detailed in Norman (1994) and Smith (1993).

Water Quality

Among the most significant potential impacts from mining and milling are those relating to water quality. For discharges to surface waters of Washington, certain provisions of Title 40, Code of Federal Regulations (CFR), Part 440—Ore Mining and Dressing Point Source Category, Subpart J—Copper, Lead, Zinc, Gold, Silver, and Molybdenum Ores Subcategory apply to mining. This federal regulation sets maximum daily and average monthly Effluent Limit

Guidelines (ELGs) for copper, lead, zinc, cadmium, mercury, pH, and total suspended solids for new open pit and underground mines, regardless of whether heap-leach techniques are applied. ELGs are included in the federal National Pollutant Discharge Elimination System (NPDES) permit issued and administered by the Washington Department of Ecology for discharges to surface water.

The federal Environmental Protection Agency (EPA) considers mine drainage to include any waters that originate or drain from crushers, spent ore piles, ore stockpiles, or waste rock and overburden piles. It also includes dams or dikes and onsite haul roads that are constructed from waste rock or spent ore. The EPA also considers water draining from a pit or underground working, whether pumped or drained by gravity, and water from a seep or french drain associated with the mine to be mine drainage. Precipitation on any of these mine elements that results in a discharge to surface water is also considered mine drainage and is subject to Effluent Limit Guidelines (ELGs).

If ore is milled, 40 CFR 440 sets a "zero discharge" standard for process wastewater from mills that use cyanidation processes, tailings facilities, and (or) heap-leach piles. In Washington, the NPDES permit is issued according to the requirements of Chapter 173-220 Washington Administrative Code (WAC). In addition to the ELGs in 40 CFR 440, discharges to surface waters of the state are subject to the surface-water quality standards in Chapter 173-201A WAC.

Several other Washington state regulations address water quality. Discharges to the ground are covered by a state Waste Discharge Permit in accordance with Chapter 173-216 WAC. Typically, this permit is combined with the NPDES permit for discharges to surface water. Discharges of storm water or process water to the ground are subject to the ground-water quality standards in Chapter 173-200 WAC; these include antidegradation requirements intended to preserve the beneficial use of ground water. This chapter also defines a process for evaluating the ground-water impacts of a facility. Chapter 173-240 WAC requires submittal of an engineering report, an operations and maintenance manual, and a facility plan for review and approval by the Department of Ecology before discharge permits can be issued.

Water Resources

The permit and water rights application procedures for mining projects follow the same considerations as for other proposed uses of water. Considerations and studies deemed necessary by the Department of Ecology Water Resources Program are:

- *Applications for permit.* Before water is appropriated, four basic questions must be answered:
  - Does the applicant propose a beneficial use of the water?
  - Can a water-use be carried on without detriment to the public interest?
  - Is water available for the proposed project uses?
  - Can water be appropriated without impairing existing rights?
- *Applications for change to existing water rights.* Changes to existing rights may be approved if the following conditions are met:
  - There is a pre-existing water right for which a change may be considered.
  - The proposed change will not be detrimental to existing rights.

- The proposed change can be accomplished without detriment to the public interest.

Air Quality

Metallic mineral processing plants, including heap-leach processing, must register as sources of air pollutants with the state's Department of Ecology or the regional air pollution authority. One air quality permit, the Notice of Construction, is now required for new or modified heap-leach operations. A Prevention of Significant Deterioration Applicability form is used to determine whether a second air-quality permit, the Prevention of Significant Deterioration (PSD) permit is required. For heap-leach processing, the PSD permit is required if emissions of a criterion pollutant (excluding fugitive emissions) exceed 250 tons per year.

Dangerous and Hazardous Waste

The dangerous and hazardous waste regulations may be applied to any industry that uses toxic substances and generates dangerous wastes. Cyanide heap-leach operations are included in one of two ways:

- *Dangerous and hazardous waste management facilities.* These facilities include those that treat, dispose of, or store dangerous wastes for longer than 90 days. They must be permitted prior to beginning operations. The permitting process for a dangerous waste management facility requires detailed review of a great deal of technical information submitted by the applicant. For some proposals, there is a lengthy permit-writing period that includes public involvement at various stages.

  Furthermore, a permit application is required (Chapter 173-303-800 WAC), and a Notice of Intent (Chapter 173-303-281 WAC) must be filed. The purpose of the Notice of Intent is to notify the Department of Ecology, the local community, and the public that siting a dangerous waste facility is being considered. The Notice of Intent also provides general information about the proposed facility, its owner/operator, and the types of wastes that will be managed. It describes compliance with siting criteria. Siting criteria have been established (Chapter 173-303-282 WAC) to serve as an initial filter during consideration of sites for Dangerous and Hazardous Waste Management Facilities.

- *Dangerous and hazardous waste generators.* Many mines generate dangerous wastes. In Washington, when the wastes are generated in quantities exceeding specific threshold levels, they become subject to waste designation, reporting, storage, labeling, spill notification, and transport requirements. Dangerous waste generators do not have to obtain permits if they store dangerous waste in containers and tanks for less than 90 days. They may not treat or dispose of their stored dangerous wastes. They must obtain a state/EPA identification number if they intend to transport their waste to a permitted Dangerous Waste Management Facility, and they must annually report the quantities and types of wastes generated to the Department of Ecology.

  Dangerous waste generators that produce greater than 2,640 pounds of dangerous waste per year must also prepare a pollution prevention plan (Chapter 173-307 WAC). Pollution-prevention planning requires a comprehensive analysis of toxic substance use and methods of waste generation for the purpose of identifying and analyzing strategies to reduce both toxic releases and the amount of waste generated. Implementation of those strategies is voluntary.

Determining how the dangerous waste regulations will apply to a specific proposed business, such as cyanide heap-leach operations, can be accomplished only through the review of the types of industrial processes used, the specific waste-handling practices proposed, and the types and quantities of wastes that will be generated.

Surface Mine Reclamation Act

The Department of Natural Resources (DNR) administers the Surface Mine Reclamation Act, a law that requires a permit for each surface mine that (1) results in more than 3 acres of disturbed ground or (2) has a highwall that is both higher than 30 feet and steeper than 45 degrees (Chapter 78.44 RCW, Chapter 332-18 WAC).

The purpose of the Surface Mine Reclamation Act is to assure that every surface mine in the state is thoroughly reclaimed. A high-quality reclamation plan is required for each mine. The focus of reclamation is to ensure that the site is stable and natural-appearing after reclamation. Some of the most important aspects of the Surface Mine Reclamation Act are:

- segmental reclamation (where possible),
- preservation of the topsoil,
- slope restoration such that highwalls are rounded in plan and section for all mines,
- stable slopes/cliffs in consolidated materials,
- final topography that includes sinuous contours, chutes and buttresses, spurs, and rolling mounds and hills, all of which blend with adjacent topography to a reasonable extent, and
- effective revegetation with diverse ground-cover plants and trees.

The state surface-mine reclamation permit issued by DNR applies to most surface mines in Washington. DNR does not regulate reclamation of underground mines or the related surface disturbances. DNR has not regulated on federal lands prior to the Crown Jewel Project proposed by Battle Mountain Gold Corporation.

Metal Mining and Milling Act

The Metal Mining and Milling Act (Chapter 232, Laws of 1994) addresses conditions for construction, operation, reclamation, and closure of metal mines and milling operations. The Act applies to new or expanded base-metal or precious-metal open-pit and underground mining operations. Milling is defined as the process of grinding or crushing ore and extracting base metals or precious metals by chemical solution, electrowinning, or flotation processes.

Open pit and underground mining methods and the waste rock that is generated are not unique to cyanide heap-leach facilities. The unique component that sets heap-leach processing apart from conventional mining and milling is the processing area that includes the leach pad and various ponds.

While the Metal Mining and Milling Act addresses other components of mining methods and waste rock placement, it does not include language that could be specifically applied to some aspects of heap-leach operations. Sections of the Act set conditions for permitting, siting, and operation, but some of these requirements cannot be applied to an active heap-leach operation. The Metal Mining and Milling Act addresses waste rock and tailings in Section 10, but it does not identify spent ore generated by a heap-leach facility. Spent ore could be regulated in the same manner as tailings. The chemistry and reclamation of waste rock will differ from site to site, but the Act specifies a process intended to identify and address conditions that have potential adverse environmental impacts. Section 10 (1 (a)(i)) limits the concentration of toxic materials in the tailings facility to assure protection of wildlife and human health. Since solution ponds and heaps are part of a processing operation, tailings facility toxicity requirements do not readily apply. In particular, solutions that are sprinkled or dripped onto ore rock do not meet this standard of protection. Upon completion of leaching, successful detoxification of the heap through one or more of the methods discussed in the Appendix would result in compliance with this requirement, although the required standard of protection is conflicting and vague. For these reasons, the minimum design criteria for tailings impoundments (Section 10) may not be adequate for heap-leach operations.

Siting criteria (Section 9) for tailings impoundments include requirements that are conceptually appropriate to heap-leach operations due to their similarity to conventional mining and milling operations. Siting of a heap-leach pad and pond system should be based on the same site characteristics required for a tailings facility. The process for determining and maintaining performance security (Section 11) for activities covered by the Act is equally applicable to heap-leach operations.

Some other aspects of the Metal Mining and Milling Act are:

- Agencies with regulatory authority are required to inspect mining and milling facilities four times a year.
- The Department of Ecology will hold all state performance securities (bonds) for each site.
- Criteria for tailings impoundment design and siting, including site geology, liner design, and leak detection and collection, are established.
- A waste-rock management plan must be developed by the operator and approved by the Departments of Ecology and Natural Resources.
- Citizens can observe and verify water sampling by either the mine operator or the Department of Ecology.
- Agencies are required to conduct post-closure monitoring.
- Citizens are allowed to file lawsuits.

REGULATIONS OF OTHER STATES

For comparative purposes, the regulations of several other states are briefly discussed here. One major difference between Washington and other states is SEPA. Many states do not have an equivalent of SEPA and must rely on other methods of permitting and project review.

Idaho

Idaho regulates any facility that uses cyanide in its ore processing and has a specific statutory section for cyanide heap-leach operations. Idaho's "Rules and Regulations for Ore Processing by Cyanidation" have the intent of establishing procedures and requirements for ore-processing facilities that use cyanidation and that intend to contain, treat, or dispose of water containing cyanide. Neutralization requirements are based on site characteristics and are expressed in terms of pH range or free and (or) WAD cyanide. Regulations do not specify one universal CN^- standard. Idaho has recently revised its water-quality standards for cyanide facilities in order to allow use of the WAD cyanide method. The Idaho Department of Environmental Quality will evaluate each site in terms of proximity to surface water and quality of water. Bonding requirements specify a minimum of $25,000 and a maximum of $100,000.

Oregon

Oregon has the most stringent environmental standards for chemical process mining of any state reviewed for this report. In 1991, the Oregon Legislature passed the Chemical Process Mining Law, which includes the cyanide heap-leach process. The law establishes a consolidated permit application process (SEPA equivalent) that requires a common application for all necessary state permits and a review of the application jointly by all permitting agencies. Each permitting agency has its own law and rules that apply to heap leaching. The legislation sets out specific standards for financial security for chemical process mines. Security must be posted for the credible accident, site reclamation, and long-term environmental effects. The law is highly procedural and details the entire permitting process—from approval of baseline data collection methodologies through construction, mining, and final bond release. All costs related to permitting are paid by the applicant.

Nevada

Nevada has had more cyanide heap-leach processing facilities than any other state. The state uses an approach in which minimum design criteria are given in law, but it also provides for site-specific regulation. Discharged cyanide-bearing waters must contain less than 0.2 mg/l free cyanide, which falls within drinking water guidelines established by the EPA. However, each site is evaluated for proximity to valuable surface water, and the 0.2 mg/l discharge limit can be modified during permitting if no impacts to surface or ground water can be demonstrated, or if an exemption is granted.

Colorado

Colorado has no specific law for heap leaching. Rather, cyanide heap leaches are included in a group of mining techniques that use chemicals as part of their ore processing. In 1993, the Colorado Legislature modified their Mined Land Reclamation Act, partially in response to the heap-leach abandonment at Summitville. The Colorado Mined Land Reclamation Division has prepared guidelines and minimum design criteria for the chemical mining category. Site-specific problems can be dealt with in the permitting process. Some important changes to Colorado's Mined Land Reclamation Act are:

- It develops a new class of mining operation. Most metal mining operators are required to meet more stringent permitting requirements and to develop an environmental protection plan.
- The Act allows the Mined Land Reclamation Board to enforce compliance with new environmental or public health requirements.
- The Board can deny a permit if there are serious or unresolved public-health or environmental concerns.

RECOMMENDED APPROACH TO HEAP LEACH REGULATION IN WASHINGTON

The Departments of Natural Resources and Ecology do not recommend passage of new legislation specific to cyanide heap leaching. The Departments do recommend the following:

- **Use the Metal Mining and Milling Act to regulate heap-leach operations.**

Despite its limitations and imprecision, the Metal Mining and Milling Act appears to be the best readily available vehicle for regulating heap-leach operations. Impacts that were inadequately regulated by the waste management laws appear to be covered by the new Metal Mining and Milling Act. Because the Act specifies that operations using chemicals in their processing are regulated, all cyanide heap-leach mines are included and must prepare an Environmental Impact Statement (EIS). The Department of Ecology is the SEPA lead agency for the EIS. Any new cyanide heap-leach operation would trigger a site-specific investigation as part of the EIS. Public involvement is an integral part of the SEPA process.

- **Give legislative intent but not detailed descriptions of procedures or standards.**

Any changes to existing statutes should give legislative intent but not detailed descriptions of procedures or standards. Regulation of heap-leach processing is compatible with the existing Metal Mining and Milling Act combined with guidance documents jointly prepared and accepted by the two agencies.

- **Develop heap-leach performance standards and guidelines.**

Development of rigid design criteria that would be applied statewide is not practical due to the wide range of geologic, hydrologic, and climatic conditions in Washington. However, it may be appropriate to develop heap-leach performance standards and guidelines. Several states, such as Colorado and Nevada, have opted to develop heap-leach guidelines instead of detailed regulation.

The flexibility to develop site specific requirements is written into the Metal Mining and Milling Act. This flexibility is consistent with conclusions reached by the EPA (NUS Corporation and U.S. Environmental Protection Agency, 1988) with regard to the development of draft criteria for designing Municipal Solid Waste Landfill containment systems. EPA studies showed that a site-specific, risk-based approach would be most appropriate in these circumstances. In reaching its conclusion, the EPA specifically recognized the importance of climate and geologic site factors, including impacts to ground water (Ellison and others 1992).

In response to the direction given in the Metal Mining and Milling Act, guidelines are being prepared for the design of tailings facilities. A similar approach could be used for design of heap-leaching operations. Guidelines serve several purposes:

- When engineering design criteria for critical components are established, then site-specific conditions are easy to develop.
- Areas of acute environmental concern and expectations for mitigation are identified early in the review process.
- The result will be a more efficient and streamlined environmental review and permitting process.

■ **Regulate reclamation of new underground mines and their related surface disturbance under RCW 78.44.**

The Department of Natural Resources recommends that reclamation of new underground mines and their related surface disturbance should be regulated under RCW 78.44. Underground mining has the same components as any other mining operation—waste rock, tailings, processing facilities, and roads—all of which require reclamation.

■ **Eliminate size threshold for reclamation of metal mines.**

Because the potential impact of a metal mining operation is independent of the size of the mine, the Department of Natural Resources recommends that the size threshold be eliminated for reclamation of metal mines. However, adits and prospects should not be regulated unless they exceed the exploration threshold given in RCW 78.44.031.

■ **Establish an adequate funding source.**

An adequate funding source established by the legislature would be necessary for proper regulation under RCW 78.44 and for preparation of the guideline documents.

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An Overview of Heap Neutralization

After the economic supply of metal has been leached from the heap, the mine must be decommissioned. An essential component of decommissioning is neutralizing (detoxifying) the heap. Each heap has a unique set of characteristics. Choice of neutralization method will be influenced by many factors. Some of the methods available for detoxifying cyanide are:

- natural degradation,
- fresh-water rinse,
- alkaline chlorination,
- use of hydrogen peroxide,
- use of sulfur dioxide and air,
- acidification, volatilization, and recovery (AVR), and
- biological processing.

Natural Degradation

Natural degradation of cyanide in the heap or ponds is a combination of physical, chemical, and biological processes and includes reactions with sunlight, bacteria, and air. Environmental factors that influence the speed of degradation include elevation, temperature, and precipitation. Elevation correlates with vapor pressure, which primarily controls the rate of volatilization—the higher the elevation, the lower the vapor pressure, and thus the more HCN that volatilizes from solution (Smith and Struhsacker, 1988; Denton and others, 1992). Higher temperatures generally increase natural degradation processes, as does higher precipitation. Precipitation passing through the heap provides oxygen and water to fuel other cyanide degradation processes and transports soluble cyanide compounds through the heap (Smith and Struhsacker, 1988; Denton and others, 1992).

There are no accurate methods for predicting the amount of time required for a heap to detoxify by natural degradation. The top 3 to 5 feet of a heap are readily detoxified by natural process. Therefore, sampling programs to verify detoxification must work at depths greater than 5 feet in order to determine whether other methods should be used for detoxification.

One of the main advantages of natural degradation is that it is inexpensive. No additional chemicals need to be added to the system; in fact, addition of some neutralization chemicals can create disposal problems as serious as those for the cyanide. The main disadvantage of natural degradation is that it requires more time and is less reliable than other neutralization methods.

Neutralization by Water Rinsing

Mine operators commonly rinse heaps with water prior to decommissioning them in order to flush remaining recoverable concentrations of soluble gold and silver cyanide from the ore. Rinsing heaps with water also expedites the natural degradation processes related to precipitation—hydrolysis, oxidation, and flushing. The effectiveness of detoxification by water rinsing is controlled primarily by the permeability of the heap, the chemistry of the rinse water, and the rate of application.

Operators can generally determine if water rinsing will efficiently detoxify spent ore before they begin to mine by performing metallurgy tests to determine the leaching parameters of the ore. The parameters include agglomeration, permeability, numbers of lifts or layers (typically 15 to 30 feet thick) of spent ore, and depth of the heap. Rinsing to enhance natural degradation processes may not sufficiently detoxify some heaps, especially those with agglomerated ore. Nonetheless, water rinsing is an excellent means of reducing cyanide concentrations before using other detoxification methods.

The advantages of water rinsing are that in arid areas it will enhance natural degradation processes and the additional volume of cyanide-laden waters can be readily disposed of through evaporation without using chemicals. In wetter climates, water rinsing has the disadvantage that large volumes of partially contaminated rinse waters can be generated that are generally unacceptable for discharge to the environment without chemical detoxification.

Alkaline Chlorination

Alkaline chlorination is a well-proven and well-documented method for destroying cyanide. It is relatively inexpensive and effective at ambient temperatures and atmospheric pressures. Alkaline chlorination has been the most commonly used chemical process for destroying cyanide compounds for the last 35 years (Denton and others, 1992). Chlorination, sustained to completion under alkaline conditions, destroys cyanide by oxidation in two stages. In the first stage, cyanide is oxidized and hydrolyzed to cyanate (CNO). This occurs in less than 5 minutes if a minimum pH of 10.5 is held:

$$NaCN + Cl_2 \rightarrow CNCl + NaCl$$

$$CNCl + 2NaOH \rightarrow NaCNO + NaCl + H_2O$$

The second stage of the alkaline chlorination process, which takes as long as 2 hours to complete, oxidizes cyanate to form nitrogen, carbon dioxide and (or) bicarbonate at a pH above 8.5:

$$3Cl_2 + 2NaCNO + 6NaOH \rightarrow 2NaHCO_3 + N_2 + 6NaCl + 2H_2O$$

Alkaline chlorination can be used to detoxify cyanide in the heap as well as cyanide in the solution ponds. If the process is monitored, maintained properly, and allowed to proceed to completion, all free, WAD, and total cyanide, with the exception of ferrocyanide, will be destroyed.

In this process, heavy metals form hydroxides, and metal concentrations can effectively be reduced to less than 1.0 mg/l. The disadvantages of alkaline chlorination are that ferro- and ferricyanides are not treated and that it is difficult to use this method for nickel- and cobalt-cyanide complexes. Toxic levels of chloramine and excess chlorine may be left in solution; these must be removed by SO_2 or SO_3 treatment. In addition, careful control of pH is required. Toxic chlorine gas and (or) hypochlorite salts may be generated. Potential hazards exist when handling and shipping chemicals such as chlorine to the site. Furthermore, alkaline chlorination is not selective, and the chemicals can react with other substances in the waste stream, which can lead to high chlorine consumption and associated reagent cost. The process generates substantial quantities of NaCl (table salt). In most states, salt may not be disposed of (either as a solid or in solution) on land.

Hydrogen Peroxide Neutralization

Hydrogen peroxide (H_2O_2) is widely used for destroying cyanide in mill tailings, but use of this process for cyanide heap-leach detoxification is still being developed. In an aqueous cyanide solution, H_2O_2 converts free cyanide and weakly complexed cyanide to ammonia, carbon dioxide, and metallic hydroxides (Smith and Mudder, 1991). Oxidation of free cyanide is a two-stage process. First, free cyanide and H_2O_2 combine to form water and a much less toxic form of cyanide, cyanate (CNO^-), according to the reaction

$$CN^- + H_2O_2 \rightarrow CNO^- + H_20.$$

Second, cyanate reacts with water to form ammonia or ammonium ions, depending upon pH and carbon dioxide concentration.

The potential advantages of hydrogen peroxide neutralization are that, under optimum conditions, the process is easy to use, and it does not add pollutants to the effluent steam or release poisonous gases such as chlorine. Neutralization can be carried out under alkaline conditions, and therefore it does not promote oxidation of sulfides and dissolution of contained heavy metals. The disadvantage of the process is that hydrogen peroxide can be expensive. Additional treatment may be required if residual concentrations of ammonia (NH_3), thiocyanate (SCN^-), and metals in the effluent exceed acceptable environmental levels.

Sulfur Dioxide and Air Process

The sulfur dioxide (SO_2) and air method is another chemical oxidation process that converts free and complexed cyanide to cyanate. The process is capable of treating all cyanide forms common in mine waste streams. The process is highly dependent on pH and temperature. For example, at 25°C (77°F) the reaction is rapid, generally requiring less than 1 hour.

The disadvantages are that, with some waste streams, the reagent (SO_2, lime, and copper sulfate) costs are high and large quantities of dissolved solids, which may be considered hazardous waste, are produced. Strict control of process pH is required. The sulfur dioxide–air and hydrogen peroxide processes have largely supplanted alkaline chlorination, especially in larger operations. Direct application of the sulfur dioxide–air process to heap leach piles is not widespread (Denton and others, 1992).

Acidification-Volatilization-Recovery (AVR) Process

The AVR process involves acidifying the cyanide solution with sulfuric acid. This converts the cyanide in solution to HCN gas, which volatilizes out of solution and is recaptured for reuse. A pH of less than 2 is necessary to completely volatilize iron-cyanide complexes. Disadvantages of AVR include the high cost of plant construction, high energy requirements for aeration, and the stringent safety precautions for working with HCN vapor (U.S. Bureau of Land Management, 1992). The AVR system has not been used on heap leaches because it is too expensive.

Biological Detoxification

Microbes, such as species of *Pseudomonas*, metabolize cyanide under aerobic conditions and can be used in treatment systems. Microbes remove forms of metal-complexed cyanide, including WAD cyanide and the stable iron-complexed cyanide. These bacteria work through a combination of oxidation and adsorption. Metals present in the wastewater are removed by adding coagulant and by adsorption. The ammonia is also reduced to very low levels by conversion to nitrate via a two-stage biological process termed nitrification (Smith and Mudder, 1991). Biological detoxification has been used successfully at the Homestake mine in Lead, South Dakota (Smith and Mudder, 1991), and at Hecla Mining Company's Yellow Pine mine in Idaho (Norman, 1993). ■