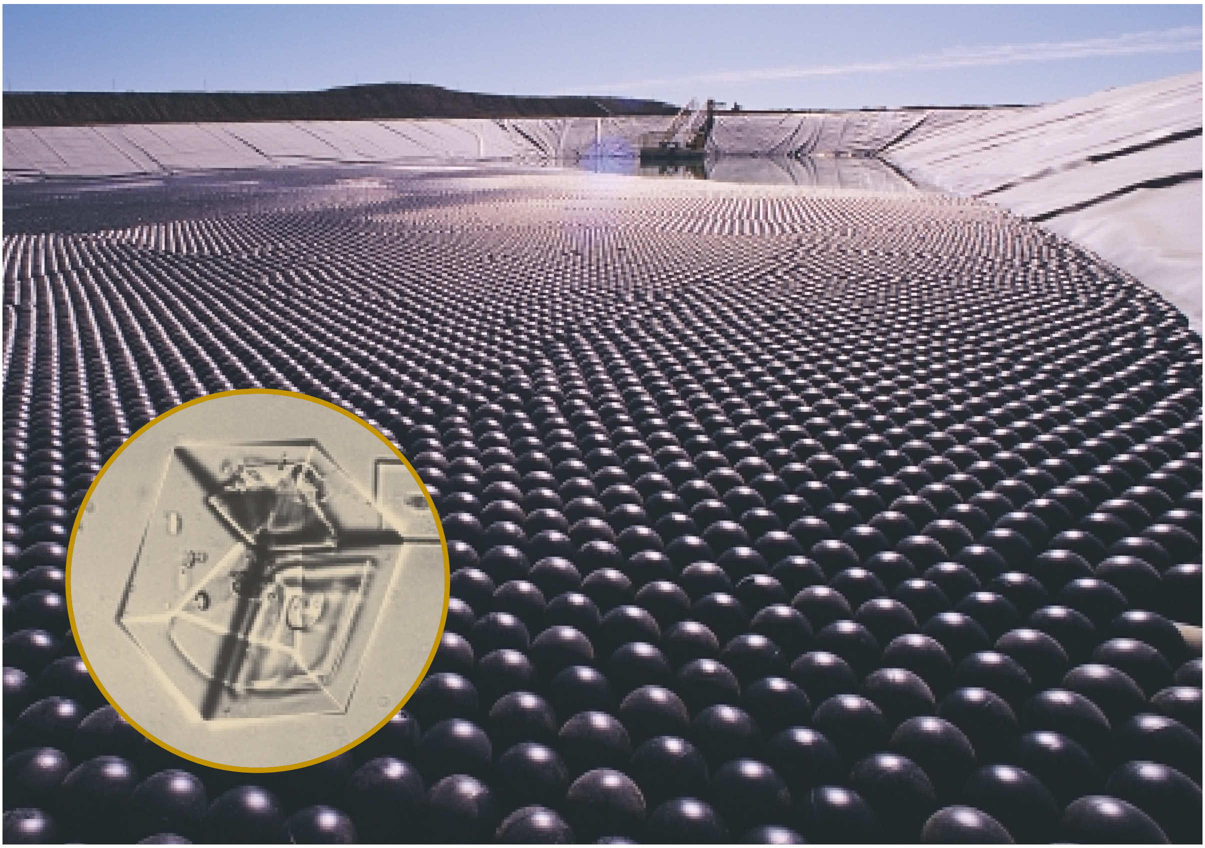
The Management of Cyanide in Gold Extraction

by

Mark J. Logsdon, MSc

Karen Hagelstein, PhD, CIH

Terry I. Mudder, PhD



International Council on Metals and the Environment

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Although the views expressed are those of the authors, ICME welcomes questions and comments on the perspectives and information contained in its documents. ICME also appreciates suggestions regarding other issues of public importance for possible future publications.

Founded in 1991, ICME is a non-governmental organization that promotes the development and implementation of sound environmental and health policies and practices in the production, use, recycling and disposal of non-ferrous and precious metals. In addition to its publications, ICME's extensive information program includes a Web site and a quarterly newsletter with a worldwide distribution.

International Council on Metals and the Environment
294 Albert Street, Suite 506
Ottawa, Ontario
CANADA K1P 6E6
Tel: (613) 235-4263
Fax: (613) 235-2865
e-mail: info@icme.com
http://www.icme.com

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Mark J. Logsdon, MSc
Karen Hagelstein, PhD, CIH
Terry I. Mudder, PhD

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International Council on Metals and the Environment

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Foreword

The mining industry, and in particular the gold mining industry, has been using cyanide in its production processes for many decades. While cyanide is commonly perceived as being a deadly substance, it is in fact a widely used chemical that is essential to the modern world. The key to its safe use is the implementation of sound management practices.

While public concern about cyanide is valid and indeed understandable, much of the recent media attention and public reaction regarding the use of cyanide in mining operations has arisen due to a lack of understanding of the nature of cyanide and its effects on health and the environment. While there is considerable technical information available to those who produce, transport and use cyanide, easy-to-understand information has not heretofore been provided for a less technical audience. In an attempt to remedy this situation and to address public concern about the use of cyanide in gold extraction, the International Council on Metals and the Environment has commissioned the present document.

The Management of Cyanide in Gold Extraction gives an overview of the chemical's uses and risks, with special emphasis on its use in the recovery of gold. The publication begins by describing the properties of cyanide and its general uses in industry, then moves on to address more specifically the life cycle of cyanide in the mining environment—its production, use in mineral extraction, and general and environmental chemistry. After presenting this information, the publication explains how the principles of risk assessment, risk management and risk communication contribute to the safe use of cyanide in gold recovery.

This work has been prepared by recognized experts and should be a useful reference for anyone involved in decision making related to the presence of cyanide in mining operations, whether from a local or global perspective. It is hoped that international regulators, policy makers, community leaders and all other interested readers, including those engaged in the mining and metals industry, will find the work to be both balanced and informative, and thereby gain a better understanding of the characteristics of cyanide and its unique role in gold recovery.

Gary Nash
Secretary General
ICME

Executive Summary

Cyanide is the chemical of choice for gold recovery.

Cyanide is one of only a few chemical reagents that will dissolve gold in water. It is a common industrial chemical that is readily available at a reasonably low cost. For both technical and economic reasons, cyanide is the chemical of choice for the recovery of gold from ores. Cyanide has been used in metal extraction since 1887 and is now safely used and managed in gold recovery around the world. Gold mining operations use very dilute solutions of sodium cyanide, typically in the range of 0.01% and 0.05% cyanide (100 to 500 parts per million).

Most of the cyanide produced is used as a basic building block for the chemical industry.

Cyanide is produced in large amounts (about 1.4 million tonnes each year) as one of a few basic compounds used chiefly to synthesize a wide range of industrial organic chemicals such as nylon and acrylics. Gold recovery accounts for approximately 18% of total world cyanide production.

Cyanide is produced naturally in a number of microorganisms, insects and plants.

Cyanide is a naturally occurring molecule of carbon and nitrogen. It existed on Earth before life began and was one of the fundamental building blocks in the evolution of life. Low concentrations of cyanide are present in nature, for example in many insects and plants, including a wide range of vegetables, fruits and nuts, where it provides protection against predators. In addition, cyanide is present in much of the everyday environment to which we are exposed, for example in road salt and automobile exhaust and as a stabilizer in table salt.

Cyanide is not persistent.

One of the major health and environmental concerns with some synthetic chemicals is that they do not decompose readily and can thereby accumulate in the food chain. Cyanide, however, is transformed by natural physical, chemical and biological processes into other, less toxic chemicals. Since cyanide oxidizes when exposed to air or other oxidants, it decomposes and does not persist. While it is a deadly poison when ingested in a sufficiently high dose, it does not give rise to chronic health or environmental problems when present in low concentrations.

Cyanide is attenuated through natural processes.

Over time, natural processes such as exposure to sunlight can reduce the concentration of toxic forms of cyanide in solutions to very low values.

The risks of cyanide production, use and disposal can be well managed.

Responsible companies in both the chemical industry and the mining industry employ stringent risk management systems to prevent injury or damage from the use of cyanide. Cyanide in mining solutions is collected, either to be recycled or destroyed, after gold is removed. Managing risks associated with the use of cyanide involves sound engineering, careful monitoring and good management practices in order to prevent and mitigate potential releases of cyanide to the environment.

Communicating information about the risks of cyanide to employees and the public is essential to sound management practices.

The environmental fate of cyanide has been well studied. Cyanide is highly regulated and its risk management is well documented. Risk communication provides information about cyanide both within the operating plant and externally, to the public. Communication of information to the internal staff is the first step in communicating the nature and extent of risk to the general public. Effective communication and emergency planning programs should also be coordinated with the proper local authorities.

SECTION 1

What Is Cyanide?

Cyanide is a general term for a group of chemicals containing carbon and nitrogen. Cyanide compounds include both naturally occurring and human-made (anthropogenic) chemicals. There are more than 2,000 natural sources of cyanide, including various species of arthropods, insects, bacteria, algae, fungi and higher plants. The principal human-made cyanide forms are gaseous hydrogen cyanide and solid sodium and potassium cyanide. Because of its unique properties, cyanide is used in the manufacture of metal parts and numerous common organic products such as plastics, synthetic fabrics, fertilizers, herbicides, dyes and pharmaceuticals.

There is justifiable public concern about the use of cyanide in industrial settings. Cyanide is a toxic substance and can be lethal if ingested or inhaled in sufficient amounts. This is also true for many other chemicals such as gasoline and common household cleaning supplies. As is the case for the thousands of other chemicals used in our modern industrial processes, knowledge, proper handling procedures and a responsible attitude are critical to the safe and beneficial use of cyanide.

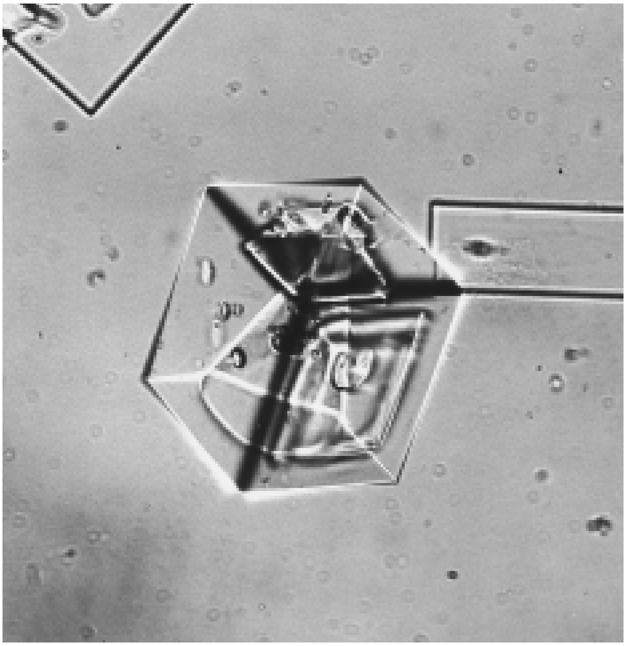


Photo courtesy of DuPont

Microscopic view of sodium cyanide crystals.

Mining is one industrial activity that uses a significant amount of cyanide—about 20% of total production. Since 1887, cyanide solutions have been used primarily to extract gold and silver from ores that otherwise could not be mined effectively. In addition, cyanide is used in low concentrations as a flotation reagent to aid in the recovery of base metals such as lead, copper and zinc.

SECTION 2

Natural Occurrences of Cyanide

Carbon and nitrogen, the two elements that make up cyanide, are present all around us. Together they make up almost 80% of the air we breathe, and both are present in the organic molecules that are the basis of all life forms. Hydrogen cyanide was formed in the earliest stages of the development of our planet as a precursor to amino acids, from which life on Earth evolved. Cyanide is formed naturally. It is produced and used by plants and animals as a protective mechanism that makes them an unattractive food source. Many organisms may either adapt to the presence of cyanide or detoxify it.

A natural source of hydrogen cyanide (HCN) is a sugar-like compound called amygdalin, which exists in many fruits, vegetables, seeds and nuts, including apricots, bean sprouts, cashews, cherries, chestnuts, corn, kidney beans, lentils, nectarines, peaches, peanuts, pecans, pistachios, potatoes, soybeans and walnuts. In the kernel of bitter almond, there is about 1 mg of HCN as amygdalin. Table 1 presents data on the amount of cyanide present in a variety of other foodstuffs.

TABLE 1. Cyanide Concentrations in Selected Plants

Plant Species	**Concentration ($mg.kg^{-1}$)**
Cassava (sweet varieties)	
leaves	377–500
roots	138
dried roots	46–<100
mash	81
Bamboo tip	Max. 8,000
Lima bean (Burma)	2,100
Almond (Bitter)	280–2,500
Sorghum (young plant, whole)	Max. 2,500

Source: Excerpted from Eisler, 1991

Cyanide compounds are produced in thousands of plant species and in other life forms. In some plants, cyanide occurs in concentrations that would be judged “hazardous” if they were associated with manufactured sources. Plants such as alfalfa, sorghum and cassava are known sources of cyanide poisoning to livestock and humans.

In addition to these naturally occurring forms of cyanide, cyanide compounds are also present in such everyday anthropogenic sources as automobile exhaust, cigarette smoke, and even road and table salt.

SECTION 3

Industrial Uses of Cyanide

Cyanide is one of the main building blocks for the chemical industry because of its composition of carbon and nitrogen—both common elements—and the ease with which it reacts with other substances.

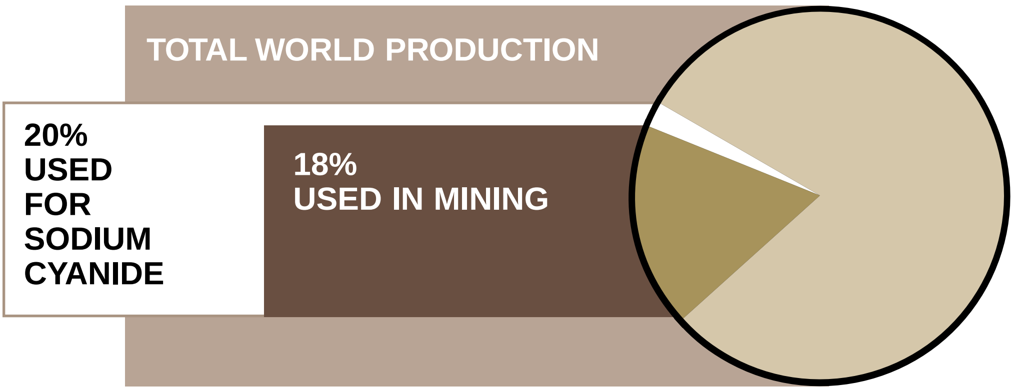
Over one million tonnes of cyanide, representing about 80% of total production, are used annually in the production of organic chemicals such as nitrile, nylon and acrylic plastics. Other industrial applications include electroplating, metal processing, steel hardening, photographic applications and synthetic rubber production.

Iron cyanides are often used in road salt as an anti-caking additive. Hydrogen cyanide vapour has been widely used to exterminate rodents and large predators, and in horticultural practice to control insect pests that have developed resistance to other pesticides.

In addition, cyanide is used in pharmaceuticals such as the anticancer substance laetrile and the blood pressure–reducing drug nitroprusside. Cyanide compounds are also used in surgical dressings that promote healing and reduce scarring.

The remaining 20% of cyanide production is used to manufacture sodium cyanide, a solid form of cyanide that is relatively easy and safe to handle. Of this, 90% (i.e. 18% of total production) is used in mining around the world, mostly for gold recovery.

FIGURE 1. Portion of World Cyanide Production Used in Mining



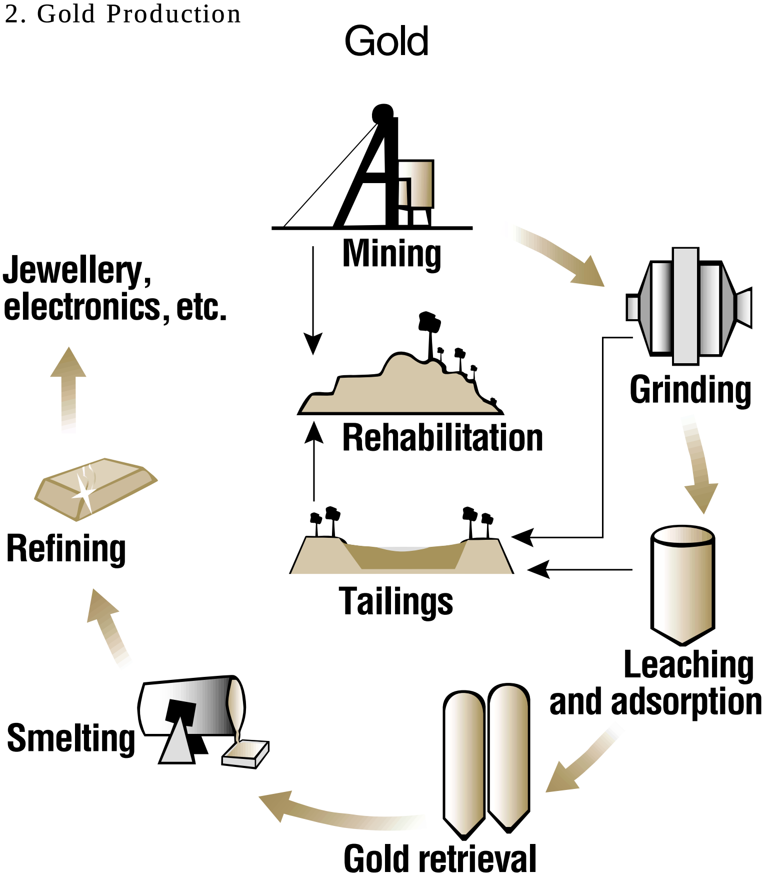
SECTION 4

Cyanide Use in Gold Production

One of the reasons for the high value placed on gold is its resistance to attack by most chemicals. One exception is cyanide, or more specifically, a cyanide-containing solution, which dissolves the precious metal.

Cyanide is used in mining to extract gold (and silver) from ores, particularly low-grade ores and ores that cannot be readily treated through simple physical processes such as crushing and gravity separation.

FIGURE 2. Gold Production



Courtesy of WMC Limited

The Process

The use of water-based solutions to extract and recover metals such as gold is called "hydrometallurgy." Gold mining operations use very dilute solutions of sodium cyanide (NaCN), typically in the range of 0.01% and 0.05% cyanide (100 to 500 parts per million). The process of metal dissolution is called leaching. The sodium cyanide dissolves in water where, under mildly oxidizing conditions, it dissolves the gold contained in the ore. The resultant gold-bearing solution is called "pregnant solution." Either zinc metal or activated carbon is then added to the pregnant solution to recover the gold by removing it from the solution. The residual or "barren" solution (i.e. barren of gold) may be re-circulated to extract more gold or routed to a waste treatment facility. Approaches to treating this waste solution of cyanide are discussed in Section 7.

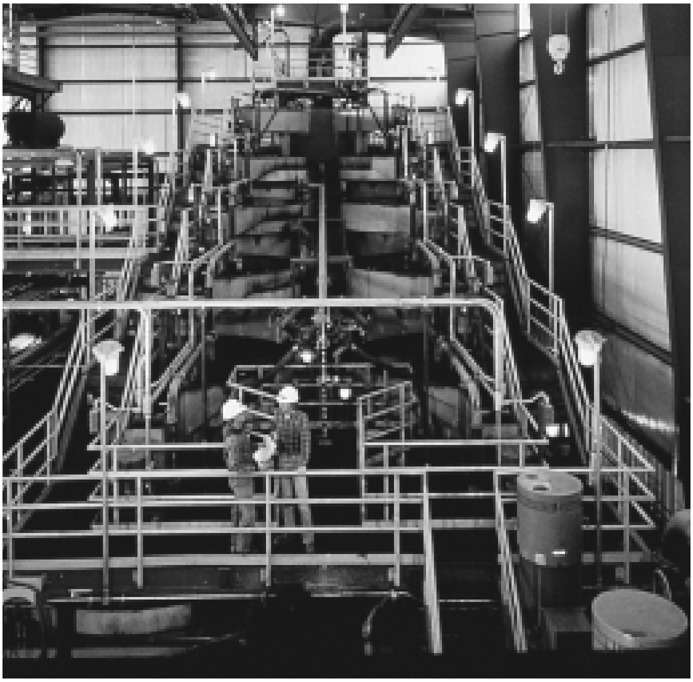


Photo courtesy of Minorco

Gold recovery from cyanide solution using activated carbon (charcoal).

There are two general approaches to leaching gold from mined ore using cyanide: tank leaching and heap leaching.

Tank leaching is the conventional method, in which gold ore is crushed and ground to a size of less than one millimetre in diameter. In some cases, a portion of the gold can be recovered from this finely ground material as discrete particles of gold using gravity-separation techniques. In most cases, the finely ground ore is directly leached in tanks to dissolve the gold in a cyanide solution. When gold is recovered in a conventional plant with leaching in tanks, the barren solution will be collected along with the solid wastes (tailings) in a tailings impoundment system. There, part of the solution will remain within the pores of the settled tailings and part will decant and collect in a pond on top of the tailings, from which it is recycled back to the plant. In most plants, because impurities

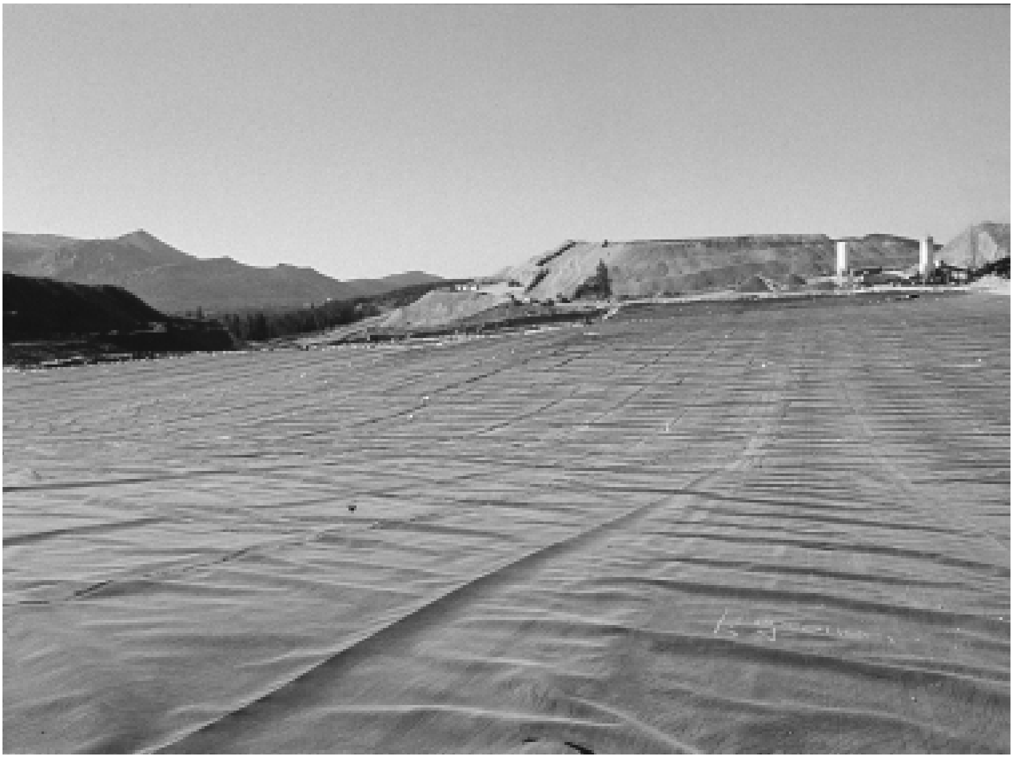


Photo courtesy of Minorco

Construction of a leach pad at Pikes Peak, Colorado, USA.

build up in these solutions, some of the cyanide-bearing solutions must be pumped to a treatment system for disposal (see Section 7).

Recent technical advances enable the heap-leaching of some gold ores. With this method, the ore is crushed to less than a few centimetres in diameter and placed in large piles or heaps. A solution of cyanide is trickled through these heaps to dissolve the gold. When heap-leaching technology is used to extract gold, the barren solution is collected in a pond, from which it is commonly recharged with cyanide and recycled back into the leaching system.

The modern gold industry uses cyanide almost exclusively as the leaching agent for gold. Other complexing agents such as thiourea, chlorides and other halides have been used to extract gold from ores, but these are not generally cost-effective and present their own environmental and health concerns. Cyanide complexes are more stable and effective, and do not require additional aggressive chemicals to effect gold recovery. Cyanide has been used in mining for over a century *(see box)*. An older technique for gold recovery, which is no longer used in modern gold plants, is amalgamation with liquid mercury. In some developing countries, artisanal miners still use liquid mercury as a means of complexing gold from small mine workings. This practice is discouraged, however, as poor management of both liquid mercury and the vapour arising from volatilizing mercury contributes to serious health problems among artisanal miners.

Box 1. History of Cyanide Use in Mining

While environmental concerns over the use of cyanide in mining have become more public only in the last few years, there actually is a very long history of cyanide use in metallurgical and related processes all around the world. Dippel and Diesbach discovered "Prussian blue" (iron ferrocyanide) in 1704. The earliest well-documented work was Scheele's studies of solubility of gold in cyanide solutions dating from 1783 in Sweden. Gold-cyanide chemistry was studied actively in the mid-19th century in England (Faraday), Germany (Elsner), and Russia (Elkington and Bagration). By 1840, Elkington held a patent for the use of potassium cyanide solutions for electroplating gold and silver. Elsner led the evaluation of the role of oxygen in gold dissolution using cyanide solutions, and "Elsner's Equation" describing the extraction of gold from ores by cyanide was known by 1846.

Patents formalized by McArthur and the Forrest brothers in 1887 and 1888 effectively established the current cyanidation process, the use of cyanide dissolution and precipitation using zinc. However, there were still earlier patents in the USA for cyanide leaching (Rae in 1869) and recovery from chlorinated solutions using charcoal (Davis in 1880). The first commercial-scale cyanidation plant began operating at the Crown Mine in New Zealand in 1889, and by 1904 cyanidation processes were also in place in South Africa, Australia, United States, Mexico and France. Therefore, by the turn of the century, the use of cyanide to extract gold from low-grade ores was a fully established metallurgical technology.

SECTION 5

Production and Handling of Cyanide

Cyanide is produced industrially in one of two ways: as a by-product of the manufacture of acrylic fibres and certain plastics, or by combining natural gas and ammonia at high temperatures and pressures to produce hydrogen cyanide (HCN) gas. Subsequently, hydrogen cyanide gas can be combined with sodium hydroxide (NaOH) to produce sodium cyanide (NaCN) and water (H_2O). The water is then removed by drying and filtering, and the sodium cyanide is formed into solid, white briquettes that are about 10 centimetres square.

The solid sodium cyanide briquettes are maintained under controlled temperature and moisture. At the manufacturing location, the briquettes are packaged in labelled, sealed containers to protect the briquettes from both crushing and moisture. The containers may be disposable plywood boxes with non-returnable liners, non-returnable steel drums, or re-useable steel bins. In some circumstances, the briquettes are dissolved and the cyanide solution is transported as a liquid in specially designed tanker trucks.

All shipments of sodium cyanide are accompanied by Material Safety Data Sheets (MSDSs) that provide the chemistry and toxicity of sodium cyanide, instructions in case of accidents, emergency telephone numbers for assistance and additional information from the manufacturer. All shipments are inventoried as material leaves the producer, and the inventory is checked against delivery records to ensure proper surveillance at all times.

There are three primary producers of solid, liquid and gaseous cyanide in the world: Dupont, in the United States, ICI, in England, and Degussa Corporation, in Germany. Annual worldwide production is approximately 1.4 million tonnes of HCN.[1] As mentioned earlier, 20% of the total HCN production is used to produce sodium cyanide (NaCN) and the remaining 80% is used in numerous other industrial activities such as the production of chemicals. Sodium cyanide is also produced in the USA by FMC Corporation.

The three primary producers are major international chemical manufacturers that understand their responsibility for their products. For example, formal corporate policies

1 1996 amounts. Usage in mining has remained essentially constant for the last decade.

Storage of drums containing sodium cyanide.

ensure that cyanide is sold only to companies that have the ability and commitment to protect workers, the public and the environment. The manufacturers contract only with selected carriers that have records of transportation safety consistent with the manufacturers' internal standards. The manufacturers maintain a staff of safety and transportation specialists to work with purchasers and others in the areas of training, facility design and related safety measures.

Mining companies store sodium cyanide in secure areas that are kept dry, cool, dark and ventilated. In the storage area, cyanide packages are placed on pallets in their original containers above watertight floors, usually made of concrete, with proper containment in the unlikely event of spillage. Regardless of the container type, empty containers are washed and the rinse water is used in the site's gold recovery plant (to take advantage of the small amounts of cyanide that could be present) or is processed through the wastewater treatment system prior to being discharged under controlled and permitted conditions.

Mining companies hold special training programs for all employees who work with or around cyanide. They also have materials handling and safety plans prepared by qualified industrial hygienists and supervised by project safety officers. These health and safety plans assign employee responsibilities and control the handling and use of sodium cyanide from its arrival at the mine site through to the metallurgical process. Area gas monitors, proper protective clothing, self-contained breathing apparatus and first-aid stations equipped with eyewash and shower facilities are utilized by cyanide-handling operations at mines. Companies' industrial hygiene programs include annual training, access to all MSDSs and air monitoring to ensure worker safety, as well as procedures for documenting all health and safety information and incidents at mine sites.

Photo courtesy of Degussa Corporation

On-site assistance and safety training are provided to gold mines by cyanide producers.

Modern industrial hygiene programs at gold mining operations have been effective at minimizing accidental cyanide poisoning at mine sites. Indeed, a search of industrial accident records in Australia, Canada, New Zealand and the United States has revealed only three accidental deaths in which cyanide was implicated at gold mine sites in the past 100 years. The first was not directly related to gold recovery, the second involved entry into an enclosed space—a fatal mistake, and the third was not conclusively attributed to cyanide.[2]

2 Both incidents were found in the 107-year fatality database of the Ontario Minister of Labour. In 1952, a blacksmith at the MacLeod-Cockshutt Gold Mines died due to cyanide poisoning following an explosion of molten cyanide; he had been preparing a bath of melted sodium cyanide to case-harden a wrench. In 1961, a worker at the Hallnor Mines Mill died of poisoning from hydrocyanic gas after climbing into an agitator tank to retrieve flake cyanide he had inadvertently thrown into the tank. In 1982, a labourer at an Arizona gold recovery operation collapsed at work and died five days later. Cyanide was suspected, but the evidence as to how the worker became exposed to cyanide was inconclusive.

SECTION 6

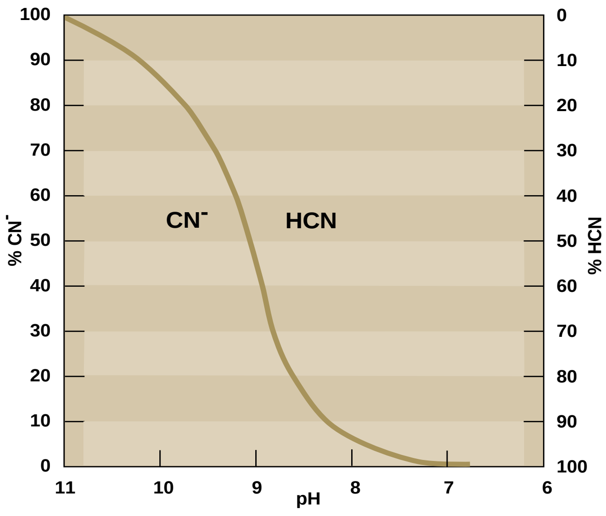
Cyanide in Solutions

After gold is extracted via the hydrometallurgical processes, three principal types of cyanide compounds may be present in wastewater or process solutions: free cyanide, weakly complexed cyanide and strongly complexed cyanide. Together, the three cyanide compounds constitute "total cyanide." An understanding of the chemistry of these three types of cyanide provides insights into their behaviour with respect to safety and the environment.

Free Cyanide

"Free cyanide" is the term used to describe both the cyanide ion (CN^-) that is dissolved in the process water and any hydrogen cyanide (HCN) that is formed in solution. The solid sodium cyanide briquettes dissolve in water to form sodium ion and the cyanide anion (CN^-). The cyanide anion then combines with hydrogen ion to form molecular HCN. The concentration of hydrogen ion in the process water is expressed by the familiar parameter pH.[3] Nearly all free cyanide is present as HCN when there is ample hydrogen ion present, (i.e. at a pH value of 8 or less). This HCN can then volatilize and be dispersed into the air. When the pH is greater than 10.5, there is little hydrogen ion present and nearly all of the free cyanide is present as CN^-. Under normal conditions of temperature and pressure, the concentrations of HCN and CN^- are equal at a pH value of approximately 9.4.

FIGURE 3. CN^-/HCN Equilibrium with pH



Source: Scott and Ingles, 1981.

3 When the pH of a solution is 7, the solution is said to be neutral. Solutions with pH less than 7 are said to be acidic, whereas those with pH greater than 7 are said to be alkaline.

These forms of free cyanide are important because they are considered to be the most toxic cyanides. However, they also happen to be the forms that are readily removed from solutions through both engineered treatment processes and natural attenuation mechanisms. The biological, chemical and physical processes that affect cyanide concentrations in water, soil and air have been extensively studied during the last two decades, so that their behaviour in the environment is well understood.

One of the most important reactions affecting free cyanide concentration is the volatilization of HCN, which, like most gases, will separate from water and escape into the air. Free cyanide is not persistent in most surface waters because the pH of such waters is usually about 8, so that HCN volatilizes and disperses. Hydrogen cyanide's volatility and subsequent transformation to benign compounds in air are important because they act as a natural mechanism for controlling free cyanide concentrations in waste and process waters at mines.

Natural processes alone can reduce the free cyanide concentration from solutions in areas open to the atmosphere in the gold production facilities, such as process ponds and tailings impoundments, to very low values—often to levels below regulatory concern or even the limits of detection.

In the gold plant, however, operators maintain the solution pH at values near 10.5 in order to prevent volatilization. This preserves cyanide in the gold extraction system where it is needed and at the same time limits the risk of worker inhalation exposure to high concentrations of HCN gas in a confined space.

Barrick Gold Corporation

Control centre for gold recovery plant (cyanidation).

Cyanide Complexes

While cyanide-bearing solutions are used in mining because they react with gold, they also react with other metals. Gold ores almost always contain other metals, including iron, copper, zinc, nickel and silver as well as other elements such as arsenic. In most ore bodies, the concentrations of other metals typically exceed the concentration of gold by several orders of magnitude. For example, a low-grade gold ore suitable for cyanide leaching might contain 0.5 to 1 gram of gold per tonne (0.5 to 1 part per million [ppm] gold); in contrast, the iron concentration of average crustal rocks is about 3.5% (35,000 ppm). Metals such as copper, zinc and nickel may be present in concentrations ranging

TABLE 2. Analyses of Barren Solutions[4]

	CONCENTRATION RANGE milligrams per litre[5] ($mg.L^{-1}$)
Total Cyanide	50–2000
Arsenic	0–115
Copper	0.1–300
Iron	0.1–100
Lead	0–0.1
Molybdenum	0–4.7
Nickel	0.3–35
Zinc	13–740

from tens to thousands of parts per million. Table 2 shows that significant amounts of other metals may be dissolved when ores containing them are leached with cyanide solutions.

Chemical analyses of process solutions and wastewater derived from the processing indicate that most of the cyanide in solution is chemically linked with metals other than the small amounts of gold or silver. When chemical elements combine in solution to form soluble species, chemists refer to them as "complexes." There is a wide range of chemical and physical interactions between the components of complexes. Some complexes are very stable, whereas others are easily destroyed. Analytical chemists are able to define the relative stability of cyanide complexes of different metals with great precision. The evaluation of the quantity and types of cyanide is important to all aspects of cyanide use. It is particularly important to be able to distinguish both accurately and precisely between the various cyanide compounds to ensure the selection of an effective detoxification methodology.

4 Scott, J. S., *Status of Gold Mill Waste Effluent Treatment*, Report to CANMET, Natural Resources Canada, March 1993.

5 In environmental studies, concentrations of cyanide and other solutes in solutions are ordinarily presented in terms of mass per unit volume, or sometimes as the dimensionless unit "part per million" (ppm). Concentrations in milligrams per litre ($mg.L^{-1}$) are the same as concentrations in grams per cubic metre ($g.m^{-3}$), and both of these are essentially identical to concentrations in ppm (because the density of solutions is usually very close to 1 kilogram per litre [$kg.L^{-1}$]).

Weak and Strong Cyanide Complexes

Conventionally, cyanide chemists distinguish "weak" from "strong" cyanide complexes. The weak cyanide complexes, often referred to as "weak acid dissociable" or WAD cyanide, can dissociate in solution to produce environmentally significant concentrations of free cyanide. The weak complexes include cyanide complexes of cadmium, copper, nickel, silver and zinc. The degree to which these complexes dissociate is dependent largely on the pH of the solution.

Strong cyanide complexes, on the other hand, degrade much more slowly than WAD cyanide under normal chemical and physical conditions. Complexes of cyanide with gold, cobalt and iron are strong and stable in solution. This stability of the gold–cyanide complex is a key factor in the use of cyanide for the extraction of gold from ores. Once gold enters into solution tied to the cyanide, it remains complexed with the cyanide until process conditions are changed in order to remove it from solution. Cobalt is present only in trace amounts but iron is virtually ubiquitous in geological materials. For most mining situations, the strong complexes of cyanide are predominantly iron cyanides.

The rate at which complexes dissociate and release free cyanide into solution depends on several other factors, including the initial concentration of the cyanide complex, the temperature, the pH of the solution, and the intensity of light, especially ultraviolet radiation.

Analysing and Monitoring Cyanide

Cyanide is generally measured by one of two analytical methods: total cyanide analysis or WAD cyanide analysis. The first is used to determine total cyanide in solutions, including free cyanide and metal-bound cyanides, such as the more stable, non-toxic iron cyanides. The analytical procedure for determining WAD cyanide is used for free and complexed forms of cyanide, except iron cyanide. An older but still used alternative method to that of WAD cyanide analysis is called "cyanide amenable to chlorination."

Cyanide analyses are needed for operational control, regulatory compliance and toxicity evaluation, as well as for public information about the handling of hazardous materials. Monitoring cyanide both during and after the gold recovery process is essential to good operating practice and the protection of both health and the environment. Rigorous sampling protocols and analytical procedures are required to ensure the quality of information available for decision making. This requires excellent planning and performance from trained personnel working with well-designed and well-managed systems.

SECTION 7

Attenuation of Cyanide Concentrations in the Environment

As explained in Section 4, once gold has been recovered, the solution becomes barren of gold but still contains cyanide. The processes that decrease the concentration of cyanide in solution, whether in the natural environment or in engineered facilities, are called “attenuation.” Volatilization of HCN, which reduces the concentration of free cyanide in solution, is the prominent natural attenuation process. Figure 4 provides a schematic representation of the relationships between forms of cyanide and the processes controlling them.

Over the past two decades, the chemical and mining industries have made major advances in handling waste cyanide solutions so that they will not harm public health or the environment. Two technologies are used, often in combination: treatment and recycling.

Cyanide Solution Treatment and Re-use

Treatment: Four general forms of cyanide solution treatment are in use:

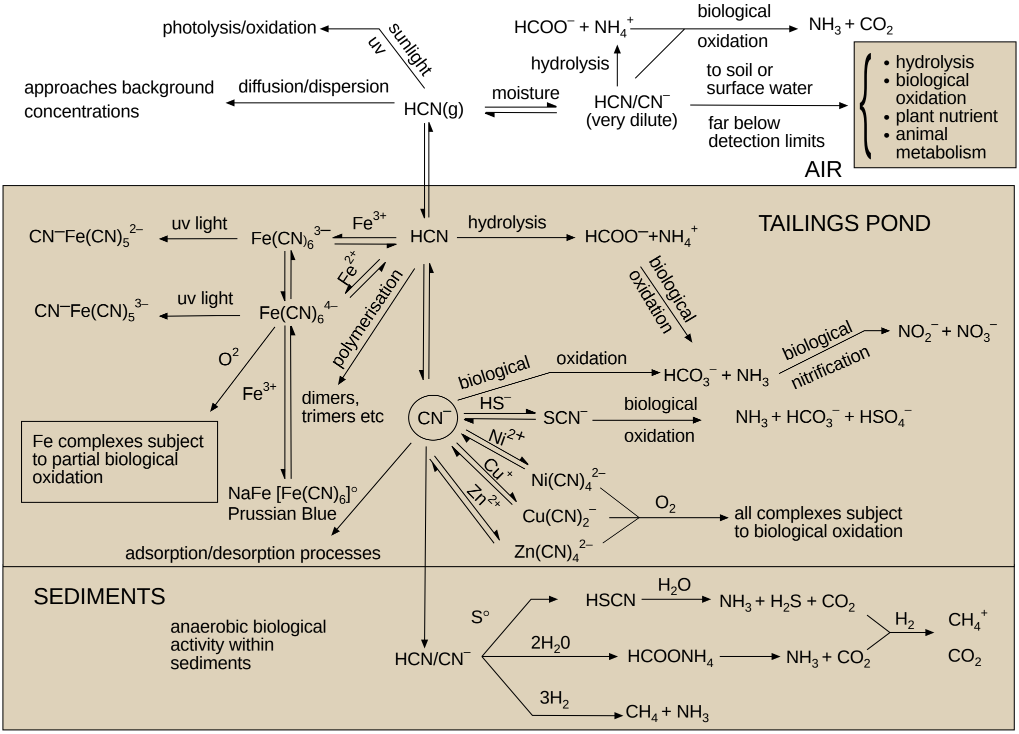
- Natural degradation
- Chemical oxidation
- Precipitation
- Biodegradation

In addition, several technologies enable the re-use of cyanide through recycling.

Natural degradation: The principal natural degradation mechanism is volatilization with subsequent atmospheric transformations to less toxic chemical substances. Other factors such as biological oxidation, precipitation and the effects of sunlight also contribute to cyanide degradation.

Cyanide species may be adsorbed on the surfaces of minerals or organic carbon debris in the soils of a pond embankment, in a clay liner, or along a groundwater flow path. In soils, bacteria assimilate the cyanide through a variety of aerobic and anaerobic reactions. In some instances, the combination of these processes of natural degradation are sufficient to meet regulatory requirements for discharge of cyanide-containing solutions.

FIGURE 4. The Cyanide Cycle



Source: Smith and Mudder, 1991.

Courtesy of Environment Australia

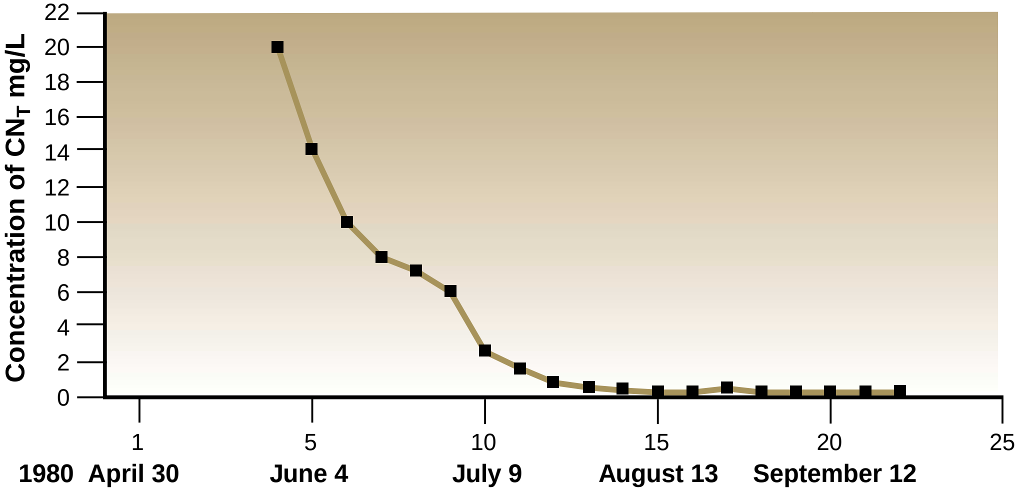
In tailings impoundments, the large surface area enables decomposition of WAD cyanide. Figure 5 illustrates a typical situation in which half of the total cyanide (CN_T) degraded naturally in less than three weeks from the initial concentration of 20 milligrams per litre. The CN_T disappeared almost completely within about 100 days.

Actual degradation rates need to be determined through test work on a site-specific basis using conditions that mimic, as closely as possible, the types of solution and the natural processes that are likely to occur at that location.

Table 3 compiles data from natural degradation systems at a number of gold mines around the world. The values in this table demonstrate the ability of natural degradation to reduce the cyanide concentration of solutions.

Chemical oxidation processes for cyanide treatment include the SO_2/Air process (developed by the Canadian mining company INCO) and the H_2O_2 (hydrogen peroxide)

FIGURE 5. Example of Cyanide Degradation in a Shallow Pond



Source: adapted from Schmidt et al., 1981.

treatment process (pioneered by Degussa). An older chemical oxidation alternative, the Alkaline Chlorination Process, is rarely used in the mining industry today.

In the SO_2/Air process, free and WAD cyanide are oxidized, and iron cyanide is precipitated as an insoluble solid. The process can be applied to either solutions or slurries, and reaction is rapid. Potential limitations are the need to obtain a licence to use the process,

TABLE 3. Natural Degradation of Cyanide in Tailings Impoundments

MINE	**CN entering the tailings system ($mg.L^{-1}$)**	**CN discharging from the tailings system ($mg.L^{-1}$)**
Lupin, NWT, Canada[a]	184	0.17
Holt McDermott, Ontario, Canada[a]	74.8	0.02
Cannon, Washington, USA[b]	284	<0.05
Ridgeway, South Carolina, USA[c]	480	0.09
Golden Cross, New Zealand[d]	6.8 (WAD CN)	0.33 (WAD CN)

Sources: a) Scott, 1993; b) Smith et al., 1985; c) Smith, 1987; d) Smith, 1994 the cost of building a processing plant, the need for empirical testing to optimize the system, and the inability of the process to oxidize intermediate by-products of cyanide.

Hydrogen peroxide, a strong oxidant, oxidizes free and WAD cyanide to ammonium and carbonate. Iron cyanides are not oxidized by peroxide, but precipitate as insoluble and stable solids. Sometimes it is necessary to add chemicals to control the copper concentration of solutions to meet environmental regulations. The peroxide system is not as well suited to the treatment of slurries because of irregular hydrogen peroxide requirements when solids are present.

Both methods of chemical oxidation are capable of producing residual concentrations of cyanide that can meet stringent discharge standards. Both processes require testing on representative samples of site-specific materials prior to the final plant design. Caro's acid, which combines sulphuric acid with hydrogen peroxide to form H_2SO_5, is also used as an oxidation agent to decompose cyanide in solution.

Precipitation of stable cyanides can be achieved by the deliberate addition of complexing agents such as iron. This reduces the free cyanide concentration and is also effective in controlling elevated levels of other metals that may be present. Iron cyanides may react with other chemicals in solution and produce solid precipitates, which may contain a dozen insoluble cyanide salts, thereby removing cyanide from solution. Some of the cyanide in process solutions will react with other chemical components within the system to form much less toxic concentrations of compounds such as ammonia, nitrate and carbon dioxide.

Biodegradation of cyanide is the basis for industrial wastewater treatment systems such as those used by Homestake Mining Company in the United States and ICI Bioproducts in the United Kingdom. A biological process has been used to treat cyanide to meet environmental discharge criteria for more than a decade at the Homestake Mine in Lead, South Dakota. Aerobic conditions are much more favourable to cyanide degradation than are anaerobic conditions, although anaerobic organisms can be effective in treating cyanide at concentrations of up to several milligrams per litre. Both active and passive biological treatment systems have been built—these systems remove cyanide using either aerobic or anaerobic micro-organisms.

At Homestake, the gold-mill barren solution is channelled through reaction vessels containing bacteria. These use oxygen from air to decompose cyanide compounds into nitrates, bicarbonates and sulfates. This microbial process is capable of oxidizing metal cyanide complexes, the metal ions from the WAD cyanide species and intermediate by-products of cyanide oxidation.

Advantages of the biological treatment process are its simple design and operational process control, low chemical costs and capacity of treating all forms of cyanide and its by-products. Potential limitations of biological treatment systems include reduced performance at cold temperatures and at very high cyanide concentrations.

Recycling: While the technologies for cyanide management have centred on cyanide destruction in single-pass systems, it is possible to recover and re-use cyanide, thus minimizing the total amount of cyanide used and reducing operational costs for some mines. Recycling lowers cyanide concentrations in waste solutions and decreases the cost of cyanide destruction.

Cyanide recovery and recycling has been used since the 1930s, notably at Flin Flon (Manitoba, Canada), Pachuca (Hidalgo, Mexico) and Golcanda Minerals (Tasmania, Australia). The basic process involves three steps: pH control, volatilization under highly controlled conditions, and capture of the cyanide that has been released. Recent engineering advances have made it a much more attractive prospect than was the case formerly, and cyanide recovery has been adapted in the last decade to treatment of slurries in a patented, commercial process called Cyanisorb. The process is being applied at the Golden Cross Mine (Waikato, New Zealand) and at the Delamar Silver Mine (Idaho, USA). Two additional Cyanisorb plants have recently been started up in Brazil and Argentina.

Research into cyanide recovery continues, including the testing of a treatment approach that separates cyanide complexes from solutions and absorbs them onto polystyrene-resin beads called Vitrokele (the Cyanosave process). Modifications of this process can be applied to either solutions or slurries, and both cyanide and metals can be recovered. The recovered cyanide is then recycled for use in the gold plant. While there have been successful tests of the process at mines in Canada, Australia and the USA, no commercial plant yet exists, and development continues.

SECTION 8

Evaluating and Managing Risks of Cyanide

The comprehensive approach to treating risk is made up of three key activities which occasionally overlap: risk assessment, risk management and risk communication. All three activities will be described in this and the following sections, beginning with risk assessment.

As stated already, it is well known that sodium cyanide and some of its derivatives are poisons and that cyanide compounds are classified as hazardous. Indeed, modern society safely utilizes many substances that are potentially hazardous, thanks to the ability to assess and manage the associated risks. Since the 1970s, it has become common practice to evaluate the risks associated with hazardous processes and materials through a systematic “risk assessment” process. Many of the concepts of risk assessment arose from more general methods developed by the insurance industry. These have their theoretical basis in probability and mathematical statistics. One of the key concepts that has carried over into environmental risk assessment is the fundamental definition of risk as the probability of a defined consequence.

Risk assessment consists of four parts:

1. Hazard identification is defined as the determination of the adverse effects which chemical, physical and biological agents have an inherent capacity or potential to cause to humans and the environment. Physical hazards include combustion, explosivity, flammability and corrosivity. Health hazards are categorized as acute (e.g. skin and eye irritation, lethal effects, asphyxiation) or chronic (e.g. carcinogenicity, sensitization, effects on reproductive system, effects on nervous system, effects on organs). Ecological hazards include mortality (acute) and reduced growth and reproduction (chronic) in representative species.

Hazard identification is only the first step in risk assessment. It is not an appropriate basis upon which to make a risk management decision. However, hazard identification is a critical step commonly carried out before chemicals and products are introduced to the market. In the case of human health and the environment, results of toxicity/ecotoxicity testing and epidemiology data are used to determine hazard.

2. Dose-response evaluation is the determination of the relationship between the magnitude of an administered, applied or internal dose and a specific biological response. The dose is the total amount of a substance administered to, ingested, inhaled or absorbed by an organism under standardized laboratory conditions used for toxicology testing. The end points of toxicity (or dose response) can be expressed as the measured or observed incidence, the percent response in groups of subjects (or population), or the probability of occurrence of a response in a population.

3. Exposure assessment is the evaluation of the pathways by which the hazard may contact a sensitive receiver. The receiver may be a single person, a real or hypothetical population, or a set of ecological recipients such as fish or wildfowl. The exposure assessment determines how and under what circumstances the receiver may be exposed to the hazard. It may also determine the quantities of the hazardous substance and the length of exposure.

4. Risk characterization summarizes the information from hazard identification, dose-response evaluation and exposure assessment into an overall conclusion on risk in a form that is useful to decision makers, legislators, the media and members of the public. Risk characterization provides a quantitative or qualitative description of the potential hazards of a particular exposure. Quantitative risk characterization conveys a numerical estimate of the magnitude of the risk that a substance poses to humans or to the environment. This risk may be expressed as individual risk or population risk. Qualitative risk characterization describes in narrative form the adverse effect or effects associated with exposure to an agent and provides some measure of the evidence for the association.[6]

Health and Environmental Impacts of Cyanide

Complete risk assessments require detailed specifications of the site-specific conditions. In the case of cyanide, its use varies so much that risk can be meaningfully evaluated only if the specific operating procedures at a particular site are considered. Nevertheless, it is possible to describe the hazards posed by cyanide and the potential exposures.

Toxicity and Epidemiology of Cyanide in Humans

Cyanide is a very fast-acting poison that is capable of killing a person within minutes if he or she is exposed to a sufficiently high dose. Humans may be exposed to cyanide by inhalation, ingestion or absorption through the skin. Cyanide prevents oxygen from being used by the cells, causing tissue hypoxia and "cyanosis" (a bluish discolouration of

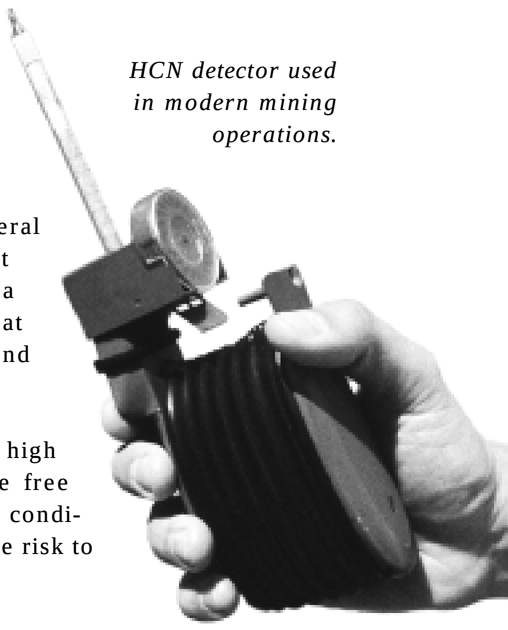
6 From George M. Gray, Jeffery, W. G. and Marchant. G. E., *Risk Assessment and Risk Management of Non-Ferrous Metals: Realizing the Benefits and Managing the Risks*, International Council on Metals and the Environment, 1997.

the skin). The respiratory system fails to nourish the cells with oxygen, a condition which, if untreated, causes rapid, deep breathing followed by convulsions, loss of consciousness and suffocation. The most common antidote is amyl nitrite, which may be taken orally or by injection.

Although there are many everyday sources of exposure to cyanide (automobile exhaust, tobacco smoke, fires), cyanide does not accumulate in tissues because the body transforms such small amounts into a less toxic compound called thiocyanate, which is then excreted. Cyanide is not known to cause cancer or birth defects or adversely affect reproduction.

The most toxic form of cyanide is HCN gas. The American Conference of Governmental Industrial Hygienists (ACGIH) lists the ceiling threshold limit of HCN at 4.7 ppm.[7] At concentrations of 20 to 40 ppm of HCN in air, some respiratory distress may be observed after several hours. Death occurs in minutes at HCN concentrations above approximately 250 ppm in air.

For free cyanide, the lethal dosage to humans by ingestion or inhalation ranges from 50 to 200 mg (1 to 3 mg of free cyanide per kg body mass). The lethal dosage for dermal absorption is considerably higher, at about 100 mg per kg of body weight.



HCN detector used in modern mining operations.

Photo courtesy of DuPont

Worker Exposure

Risk assessments address not only the impacts on the general population, but also the impacts on those who are most likely to be exposed to the hazard, such as the workers at a specific site. The potential for worker contact with cyanide at mines occurs during the receiving, unloading, handling and storage of solid sodium cyanide briquettes.

Provided that the cyanidation process is maintained at a high level of alkalinity (pH of 10.5 or above), almost all the free cyanide is present as CN^- in process solutions. Under such conditions, the volatility of HCN from solutions is low, so that the risk to workers through inhalation is manageable.[8]

7 1998 TLVs and BEIs—Threshold Limit Values for Chemical Substances and Physical Agents, published by the ACGIH.

8 Ingestion of process solution by workers (all of whom are trained and briefed on safety issues) is not considered a credible exposure pathway, because of the unlikelihood of anyone drinking such a solution.

Workers are required to wear respiratory protection against potential airborne hazards. Training in the fitting, use and testing of such equipment is incorporated into the company health and safety procedures. Most modern mining operations have HCN gas detectors or monitors that sound alarms in confined areas where HCN gas may be present. Most humans can detect the odour of hydrogen cyanide gas (a bitter almond smell) at concentrations below those that are hazardous to their health.

Environmental Toxicology and Impacts

Hazardous materials affect not only humans, but also ecological receptors. For mining environments, three groups of ecological or environmental receptors are of concern: mammals, reptiles and amphibians; birds (especially migratory wildfowl); and fish and other aquatic life.

There are few reports of major adverse impacts to animals from cyanide at mining sites. Sodium cyanide and cyanide-bearing solutions are handled in restricted areas of mining sites. Access by animals that walk or crawl is limited by walls, concrete pads, berms and fences, while the presence of humans around the mining facilities also deters animals from approaching. Government evaluations in the USA showed that standard containment designs and good engineering control have effectively mitigated threats to mammals, reptiles and amphibians.[9]

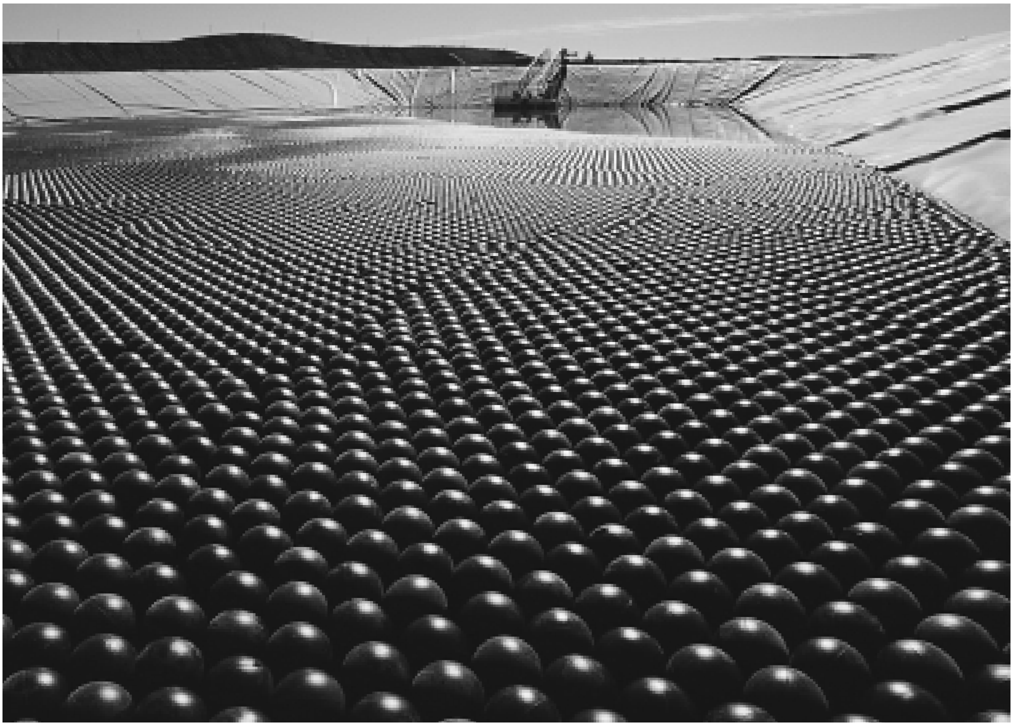
The principal concern for wildfowl has always been exposure to cyanide in open ponds, especially for migratory wildfowl passing through relatively arid regions such as the western USA, where use of cyanide in mining has become quite common. It should be noted, however, that the mortality of birds in Nevada due to exposure to cyanide solutions has been reduced dramatically from about 1,300 in 1990 to 220 in 1995, a decrease of 83%. This improvement is largely due to limiting the WAD cyanide concentration of uncovered ponds to less than 50 ppm. This concentration of WAD cyanide is not acutely toxic to ducks, which are shown to be very sensitive to cyanide as compared with other wildfowl and wildlife.

As a result of effective regulations and good management practice in mining, specific steps have been taken to further limit cyanide concentrations and exposure to wildfowl in open ponds. Netting has been useful in covering small process ponds, but netting of full-scale tailing impoundments is limited due to the weight of the nets, especially with accumulated snow or ice in cold climates, and due to the accidental trapping of wildlife in the nets. However, netting is still practised today for covering ponds in which the cyanide concentrations must be maintained at full strength for metallurgical purposes.

9 General Accounting Office (GAO), 1991.

Other methods of keeping birds away from cyanide solutions in ponds include the use of air cannons, noisemakers, plastic balls or other floating devices increasingly being used to cover the entire surface of small process ponds. This last method also aids in minimizing the loss of free cyanide due to volatilization.

Young, cold-water fish such as salmonids appear to be one of the aquatic species most sensitive to cyanide. Aquatic insects such as stoneflies, caddisflies, mayflies and beetles are generally less sensitive to the substance. It is the weak acid dissociable forms of cyanide that are considered the most "toxicologically significant." Laboratory and field studies have demonstrated that even sensitive aquatic species, such as trout, can tolerate low levels of WAD cyanide. Many discharge permits and regulatory standards are based upon WAD cyanide. In addition, site-specific standards for WAD cyanide have been promulgated for mining operations in such jurisdictions as the United States and New Zealand.



FPhoto courtesy of Placer Dome

Floating "bird balls" cover the surface of a solution containment pond at the Cortez gold mine, a Placer Dome–Kennecott joint venture in Nevada, USA.

SECTION 9

Risk Management for Cyanide in the Mining Industry

There are four major risk scenarios that need to be addressed through site-specific plans:

- Exposure of humans or ecological receptors to cyanide spilled during a transportation accident.
- Exposure of workers, particularly to HCN gas in enclosed areas.
- Exposure of humans through releases of cyanide in solution to surface or ground water that may be ingested.
- Exposure of ecological receptors, such as birds or fish, to cyanide-bearing solutions.

Transportation regulations and diligent safety programs limit the risks associated with the first scenario. As to the second, while adverse impacts from releases of process solutions have occurred in the past, scientific and engineering procedures exist to allow the safe and reliable operation of cyanidation processes. When site-specific standards relating to the third and fourth scenarios are set within the water-quality regulatory framework, protection of human health and the environment can be effectively realized.

Management Systems and Research and Development

Risk management in all of its aspects—from health and safety to prudent financial operations—is understood by today's mining industry to be an integral part of corporate management and a critical factor for the success of an industrial/commercial enterprise. Modern mining companies apply the generalized concept of "management systems" to their programs involving cyanide. Increasingly, this methodology is seen as part of good stewardship in mining, as in other industrial activities. Effective management systems involve four formal steps:

1. Plan: Written plans are prepared to detail the proper handling procedures and the accident response with respect to cyanide transportation and receiving, storage, solution preparation, metallurgical processes and waste management. Such plans include spill and containment procedures at mining operations as well as health and safety procedures for protecting employees from the potential hazards of cyanide.

2. Execute: For a program to be effective, there must be a commitment to executing the written plans routinely and continuously at every operation. Additionally, each individual employee's responsibilities for executing and documenting the actions required by the plans must be spelled out in detail and clearly defined.

3. Review and document: Part of management's responsibility is to audit performance on a routine basis. The responsibility for reviewing and documenting performance is typically given to persons who are not part of the line operation and who report to a corporate level of authority. This ensures an independent evaluation of the performance of the system. It also ensures that the appropriate level of management in the company is informed about operational performance. The corporate authority may then review and effectively manage the potential risks by implementing policies and programs applicable to multiple sites.

4. Take corrective action, if necessary: Risk management programs may have deficiencies which subsequently become evident in the daily operations and processes. When these are identified in the review process, priority must be given to taking appropriate corrective actions, and the effects of those actions must be reviewed and documented in subsequent audits.

Product Stewardship

The most important aspect of a well-managed system is the understanding that the people in contact with cyanide must take responsibility for its safe use.

Cyanide producers audit purchasers and transportation systems. They also design special packaging for the transport of cyanide. The three primary producers of industrial cyanide, Degussa, Dupont and ICI, have all committed themselves to the principles of Responsible Care®.[10] Truck, rail and barge transporters screen their employees,

10 Responsible Care®, begun in 1985 by the Canadian Chemical Producers' Association (CCPA), is a new ethic for the safe and environmentally sound management of chemicals over their life cycle which has spread to over 40 countries around the world. Under this approach, the CEO or most senior executive of every member of CCPA and of most chemical associations throughout the world must commit to implement the guiding principles and codes of practice of Responsible Care® within three years of joining the association and must agree to submit to public verification. The expectations of members and partners in Responsible Care® go beyond the required implementation of the 151 management practices called for in three codes of practice to include CEO networking via leadership groups, public input through a national advisory panel, mutual assistance through sharing best practices, peer pressure under a conformance process and the public communication of performance improvement measurements.

carefully inventory packages, and establish and maintain systems for loading and unloading. The products are handled and transported according to protocols set by the respective industries and in compliance with national and international regulations.

Mining companies establish inventory control systems, maintain worker training and industrial hygiene programs, as well as build and maintain process-solution and waste-management systems that are specifically designed to mitigate and prevent exposure to cyanide. On a project-specific basis, all risk management components of good product stewardship must be integrated to achieve success.

Conservation and Recycling

Another component of good stewardship of cyanide products is the general concept of waste minimization. By reducing the amount of cyanide physically present at a mining site, the potential exposure pathways are inevitably reduced, and therefore, so is the total risk. Costs as well as risks are reduced when the amount of cyanide used in an operation is kept to the minimum level needed to achieve production goals. This objective requires approaches, such as value engineering, that help to

Photo courtesy of Degussa Corporation

Cyanide producers provide training to ensure safe transportation and handling of sodium cyanide.

Photo courtesy of FMC Corporation

An essential aspect of a well-managed system is that the people in contact with cyanide must take responsibility for its safe use.

conserve the total amount of cyanide used and consumed in a mining process. The advent of cyanide recycling processes provides mining projects with alternatives for conserving the total amount of cyanide required.

Regulations and Voluntary Programs Addressing Worker Safety and Public Health

Regulations, imposed most often by governments, attempt to enforce the management of risks. Examples of regulations in the cyanide life cycle include: (a) establishing packaging and transportation standards; (b) setting industrial hygiene standards for cyanide concentrations in the air and worker safety; and (c) establishing limitations on effluent discharge to surface and ground waters. Governments have used results from research and development and a public-policy process to establish procedures and standards that are protective of worker safety, public health and the environment.

Some examples of regulatory standards for cyanide to protect human health and the environment were given in Section 6. For example, the most toxic form of cyanide, hydrogen cyanide gas, is regulated by industrial hygiene standards such as the ACGIH standards of 4.7 ppm in air.

On a worldwide basis, the total cyanide limit for protection of human health generally is set near the United States Environmental Protection Agency proposed drinking water standard of 0.2 $mg.L^{-1}$. Also, there is an emerging international consensus, based on technical data, that WAD cyanide concentrations in open ponds should be maintained at concentrations of less than 50 $mg.L^{-1}$ to protect migratory birds and other waterfowl against adverse impact.

But the management of risks and its enforcement are not imposed by governments alone, nor need they be. Voluntary programs can have the same effect as regulations without the onus of legal coercion. For example, the major producers of cyanide compounds have made internal decisions to deal only with end users and transportation companies that have proven records of safe performance. While the methods used by each producer may differ, all have the same result of using market mechanisms requiring specific performance criteria to protect the general public from the hazards of cyanide.

SECTION 10

Risk Communication

Risk communication is a key component in any comprehensive program for properly addressing risks related to cyanide in the mining environment. Communication is required both within the operating plant and externally with the public. Internal company education and training of the managers and workers at a site is critical. Employees at a mine or any other industrial facility are also members of the public who live near the site. They and their families, friends and neighbours have many of the same concerns about the safe use of cyanide and about protection of the environment as anyone else living nearby. The proper communication of all cyanide information to the internal staff is therefore the first step in communicating the nature and extent of risk to the general public.

Photo courtesy of Placer Dome

Placer Dome's Sigma Mine, located in Val d'Or, Quebec, Canada.

Beyond complying with formal, regulatory requirements, effective risk communication involves public information and participation. In addition to coordinating emergency planning programs with the proper local authorities, it means giving access to data about the types and quantities of cyanide compounds in the mine's operational processes and inventory, as well as monitoring data. Effective public communication is also bi-directional, encouraging public concerns to be voiced and addressed.

Mine management practices with respect to cyanide should be made public and be implemented through programs which are explained to members of the local communities by company representatives who are effective communicators. Furthermore, positive community relations programs can provide substance as well as form, and serve to show the general population that cyanide and other hazards are being handled safely in the community. Today, a growing number of mining companies around the world have embraced this approach, opening the lines of communication with local communities to the greater benefit of all concerned.

SECTION 11

Bibliography

ASTM, 1985. *Annual Book of Standards.* Section D2036, Method-C, Weak Acid Dissociable Cyanides, p. 121.

Ballantyne, B. and T. Marrs, 1987. *Clinical and Experimental Toxicology of Cyanides,* Wright Publishers, Bristol, United Kingdom.

Bureau of the Census, 1992. *The American Almanac for 1992-1993, 112th Ed.* Economics and Statistics Administration, the Bureau of the Census, the Reference Press Publishers, Austin, Texas, USA, September.

Clesceri, L. S., A. E. Greenberg and R. R. Trussell (Editors), 1989. *Standard Methods for the Examination of Water and Wastewater (17th Edition),* Part 4500-CN, Section I, Weak and Dissociable Cyanide, pp. 4-38, APHA-AWWA-WPCF.

Edelman, L. and Walline, R., 1983. "Developing a Cooperative Approach to Environmental Regulation," *Natural Resources Lawyer,* Vol. XVI, No. 3.

Eisler, R., 1991. "Cyanide Hazards to Fish, Wildlife and Invertebrates: A Synoptic Review." U.S. Fish and Wildlife Service, *Biological Reports* v. 85 (1.23).

Environment Australia, 1998. *Cyanide Management,* a booklet in a series on Best Practice Environmental Management in Mining, Commonwealth of Australia.

General Accounting Office (GAO), 1991. *Increased Attention Being Given to Cyanide Operations,* a report to the Chairman of the Subcommittee on Mining and Natural Resources, June.

Glynn, P., 1983. "Cyanide Behavior in Groundwater Environments," unpublished BSc Dissertation, Groundwater Research Institute, University of Waterloo, Canada.

Gold Institute, 1996. Cyanide. In *Gold Issues Briefing Book*, Chapter 4, pp. 1–12.

Gray, G. M., W. G. Jeffery and G. E. Marchant, *Risk Assessment and Risk Management of Non-Ferrous Metals: Realizing the Benefits and Managing the Risks*, International Council on Metals and the Environment, 1997.

Griffiths, A.W. and G. Vickell, 1989. *Treatment of Gold Effluents with H_2O_2, Operating Experience and Costs*. Proceedings of 21st Canadian Mineral Processing Conference, Ottawa, Ontario, Canada.

Habashi, F., 1987. “One hundred years of cyanidation.” *C.I.M. Bulletin*, vol. 80, pp. 108–114.

T.W. Higgs & Associates, 1992. *Technical Guide for Environmental Management of Cyanide in Mining*. Prepared for Mining Association of British Columbia, Canada, July.

Kilborn, Inc., 1991. *Best Available Pollution Control Technology*. Prepared for Ontario Ministry of Environment, Metal Mining Sector, December.

Lehninger, A., 1970. *Biochemistry*. Worth Publishers, New York, USA.

Logsdon, M. J. and T. I. Mudder, 1995. “Geochemistry of Spent Ore and Water Treatment Issues,” *Proceedings of the Tailings and Mine Waste 1995 Meeting and Summitville Forum*, Ft. Collins, Colorado, USA, January.

Marsden, J. and I. House, 1992. *The Chemistry of Gold Extraction*. Ellis Howood Publishers, New York, USA.

McNulty, T., 1989. “A Metallurgical History of Gold.” American Mining Congress, Sept. 20th, 1989. San Francisco, California, USA.

Mining Environmental Management Magazine, 1995. Special Issue on Cyanide. June, 1995.

Mudder, T. I. (Editor), 1998. *The Cyanide Monograph*. Mining Journal Books, The Mining Journal Ltd, London, United Kingdom.

Mudder, T. I. and A. Goldstone, 1989. “The recovery of cyanide from slurries.” In *Randol Conference, Gold and Silver Recovery Innovations Phase IV Workshop*, Sacramento, California, USA, November.

Mudder, T. I. and A. C. S. Smith, 1994. “An Environmental Perspective on Cyanide.” *Mining World News*, vol. 6, no. 9. October.

Queensland Government, 1990. *Guidelines on Prevention of Water Pollution from Cyanide Use in Gold Ore Processing*. Department of Environment and Heritage, Department of Resource Industries, Water Resources Commission, January.

Schmidt, J. W., L. Simovic and E. Shannon, 1981. *Development Studies for Suitable Technologies for the Removal of Cyanide and Heavy Metals from Gold Milling Effluents.* Proceedings 36th Industrial Waste Conference, Purdue University, Lafayette, Indiana, USA, pp. 831–849.

Scott, J. S., 1993. *Status of Gold Mill Waste Effluent Treatment.* Prepared for CANMET.

Scott, J. S. and J. C. Ingles, 1987. *State of the Art Processes for the Treatment of Gold Mill Effluents.* Mining, Mineral and Metallurgical Process Division, Industrial Programs Branch, Environment Canada, Ottawa, Ontario, Canada, March.

Scott, J. S. and J. C. Ingles, 1981. "Removal of Cyanide from Gold Mill Effluents," *Canadian Mineral Processors, Thirteenth Annual Meeting*, Ottawa, Ontario, Canada, January 20-22, pp. 380–418.

Simovic, L. and W. J. Snodgrass, 1989. "Tailings Pond Design for Cyanide Control at Gold Mills Using Natural Degradation." *Proceedings of Environment Canada's Gold Mining Effluent Treatment Seminar*, Mississauga, Ontario, Canada, March 22-23, pp. 57–81.

Smith, A. C. S., 1994. "The Geochemistry of Cyanide in Mill Tailings." In J. L. Jambor and D. W. Blowes (Eds.), *The Environmental Geochemistry of Sulfide Mine-Wastes.* Mineralogical Association of Canada Short-Course Handbook, Volume 22, pp. 293–332.

Smith, A. C. S., 1987. Testimony to Department of Health and Environmental Control, South Carolina, Permit No. SC 0041378 Appeal Hearing, Columbia, South Carolina, USA, December.

Smith, A. C. S., A. Dehrman and R. Pullen, 1985. "The Effects of Cyanide-Bearing Gold Tailings Disposal to Water Quality in Witwatersrand, South Africa." In D. Van Zyl (Ed.), *Cyanide and the Environment*, Colorado State University, Fort Collins, Colorado, USA, pp. 221–229.

Smith, A. C. S., D. Moore and J. Caldwell, 1985. "Prediction of Groundwater Impact of Tailings Disposal." *Proceedings of 2nd Annual Can/Am Conference on Hydrogeology*, Banff, Alberta, Canada.

Smith, A. C. S. and T. I. Mudder, 1991. *The Chemistry and Treatment of Cyanidation Wastes*, Mining Journal Books, London, United Kingdom.

Stanley, G. G., 1987. *The Extractive Metallurgy of Gold in South Africa*. South African Institute of Mining and Metallurgy, Monograph M7.

The Handbook of Chlorination, 1986. Van Nostrand Reinhold, New York, USA.

US EPA, 1985. "Basis for Listing Hazardous Waste," 40 CFR 261, App. VII, EPA, 1985.
US EPA, 1981. "An Exposure and Risk Assessment for Cyanide." Office of Water, EPA-440/4-85-008, Washington, DC, USA, December.

US Fish and Wildlife Service, 1991. "Cyanide Hazards to Fish, Wildlife, and Invertebrates: A Synoptic Review," *Biological Report 85 (1.23), Contaminant Hazard Reviews Report 223,* December.

Ulman's Encyclopedia of Industrial Chemistry, 1987. Volume A8, Fifth Edition, VCH Publishers, New York, USA.

Unifield Engineering, Inc., Coeur d'Alene Mines Corp., TIMES Ltd., and Coeur Gold N.Z. Ltd., 1994. "Recovery of Cyanide from Mill Tailings." *Proceedings, 100th Annual Northwest Mining Association Conference,* Spokane, Washington, USA.

Western Australia, Department of Minerals and Energy, 1992. *Cyanide Management Guideline.* Mining Engineering Division, July.

Whitlock, J. L. and T. I. Mudder, 1986. "The Homestake Wastewater Treatment Process: Biological Removal of Toxic Parameters from Cyanidation Wastewaters and Bioassay Effluent Evaluation." In R. W. Lawrence (Ed.) *Fundamental and Applied Biohydrometallurgy,* pp. 327–339.

About the Authors

Mark J. Logsdon, AB, MSc

Mark J. Logsdon is currently President and Principal Geochemist of Geochimica, Inc., a consulting firm located in Ojai, California, USA. He holds an AB Honors in Geology from Princeton University as well as an MS in Geology from the University of New Mexico. Mr. Logsdon specializes in hydrogeochemistry and environmental geochemistry, particularly related to waste management. In addition to consulting experience, Mr. Logsdon's 30-year career has encompassed research and academic instruction as well as governmental experience, notably with the USA's Nuclear Regulatory Commission and the New Mexico Bureau of Mines and Mineral Resources. Particular skills and experience include designing and implementing multidisciplinary earth science investigations involving waste characterization, geochemistry and hydrology. Geochimica projects include hydrogeology and hydrogeochemistry studies of acid mine drainage, cyanide hydrogeochemistry at mining sites and water-quality site investigations.

Karen Hagelstein, BS, MS, PhD, CIH

Karen Hagelstein is a Partner and Senior Environment Scientist at Times Limited, an environmental science and engineering firm located in Bozeman, Montana, USA, specializing in water and waste-water engineering, aquatic toxicology and human health evaluations. Dr. Hagelstein is a Certified Industrial Hygienist and received her BS from the University of South Dakota, her MS in Physiology and Biophysics from the University of Iowa, and her PhD in Civil and Environmental Engineering from the University of Iowa. During her career of over 15 years, Dr. Hagelstein has held positions as Senior Environmental Scientist, Environmental Engineer, and Health and Safety Officer with a number of consulting firms, and also spent six years as Associate Professor at the South Dakota School of Mines and Technology. Mining-related projects undertaken at Times Limited include reviewing and summarizing human toxicity data and risks with respect to environmental hazard exposures, air-dispersion modelling for estimating pollutant concentrations, and summarizing biological and chemical water quality monitoring data.

Terry I. Mudder, BS, MS, PhD

Terry I. Mudder is co-owner of Times Limited. He has a BS and MS in organic and analytical chemistry, and a PhD in environmental science and engineering. Dr. Mudder has 20 years' experience in the investigation of the chemistry, analysis, fate, aquatic toxicity and disposal of cyanide-bearing wastes. He has served as adjunct professor, thesis advisor and guest lecturer at universities throughout the world. He has worked on over 100 precious metal and non-ferrous mining-related projects on six continents and has written over three dozen technical papers. He has given numerous lectures and been involved with short courses and workshops on cyanide. He has co-authored several pamphlets and books, including *The Chemistry and Treatment of Cyanidation Wastes* and *The Cyanide Monograph*, both published by Mining Journal Books. He has been instrumental in the development and application of many of the chemical, physical and biological treatment processes for cyanide and metals, for which he has received both national and international awards, and obtained worldwide patents. He has provided technical assistance to the BC Ministry of Environment, Environment Australia, the Peruvian Environmental Protection Service, the US EPA, US State regulatory agencies, as well as to several industry-based organizations.