From: John Anderson
To: Durr, Eurika
Subject: UIC 17-02
Date: Thursday, July 27, 2017 8:56:23 PM
Attachments: EPA Response.pdf

Today, one of the Hearing Board member ask that I send my data concerning the Arizona Geological Survey. It was part of my original submission. I did not make that clear, so I have attached a copy of the original Appeal Submittal. Please pass this on the Board members.

Again, I thank the EPA for the opportunity to present my case today and appreciate their patients with me. I was rather nervous.

Regards,

John L. Anderson

2631 N. Presidential Dr., Florence, AZ 85132
520-233-6066 (H) 520-840-1573 (C)

John L. Anderson
2631 N. Presidential Dr.
Florence, AZ 85132
jla@johnlanderson.com
December 28, 2016

Clerk of the Board
U.S. Environmental Protection Agency
Environmental Appeals Board
1200 Pennsylvania Avenue, NW
Mail Code 1103M
Washington, DC 20460-0001

Subject: Issuance of the Class III In-Situ Production of Copper Permit No. R9UIC-AZ3-FY11-1

It is difficult to understand how agencies within the U.S. Government and the State of Arizona could approve any type of in-situ mining in or near an aquifer that is used for drinking water and farming. The proposed Florence Copper, Inc. will be polluting the same aquifer that supplies drinking water to my community. The mine well is within one mile of residential community wells and agriculture wells. Also, the EPA did not respond to my specific concerns and comments made at the hearing held in Florence on January 22, 2015.

The U.S. Geological Survey has numerous studies and documents reporting on the adverse environmental effects of in-situ recovery mines. Most of their data is on uranium and coal mines. While the target ores may differ, the process is similar and the acid extraction and contamination will also be similar with in-situ copper mining. I have attached a sample document which shows a table of the heavy metals that were released by the in-situ process. These releases are a non-recoverable contamination of the aquifer. There has never been an in-situ mine where the aquifer was recovered to drinking water standards during or after the mine was abandoned.

Attached is a better and more specific article that was published by the Arizona Geological Survey, Recovery of Copper by Solution Mining Methods, Contributed Report CR-15-A, August 2015. Some interesting observations is that the report does address Conoco's decision to abandon the mine at the Florence site (see page 5.) More to the point of why the project should not be allowed are the 'CONS' on page 6. Any one of these 'CONS' should justify disapproval of this project:

- Loss of leach solutions can result in ground water contamination, reduced metal recovery and loss of reagents.

- Planning and development of solution mining projects requires considerable field testing, which sometimes proves to be difficult and costly.

- Both physical and chemical constraints limit its application to a few sites, where conditions are favorable.

- Total copper recoveries are generally less than conventional methods.

- Time required for metal extraction is generally greater than conventional mining and processing.

- Like conventional heap leach operations, in-situ methods only recover copper. They are unable to recover by-product metals (i.e. molybdenum, gold and silver).

- By its very nature, solution mining technology relies on hydrological models and predictions. It is generally very difficult to observe what is really happening below the earth's surface.

- Solution flow patterns are very difficult to accurately quantify, engineer and control.

- Solution mining works best under saturated conditions.

- Leachable deposits are not always located below the water table. *

- Environmental management works best when the ore body can be isolated from adjacent aquifers**

*The copper is within the water table per Florence, Inc. documents.

**The aquifers used by the proposed mine are the same aquifers used by bordering communities and farms.

The EPA engineers told me at our meeting in Florence that their model showed the migration from the proposed mine would not reach the well that services my community for twenty years. EPA openly admitted their model showed migration. It may not affect me personally, but what about my children?

This project must be stopped.

Respectfully,

John L. Anderson

John L. Anderson

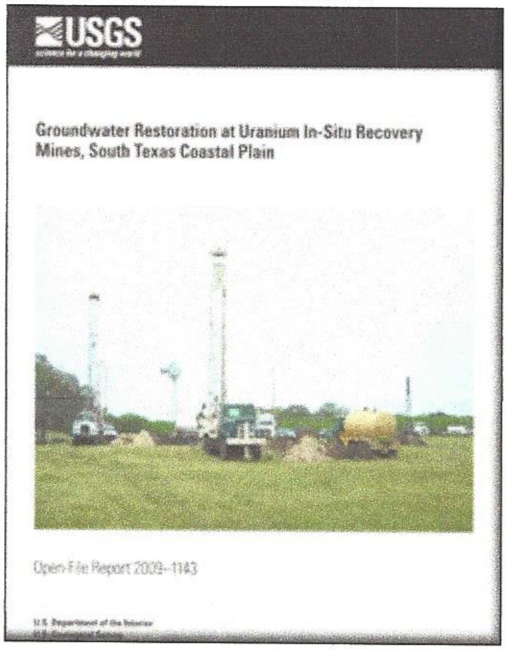
USGS Home
Contact USGS
Search USGS

Open-File Report 2009–1143

>> Pubs Warehouse > OF 2009-1143

Groundwater Restoration at Uranium In-Situ Recovery Mines, South Texas Coastal Plain

By Susan Hall



Groundwater Restoration at Uranium In-Situ Recovery Mines, South Texas Coastal Plain

Open-File Report 2009–1143

U.S. Department of the Interior

Abstract

This talk was presented by U.S. Geological Survey (USGS) geologist Susan Hall on May 11, 2009, at the Uranium 2009 conference in Keystone, Colorado, and on May 12, 2009, as part of an underground injection control track presentation at the Texas Commission on Environmental Quality (TCEQ) Environmental Trade Fair and Conference in Austin, Texas.

Texas has been the location of the greatest number of uranium in-situ recovery (ISR) mines in the United States and was the incubator for the development of alkaline leach technology in this country. For that reason, the author chose to focus on the effectiveness of restoration at ISR mines by examining legacy mines developed in Texas. The best source for accurate information about restoration at Texas ISR mines is housed at the TCEQ offices in Austin. The bulk of this research is an analysis of those records.

First posted July 14, 2009

- **Report** PDF (3.2 MB)

For additional information contact:

Team Chief Scientist,
USGS Central Energy
Resources Team
Box 25046, Mail Stop 939
Denver, CO 80225
http://energy.cr.usgs.gov/

Suggested citation:

Hall, Susan, 2009, Groundwater restoration at uranium in-situ recovery mines, south Texas coastal plain: U.S. Geological Survey Open-File Report 2009–1143, 32 p.

Accessibility FOIA Privacy Policies and Notices

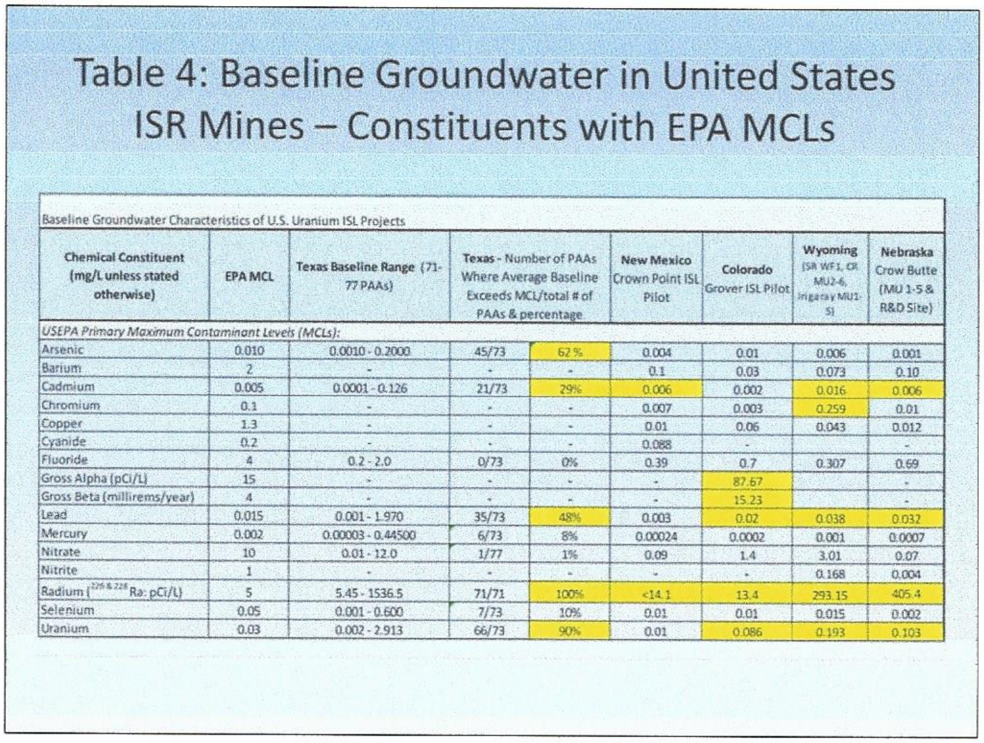


Table 4: Baseline Groundwater in United States ISR Mines – Constituents with EPA MCLs

Baseline Groundwater Characteristics of U.S. Uranium ISL Projects

Chemical Constituent (mg/L unless stated otherwise)	EPA MCL	Texas Baseline Range (71-77 PAAs)	Texas - Number of PAAs Where Average Baseline Exceeds MCL/total # of PAAs & percentage		New Mexico Crown Point ISL Pilot	Colorado Grover ISL Pilot	Wyoming (SR WF1, CR MU2-6, Irigaray MU1-5)	Nebraska Crow Butte (MU 1-5 & R&D Site)
USEPA Primary Maximum Contaminant Levels (MCLs):								
Arsenic	0.010	0.0010 - 0.2000	45/73	62 %	0.004	0.01	0.006	0.001
Barium	2	-	-	-	0.1	0.03	0.073	0.10
Cadmium	0.005	0.0001 - 0.126	21/73	29%	0.006	0.002	0.016	0.006
Chromium	0.1	-	-	-	0.007	0.003	0.259	0.01
Copper	1.3	-	-	-	0.01	0.06	0.043	0.012
Cyanide	0.2	-	-	-	0.088	-		-
Fluoride	4	0.2 - 2.0	0/73	0%	0.39	0.7	0.307	0.69
Gross Alpha (pCi/L)	15	-	-	-	-	87.67		-
Gross Beta (millirems/year)	4	-	-	-	-	15.23		-
Lead	0.015	0.001 - 1.970	35/73	48%	0.003	0.02	0.038	0.032
Mercury	0.002	0.00003 - 0.44500	6/73	8%	0.00024	0.0002	0.001	0.0007
Nitrate	10	0.01 - 12.0	1/77	1%	0.09	1.4	3.01	0.07
Nitrite	1	-	-	-	-	-	0.168	0.004
Radium ($^{226\,\&\,228}$Ra: pCi/L)	5	5.45 - 1536.5	71/71	100%	<14.1	13.4	293.15	405.4
Selenium	0.05	0.001 - 0.600	7/73	10%	0.01	0.01	0.015	0.002
Uranium	0.03	0.002 - 2.913	66/73	90%	0.01	0.086	0.193	0.103

Baseline Characterization of Groundwater in U.S. ISR Well Fields

Baseline standards for all 77 Texas PAAs can be used to characterize Texas ISR well fields that serve as a basis of comparison with baseline values determined for other ISR well fields in the United States. The argument is commonly made that before mining, groundwater in ISR well fields is so contaminated that it should not be used for human consumption. Before mining, these aquifers are typically granted exemptions from the Clean Water Act, termed aquifer exemptions, by the U.S. Environmental Protection Agency (USEPA).

In Texas, more than 25 percent of PAAs are characterized by baseline groundwater above the maximum contaminant level (MCL) for arsenic, cadmium, lead, radium, and uranium (shown highlighted on Table 4). MCL is set by the U.S. Environmental Protection Agency (USEPA; http://www.epa.gov/safewater/contaminants/index.html) for those elements with well-established links to negative human health effects. All PAAs contain radium above MCL, and 90 percent contain uranium above MCL. Although baseline is artificially elevated in this database because the operator is selecting the highest average value within the production or mine area, this value does serve to identify elements of concern in these well fields.

In the Crown Point pilot project in New Mexico, only cadmium was elevated above MCL. At the Grover pilot project in Colorado, baseline water showed gross alpha, gross beta, radium, and uranium above MCL. In Wyoming, averaged values for the Smith Ranch 1, Christensen Ranch 2-6, and Irigaray 1-5 mine units were elevated above MCL for cadmium, chromium, lead, radium, and uranium.
In Nebraska (Crow Butte mine units 1-5 and the Crow Butte R&D site), average cadmium, lead, radium, and uranium were elevated above MCL. Elements above MCL are highlighted in the table.

With the exception of the New Mexico deposit (Crown Point), these well fields are characterized by groundwater elevated in multiple MCLs prior to mining. Radium is almost always elevated above MCL while uranium is typically elevated and cadmium and lead commonly elevated. These well fields would require pretreatment to be used as a source for drinking water.

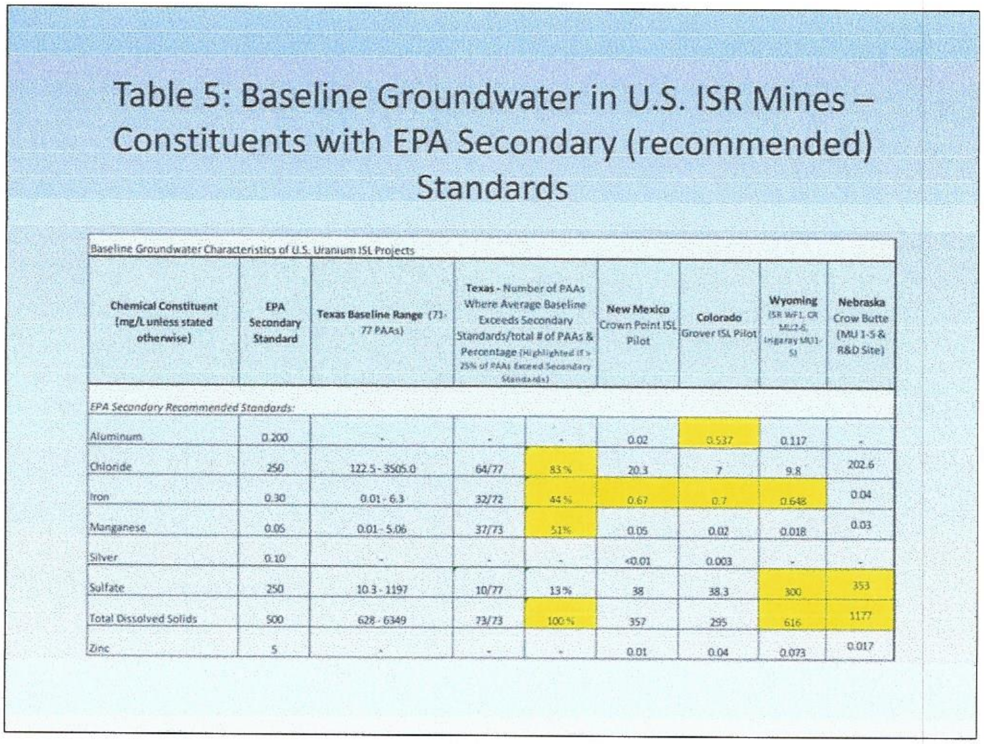


Table 5: Baseline Groundwater in U.S. ISR Mines – Constituents with EPA Secondary (recommended) Standards

Baseline Groundwater Characteristics of U.S. Uranium ISL Projects

Chemical Constituent (mg/L unless stated otherwise)	EPA Secondary Standard	Texas Baseline Range (73-77 PAAs)	Texas - Number of PAAs Where Average Baseline Exceeds Secondary Standards/total # of PAAs & Percentage (Highlighted if > 25% of PAAs Exceed Secondary Standards)		New Mexico Crown Point ISL Pilot	Colorado Grover ISL Pilot	Wyoming (SR WF1, CR MU2-6, Irigaray MU1-5)	Nebraska Crow Butte (MU 1-5 & R&D Site)
EPA Secondary Recommended Standards:								
Aluminum	0.200	-	-	-	0.02	0.537	0.117	-
Chloride	250	122.5 - 3505.0	64/77	83 %	20.3	7	9.8	202.6
Iron	0.30	0.01 - 6.3	32/72	44 %	0.67	0.7	0.648	0.04
Manganese	0.05	0.01 - 5.06	37/73	51%	0.05	0.02	0.018	0.03
Silver	0.10	-	-	-	<0.01	0.003	-	-
Sulfate	250	10.3 - 1197	10/77	13 %	38	38.3	300	353
Total Dissolved Solids	500	628 - 6349	73/73	100 %	357	295	616	1177
Zinc	5	-	-	-	0.01	0.04	0.073	0.017

Recommended secondary standards are set by the USEPA for constituents that, in high enough concentrations, negatively affect the esthetic quality of groundwater, but are not conclusively linked to any negative human health effect. Of those elements for which secondary standards are set by the USEPA, iron, sulfate, and total dissolved solids (TDS) are commonly elevated above recommended levels in pre-mining water at ISR facilities. Chloride and manganese are commonly high in Texas PAAs before mining, while TDS is elevated above the recommended standard in all pre-mining Texas PAAs. Elements elevated above secondary standards are highlighted in Table 5.

Recovery of Copper by Solution Mining Methods

David F. Briggs
Economic Geologist

In-place leaching of rubblized and terraced walls of the Oxide pit at the Silver Bell mine, Pima County, Arizona (Satellite Photo from Google Earth - 12/20/2014)

CONTRIBUTED REPORT CR-15-A

August 2015

Arizona Geological Survey

www.azgs.az.gov | repository.azgs.az.gov

Arizona Geological Survey

M. Lee Allison, State Geologist and Director

Manuscript approved for publication in August 2015
Printed by the Arizona Geological Survey
All rights reserved

For an electronic copy of this publication: www.repository.azgs.az.gov
Printed copies are on sale at the Arizona Experience Store
416 W. Congress, Tucson, AZ 85701 (520.770.3500)

For information on the mission, objectives or geologic products of the
Arizona Geological Survey visit www.azgs.az.gov.

Recommended Citation: Briggs, D.F., 2015, Recovery of Copper by Solution Mining Methods. Arizona Geological Survey Contributed Report CR-115-A, 10 p.

Recovery of Copper by Solution Mining Methods

David F. Briggs, Economic Geologist
3514 West Blacksill Drive
Tucson, Arizona 85741
Phone - 520-744-4195
Cell - 520-784-3954

Introduction

Solution mining is a mining practice that employs solutions (i.e. water or dilute acid) to recover a desired commodity from an ore deposit where it stands without also extracting the rock. There are essentially two types of solution mining: 1) in-situ and 2) in-place. In-place solution mining employs permeability enhancement techniques such as blasting or previous mining activities (i.e. block-caving) to fragment or increase the permeability of the rock prior to applying a leaching solution to liberate a desired commodity from the ore. In-situ methods rely solely on the naturally occurring permeability of the ores.

Copper as well as a number of other commodities are harvested by solution mining methods. Water-soluble salts such as potash (sylvite), rock salt (halite), thenardite (sodium sulfate) and nahcolite (sodium bicarbonate) are commonly derived from massive sedimentary deposits by in-situ methods. Prior to 2000, mining operations in the Gulf of Mexico region recovered sulfur by a solution mining method, known as the Frasch process, which injected superheated water to melt the sulfur so it can be pumped to the surface (Christensen et. al., 1991). Approximately ninety percent of the uranium mined in the United States is also recovered by solution mining methods (U. S. Energy Information Agency, 2013).

How Solution Mining of Copper Works

Solution mining of copper replicates a natural process of dissolution and reprecipitation that has occurred for millions of years and continues today. Known as supergene enrichment, this natural process has been observed at many of the world's copper deposits. It occurs when hypogene (i.e. primary) ores, containing sulfide minerals such as pyrite (FeS_2), chalcopyrite ($CuFeS_2$) and bornite (Cu_5FeS_4), are oxidized as these rocks are exposed to chemical weathering. During the oxidation process, iron contained within these minerals is transformed into red, reddish brown, orange and yellow-colored iron oxides, while sulfur is combined with groundwater to produce a weak sulfuric acid solution. Copper within the rock is dissolved in the acidic solutions as it percolates downward to the water table, where reducing conditions (i.e. oxygen-poor environment) promote copper precipitation as chalcocite (Cu_2S). Over time, this action forms an oxidized zone (i.e. leached cap) above a thick, copper-rich blanket-shaped zone, known as an enrichment blanket. It is the presence of large enrichment blankets (as shown in Figure 1) at many of the world's porphyry copper systems that make it economical to mine the copper contained within these deposits (Guilbert and Park, 1986).

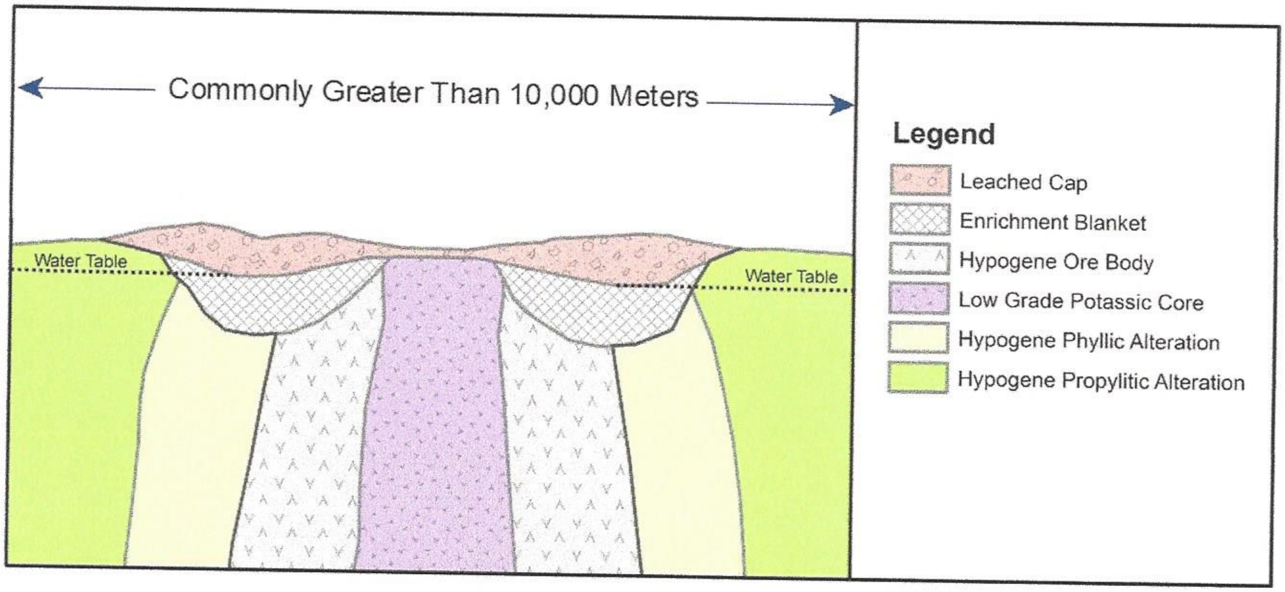


Figure 1: Simplified cross-section through a porphyry copper system showing supergene/hypogene alteration and mineralization (modified from Gilbert and Park (1986)

Solution mining replicates the natural process of oxidation and reduction, described above. Dilute acidic solutions are introduced to the copper-bearing ores, causing dissolution of soluble copper minerals (Table 1) remaining in the leached cap and underlying enrichment blanket. This produces a "pregnant" solution that is collected and transferred to surface processing facilities, where the copper is recovered.

Table 1: Common soluble copper-bearing minerals

Mineral Name	Chemical Composition
Antlerite	$Cu_3SO_4(OH)_4$
Atacamite	$Cu_2Cl(OH)_3$
Azurite	$Cu_3(CO_3)_2(OH)_2$
Brochantite	$Cu_4SO_4(OH)_6$
Chalcanthite	$CuSO_4{\cdot}5H_2O$
Chalcocite	Cu_2S
Chrysocolla	$Cu(Fe,Mn)O_x\text{-}SiO_2\text{-}H_2O$
Cuprite	Cu_2O
Malachite	$CuCO_3{\cdot}Cu(OH)_2$
Tenorite	CuO

Thick mature, oxidation profiles (i.e. leach caps) accompanied by well-developed zones of supergene enrichment are promoted by long uninterrupted periods of supergene activity, which generally last at least 3 to 9 million years. Optimum development occurs in regions characterized by hot, semi-arid to rainy climates that experience tectonically induced uplift to depress water tables; progressively exposing sulfides to weathering processes. The preservation of thick oxidation profiles is dependent on erosion rates, that do not exceed the supergene processes (Sillitoe, 2005).

This setting is ideal for development of large deposits that are amenable to solution mining methods. More than 50% of the world's mined copper is derived from supergene ores located in the central Andes and southwestern North American porphyry copper provinces (Sillitoe, 2005). Many copper projects in southwestern North American have either used this technology or have been considered potential candidates for its use (Figure 2).

solution mining operations are designed to maximize copper recovery at a particular locality, while complying with all regulatory standards set forth in the permits that govern the design and operation of these projects (Weeks and Millenacker, 1988). A number of methods are employed to achieve this goal.

In-place solution mining operations at the Miami Mine in Arizona extracted copper from a broken and fragmented zone located above a closed, underground block-caving operation (Figure 3), where nearly 75% of the leachable copper is present as chalcocite (Carstensen and Neira, 1997). A dilute sulfuric acid-ferric sulfate solution (0.5% H_2SO_4) was applied using perforated pipes laid out over the surface above the ore body and by a series of shallow injection wells that introduced solutions below the Gila Conglomerate east of the Miami fault (Fletcher, 1985). The copper-bearing solutions were recovered from sumps located on the 1,000-foot level of the underground mine workings and pumped to the surface, where the copper was initially recovered by precipitation onto tin cans or scrap iron and later by solvent extraction-electrowinning (SX-EW) methods (Ahlness and Pojar, 1983).

In-place leaching activities at Asarco's Silver Bell Mine northwest of Tucson, extract copper from low-grade surface ores, which remain in the walls of the open pits that do not support the cost of further stripping (Figure 4). Each of the rubble leach panels are drilled to the base of the zone of supergene enrichment (up to 240 feet) with 9-inch blast holes. This is done on a retreating basis, which creates a hydraulic gradient from lower to higher benches. After the drill pattern has been blasted, the rubble leach panel is ripped and terraced by bulldozers prior to applying the leach solution with sprinklers. The copper-bearing solutions flow by gravity to the bottom of the open pit, where they are recovered and pumped to a processing plant that employs SX-EW technology (Browne and Miller, 2002).

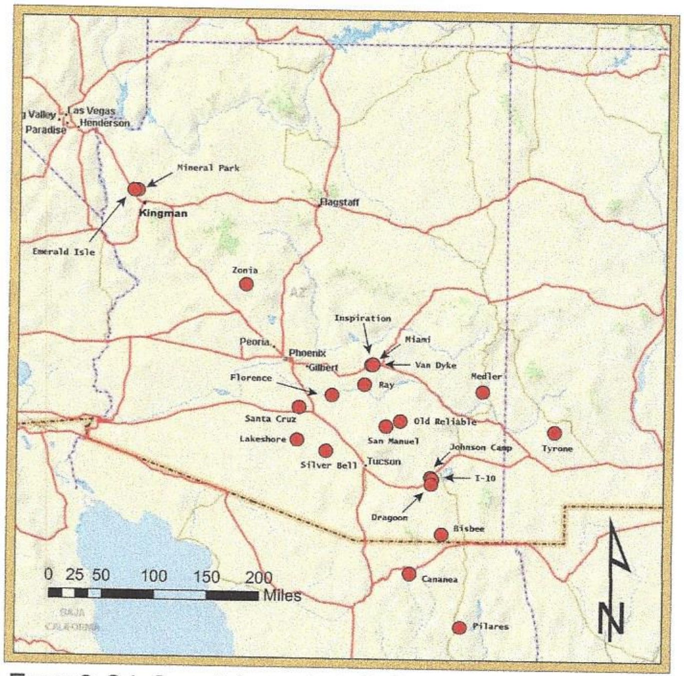


Figure 2: Solution mining projects in SW North America

Supplementing production from conventional heap leach operation, the in-place rubble leaching project at Silver Bell is estimated to recover 20 to 25% of the contained copper. The relatively low recovery achieved by this method is most likely due to the presence of insoluble hypogene copper sulfides, inadequate contact of the leach solutions with soluble copper minerals (i.e. channeling) and poor oxygenation (O'Gorman et. al, 2004).

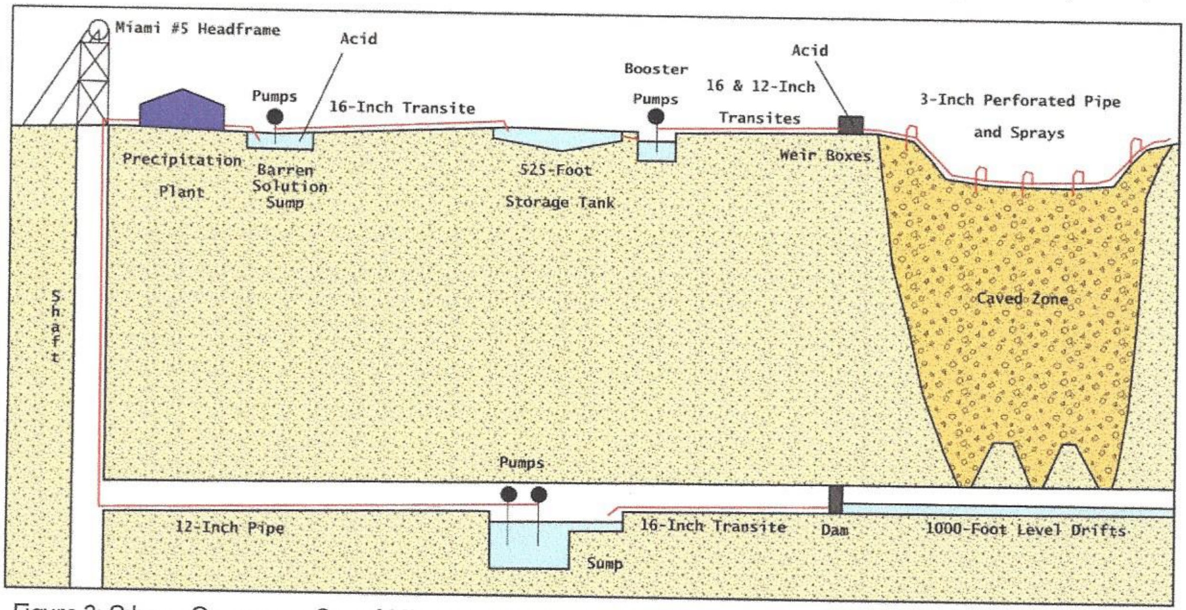


Figure 3: Schematic cross section of Miami Copper in-place leaching operation (modified from Fletcher, 1971).

The proposed in-situ project at Florence, Arizona will introduce dilute sulfuric acid solutions (99.7% water and 0.3% H_2SO_4 by volume) via injection wells to the copper-bearing ores, which are characterized by highly fractured bedrock that contains chrysocolla, lesser amounts of tenorite, cuprite and native copper with trace amounts of azurite and brochantite (Figure 5). Lying within the saturated zone beneath the water table, the movement of these fluids through the rock will be controlled by pumping the solutions from neighboring recovery wells, which will create a hydraulic gradient that causes the introduced solutions to flow from the injection wells to adjacent recovery wells (Sherer, 2011). After being pumped to the surface, the copper-bearing solutions will be processed by solvent extraction and electrowinning technology to recover the dissolved copper and produce a marketable copper cathode product (M3 Engineering and Technology Corporation, 2013).

A Brief History of Copper Recovery by Solution Mining Methods

As early as the 1670, copper-bearing mine waters at the Rio Tinto mine in Spain were known to chemically precipitate copper onto iron (Arbiter and Fletcher, 1994). This process became known as the "cementation process", which is apparently derived from the Spanish word "cementación", meaning precipitation. Over the next three centuries, it was the primary method used to recover dissolved copper from dilute leach solutions, before being replaced by solvent extraction-electrowinning (SX-EW) technology, which saw its first commercial application at Ranchers Exploration and Development Corporation's Bluebird mine (Miami, Arizona) in 1968 (Power, 1985).

The presence of dissolved copper in waters of Bingham Creek near Salt Lake City, Utah was first noted in 1885, leading prospectors to construct sluices that were filled with scrap iron. The stream flow was then diverted through these sluices. Over a period of six to ten weeks, the iron was replaced by masses of metallic copper that assayed approximately 85% pure copper (Krahulec, 1997). This was one of the earliest commercial applications of in-situ leaching of copper-bearing ores in the U.S The dissolved copper recovered by this operation was derived from the natural oxidation and leaching of sulfide mineralization in a major porphyry copper deposit located in the headwaters of Bingham Creek. This is the present site of the large-scale, open pit operation at Bingham Canyon, which commenced operations in 1906 and continues to produce approximately 15 to 25% of U. S. copper.

The recovery of copper through passive in-situ methods such as those used at Bingham Canyon during the 1880s eventually led to a more active approach, where water from underground mine sumps was applied to the ores and the resulting copper-bearing solutions collected and the copper recovered. One of the earliest attempts that employed this technique occurred in the Morenci Mining District of Arizona at the Medler mine from 1906 until

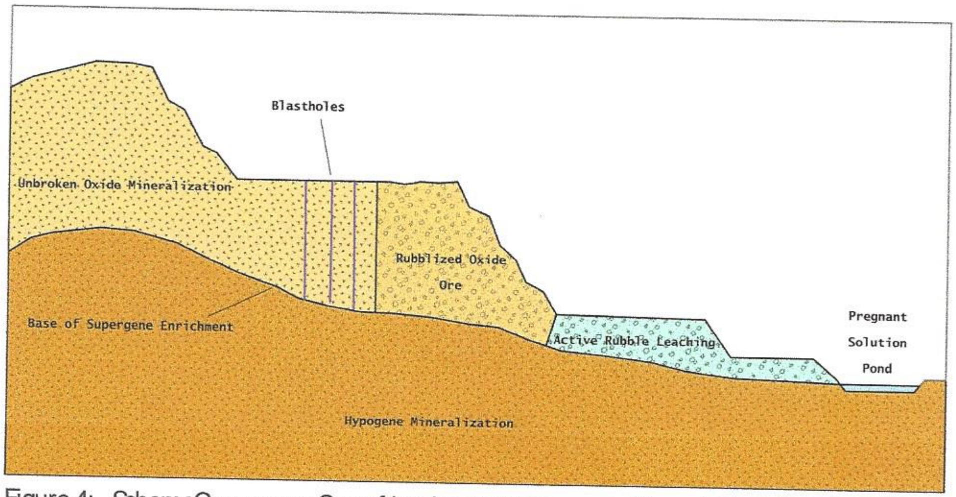


Figure 4: Schematic cross section of in-place leaching operations at Silver Bell (modified from Browne and Miller, 2002)

1909. This in-situ project involved flooding the drifts on the second level of the underground Medler mine and allowing the solutions to percolate downward to the third level, where they were collected and transferred to a precipitation plant for treatment (Ahlness and Pojar, 1983).

The productivity of solution mining techniques is directly dependent on the solution's contact with the soluble copper-bearing minerals and its ability to circulate throughout the ore. Practical application of these concepts evolved into one of the most productive uses of solution mining employed by the copper industry to date; the recovery of copper from ores that have already been broken and fragmented by previous mining activity. Primarily employed in a secondary or tertiary role, this method has mainly been used to supplement production from existing operations or to recover residual copper after conventional mining operations have ceased. The first attempts to use this in-place technique occurred at the Ohio Mine in the Bingham Canyon Mining District in 1922 and the Brooks Mine in the Robinson Mining District located near Ely, Nevada in 1925.

During the 1930s, miners at Anaconda Minerals' Butte operation in Montana discovered that water used to fight underground fires dissolved significant amounts of copper. This led to the practice of recovering copper from low grade waste rock that was used to back-filled stopes at the Leonard, Mountain Con and Steward mines. Leaching of underground stopes at Butte was discontinued, when a more productive technique of recovering copper from surface dumps was introduced in 1964 (Ahlness and Pojar, 1983).

One of the most long-lived and productive in-place solution mining projects occurred at the Miami Copper Mine located in Gila County, Arizona. Small scale operations began in an abandoned portion of this underground mine in December 1941 (Fletcher, 1971). Full scale solution mining operations took place after conventional underground mining ceased in June 1959 and continued to recover copper until commercial leaching activities were suspended in 2013. Over its seventy-one year life, the estimated production at this in-place solution mining project was approximately 693 million lbs. of copper, representing 22.4% of the total production from the Miami project (1911-2013).

Other in-place solution mining projects located in Arizona, New Mexico and Sonora that have produced copper from broken and fragmented rocks located above block-caving operations include: Ray (1937-1961), Tyrone (1941-1949), Pilares (1946-1960), Inspiration (1965-1974), Lakeshore (1983-1994) and San Manuel (1995-2002).

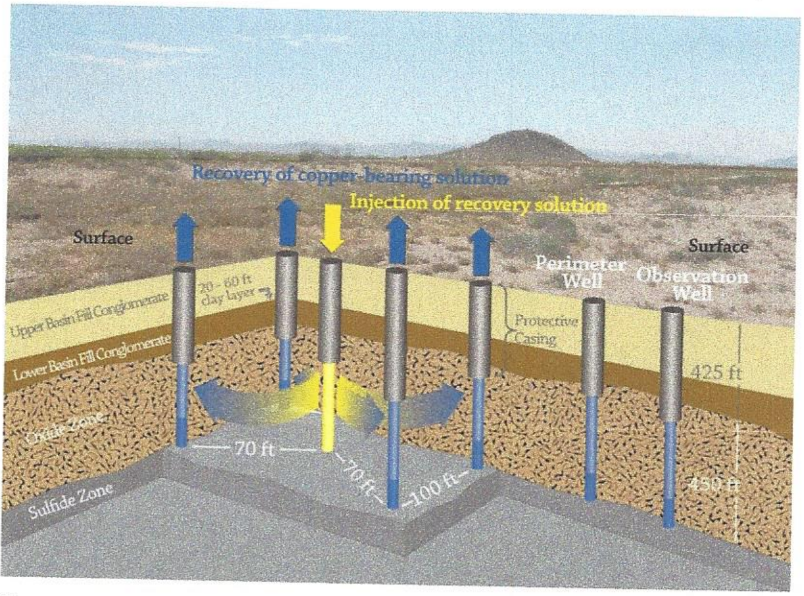


Figure 5: Schematic cross-section of proposed Florence in-situ leach project (Hoffman et. al, 2012)

Another approach to in-place solution mining of copper-bearing ores was to fragment the ores by blasting prior to conducting leaching operations. This method was initially tested during the 1970s at several small in-place projects: including the Old Reliable mine (1972-1981) near Mammoth, Arizona; the Zonia project (1973-1975) located south of Prescott, Arizona; and the Big Mike mine (1973-1979) in Pershing County, Nevada (Ahlness and Pojar, 1983). Over time, blasting and fragmenting ore has gradually been occurring at an ever increasing scale. At Mineral Park (1981-1994), near Kingman, Arizona, it was used to rubblize low-grade oxide ores contained in the walls of the open pits. This approach of further fragmenting before leaching in-place is ongoing at the Silver Bell project (1996-present) located northwest of Tucson.

During the final decades of the twentieth century, interest in solution mining of copper resulted in a number of joint research efforts involving the mining industry and the United States Bureau of Mines. Sites evaluated include: Emerald Isle (1974-1975), Johnson Camp (1977) and Mineral Park (1993). Substantial research was focused on ASARCO/Freeport McMoRan's Santa Cruz property (1988-1999) located northwest of Casa Grande, Arizona (O'Neil, 1991 and United States Bureau of Mines, 1994). This project studied the feasibility of in-situ mining a large, high grade, copper oxide resource, located at a depth of 1,250 to 2,360 feet (Weber, Barter and Kreis, 2000). Although this effort was not deemed commercially viable, the data and knowledge obtained from this research project has benefitted other in-situ programs.

Since the mid-1970s, the evaluation of the commercial feasibility of solution mining copper from naturally occurring ores without fragmentation prior to leaching has been ongoing. In addition to the Santa Cruz project, other Arizona projects that fall into this category include Van Dyke (1976-present), Florence (1992-present), I-10 (2010-present) and Dragoon (2010-present). The in-situ program at Bisbee (1975-2002 (?)) was designed to recover residual copper remaining in the Lavender pit and underground workings of the Campbell mine following the suspension of commercial production in June 1975 (Ahlness and Pojar, 1983). In addition to its in-place solution mining operations, the San Manuel project also employed in-situ methods (1986-2002) to recover copper from oxidized granitic host rocks lying outside of the perimeter of the caved zone (Briggs, 2014).

Solution Mining Versus Conventional Methods

Copper mining operations employ conventional mining methods (i.e. open pit, underground), solution mining methods (i.e. in-place, in-situ leaching) or a combination of these methods. Factors that determine how a particular ore deposit is mined vary from site to site include:

- depth and spatial distribution of the ore body
- ore and gangue mineralogy of the host rocks
- nature of the mineralization (i.e. disseminated, fracture-controlled)
- tenor of the mineralization
- geotechnical character of the rocks (i.e. competency)
- position of water table (i.e. saturated versus unsaturated)
- permeability and porosity of the ores
- capital expenditures, operational and reclamation costs
- environmental impacts.

The pros and cons of solution mining are summarized in Table 2. The costs of stripping restrict conventional open pit mining methods to sites where the ore bodies are located close to the surface. Other factors include the grade of the ores, geotechnical character of the rocks (i.e. angle of pit slopes and stripping ratios) and position of water table (i.e. dewatering costs). More expensive underground mining methods are constrained by similar factors. Following the discovery of the Florence deposit in 1969, Conoco initially envisioned developing this resource as a large open pit (Hoag, 1996). However, economic factors related to the depth of overburden, competency of the oxide ores, low tenor of the mineralization and potential impacts related to dewatering ruled out the use of conventional mining methods at this site.

Solution mining methods cannot be used to recover copper from hypogene ores that contain insoluble copper-bearing minerals, such as chalcopyrite and bornite. These ores have to be mined by conventional mining methods and processed through a flotation mill, which produces a concentrate product that must be further treated (i.e. smelting and refining) to produce a marketable product. Like conventional mining operations that employ heap leaching, solution mining operations only recover copper from soluble minerals, such as chrysocolla, brochantite, azurite, malachite and chalcocite. Composition of the gangue mineralogy of the ores is also important. The presence of significant amounts calcite or other soluble minerals can significantly impact the economic viability of solution mining projects. One of the most difficult challenges facing Excelsior's Gunnison project (aka I-10 and Dragoon) is the presence of significant amounts of calcite, contained within the copper-bearing skarn host rocks (M3 Engineering and Technology Corporation, 2014). Its presence not only increases the amount of sulfuric acid required to treat the ores, increasing costs, but also will result in the precipitation of gypsum within the fractures and pore spaces. This results in two problems. The gypsum coats the copper minerals within the fractures isolating them from the leach

Table 2: Pros and cons of solution mining of copper (modified from Bhappu, 1985 and O'Gorman et. al. 2004)

Pros	Cons
Smaller, ephemeral, environmental footprint with less surface disturbance (waste dumps, tailings ponds, etc.) and less water and air pollution than conventional mining projects.	Loss of leach solutions can result in ground water contamination, reduced metal recovery and loss of reagents.
Reclamation can be progressively performed throughout the life of the operation, allowing it to the funded by operation's cash flow.	Planning and development of solution mining projects requires considerable field testing, which sometimes proves to be difficult and costly.
Operating and total costs are generally less than conventional mining methods.	Both physical and chemical constraints limit its application to a few sites, where conditions are favorable.
Can be used at sites that are not economic to mine by conventional mining methods.	Total copper recoveries are generally less than conventional methods.
Total energy consumption is less than conventional mining methods.	Time required for metal extraction is generally greater than conventional mining and processing.
Total water consumption is less than conventional methods as a result of reduced evaporation and elimination of water contained within conventional tailings impoundments.	Like conventional heap leach operations, in-situ methods only recover copper. They are unable to recover by-product metals (i.e. molybdenum, gold and silver).
Employs SX-EW technology, which offers several advantages over the older and more costly pyrometallurgical processes (i.e. smelting) employed at some conventional mining projects.	By its very nature, solution mining technology relies on hydrological models and predictions. It is generally very difficult to observe what is really happening below the earth's surface.
Can be used in conjunction with existing conventional mining operations increasing the overall profitability of the project.	Solution flow patterns are very difficult to accurately quantify, engineer and control.
Initial capital costs are significantly less than sustaining capital expenditures, allowing a higher percentage of its total capital costs to be funded by the operation's cash flow.	Solution mining works best under saturated conditions. Leachable deposits are not always located below the water table.
Can be used at sites where pre-existing, surface infrastructure (i.e. highways, railroad, towns) is present.	Environmental management works best when the ore body can be isolated from adjacent aquifers.

solutions; thereby reducing their ability to dissolve the copper (i.e. reduces copper recovery). It also fills the fractures, impeding the flow of the solutions through the rock, interfering with the solution mining operation.

Unlike conventional mining projects, the successful application of in-place/in-situ mining methods requires a porous and permeable host, which allow the leach solutions to freely migrate through the rock. This porosity and permeability can be man-made or natural. Many types of copper deposits occur within relatively impervious hosts, where the natural permeability of the rock is primarily dependent on the density of open fractures. Leach solutions must come in physical contact with the soluble copper-bearing minerals; making copper ores dominated by fracture-controlled mineralization more favorable than ores where the copper minerals are disseminated throughout the rock.

This is illustrated by tests that have been conducted at two Arizona copper deposits; Santa Cruz and Florence. The geological setting of each of these deposits is similar with the ores being hosted primarily by Precambrian Granite and Laramide porphyries of granodioritic to quartz monzonitic composition. Both lie beneath a thick section of post-mineral alluvial sediments that characterize the Basin and Range province. Oxide mineralization is fracture-controlled and consists of soluble copper oxides. Neither of these sites has had historical mining activity. Both occur below the water table and rely solely on the natural porosity and permeability of the host rocks to transfer the leach solutions from the injection to recovery wells.

Located at a depth of 1,200 to 2,360 feet, the oxide ores at Santa Cruz contain very few fractures (1 to 2 fractures per foot); making their permeability very low (Dahl, 1989). On the other hand, the high permeability of the very strongly broken oxide ores at Florence (depths - 425 to 1,200 feet) are characterized by numerous open fractures (11 to 15 fractures per foot), making it a more favorable candidate for in-situ leaching (M3 Engineering and Technology Corporation, 2013a).

Overall copper recovery is also dependent on the efficiency of the "sweep" of the leach solutions through the rock. Solution mining projects that occur beneath the water table are generally more efficient than those occurring above the water table, with projected total copper recoveries of 35 to 70% compared to less than 35% for unsaturated conditions. Contrast this with copper recoveries at conventional heap leach operations, which generally range from 70 to 85% (Dhawan et. al., 2012), while conventional milling projects vary from 75 to 95% (United States Congress, 1988).

Under saturated conditions a hydraulic gradient can be created allowing the leach solutions to thoroughly permeate the rock as they move from the injection to recovery wells. Under unsaturated conditions (i.e. above the water table) leach solutions tend to percolate downward under the force of gravity; commonly being negatively impacted by channeling of the solutions (as discussed above at Silver Bell), which can leave significant volumes of the rock unexposed to the leach solutions. In general, the more surface area of the rock exposed to the leach solutions the better.

Solution mining projects can be developed at sites, where pre-existing infrastructure, such as highways, railroads or town sites, would prohibit the use of conventional mining methods. Excelsior Mining's I-10 deposit (part of the Gunnison project, aka North Star) lies beneath Interstate 10, approximately 2.5 miles northeast of Texas Canyon, while the Dragoon deposit (also a part of the Gunnison project, aka South Star) underlies the Southern Pacific railroad right of way, about one mile southwest of the town of Dragoon, Arizona. Copper Fox's Van Dyke deposit lies 1,000 to 2,100 feet beneath the town of Miami, Arizona (Moose Mountain Technical Services, 2015).

Solution mining techniques have been commercially employed to recover copper in North America for more than 100 years. Historically, this process has been primarily used to supplement production derived by other processing methods (i.e. San Manuel, Mineral Park, Inspiration, Silver Bell, Butte and Cananea) or has been employed in a tertiary or salvage role to produce copper at projects where conventional mining activities have ceased (i.e. Miami, Bisbee, Lakeshore, Tyrone and Pilares). Benefiting from the presence of existing infrastructure, the economics of such projects make them very attractive, because they enhance the overall profitability of the mining operation. Furthermore, the cash flow from these projects can be used to help fund reclamation activities at sites where commercial mining activities have ceased.

Advancements in science and technology combined with the increased costs of conventional mining and compliance with environmental regulations are such that at today's copper prices there are real opportunities to develop stand-alone, in-situ solution mines at sites that have had no previous mining activity. Candidates for this approach include Florence, Santa Cruz and Gunnison projects Note: Abbreviations for the Type of Operation include: conventional open pit/heap leach (Conv OP/HL), conventional open pit/mill (Conv OP/Mill) and conventional underground/mill (Conv UG/Mill). Initial capital expenditures represents the percentage of initial capital costs within the total projected life-of-mine capital expenditures. Rate of Return is before taxes.

Table 3: Economics of solution versus conventional mining methods

Project	Location	Type of Operation	Total Capital Costs ($/lb Cu)	Initial Capital Costs (%)	Operating Costs ($/lb Cu)	Total Costs ($/lb Cu)	Rate Of Return %
Florence	Pinal Co., Az	In-situ	0.481	23.2	0.799	1.590	35.8
Gunnison	Cochise Co., Az	In-situ	0.525	32.2	0.687	1.342	59.7
El Pilar	Sonora, Mexico	Conv OP/HL	0.431	63.4	1.326	1.783	52.9
MacArthur	Lyon Co., Nv	Conv OP/HL	0.509	61.2	1.891	2.553	29.3
Zonia	Yavapai Co., Az	Conv OP/HL	0.387	70.2	1.526	1.913	35.2
Ann Mason	Lyon Co., Nv	Conv OP/Mill	0.336	69.5	1.719	2.055	14.8
Copper Creek	Pinal Co., Az	Conv UG/Mill	0.530	71.4	1.805	2.421	11.8
Copper Flat	Sierra Co., NM	Conv OP/Mill	0.535	85.2	1.614	2.340	23.3
Pumpkin Hollow	Lyon Co., Nv	Conv OP/Mill	0.441	55.0	1.818	2.308	20.2
Rosemont	Pima Co., Az	Conv OP/Mill	0.249	81.4	1.200	1.588	45.6

Operating costs include mining, processing, general and administrative expenses, shipping, smelting and refining costs. Total costs include operating costs plus royalties, severance and property taxes, reclamation expenses and depreciation.

This conclusion is supported by economic data presented in Table 3. This comparison examines the estimated life-of-mine (LOM) capital expenditures, operating costs and total costs (US$/lb. of copper basis) and rate of returns (before taxes) for ten proposed North American mining projects. Ratios of initial capital expenditures divided by total capital expenditures (%) for each project are also presented below. Data contained in this table was derived from cash flow models presented in recent NI 43-101 reports (2011-2014) filed with Canadian regulatory authorities.

Analysis of Table 3 shows total capital expenditures for stand-alone, in-situ mining projects are competitive with conventional mining projects; although located at the higher end of the range of costs. One of in-situ mining's advantages is the percentage of life-of-mine (LOM) capital expenditures required to bring a project on line (23-32%). It is significantly less than that required for conventional mining projects (55-85%); allowing a greater proportion of the capital expenditures to be funded by the cash flow of the project.

Figure 6. a) In-situ leach well field (established during a production test by BHP Copper in 1997-1998) at Florence, Arizona. b) Conventional open pit operation at ASARCO's Mission mine near Tucson, Arizona

Both physical and chemical constraints limit the application of solution mining technology to a few sites, where conditions are favorable (Figure 6a & b). Competitive operating and total costs of stand-alone, in-situ leaching projects make them an attractive option at sites where conventional mining methods are not possible.

Benefits from stand-alone, in-situ mining projects include employment opportunities as well as a source of tax revenues for state and local governments without the need to excavate a large open pit, its extensive waste dumps, conventional mill/heap leach facilities and tailings ponds with their associated high capital, operating and reclamation costs. In addition to the small, ephemeral, environmental footprint, the surface of the site remains relatively undisturbed. Limited surface facilities associated with in-situ projects are easily removed and the site reclaimed with an ultimate goal of returning the land to productive use by the local community once mining activities have been completed.

Acknowledgements

This publication is a modified version of a report that was prepared for Hunter Dickinson Services, Inc. during the summer of 2014. We thank Hunter Dickinson Services, Inc. and Taseko Mines Ltd. for their permission to publish this article.

References

Ahlness, J. K. and Pojar, M. G., 1983, In Situ Copper Leaching in the United States: Case Histories of Operations: U. S. Bureau of Mines Information Circular 8961, 37 p.

AGP Mining Consultants, Inc., 2012, Preliminary Economic Assessment on the Ann Mason Project Nevada, U.S.A.: NI 43-101 Technical Report prepared for Entrée Gold Inc., November 14, 2012, 345 p.

Arbiter, N. and Fletcher, A. W., 1994, Copper Hydrometallurgy - Evolution and Milestones: Mining Engineering, v. 46, n. 2, p. 118-123.

Bhappu, R., 1985, In Situ Mining and Extraction; in Frontier Technology in Mineral Processing: John F. Spisak and Gerald V. Jergensen (eds.), Society of Mining Engineering of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Chapter 12, p. 123-132.

Briggs, D. F., 2014, History of the San Manuel-Kalamazoo Mine, Pinal County, Arizona: Arizona Geological Survey Contributed Report, CR-14-A, 9 p.

Broch, M., 2012, NI 43-101F1 Technical Report Feasibility Study El Pilar Project, Sonora Mexico: Prepared for Mercator Minerals Ltd., October 18, 2012, 320 p.

Browne, Q. J. and Miller, M. A., 2002, Use of Geologic Parameters for the Development of Low-Grade Copper Reserves, Silver Bell Mine, Az.: SME Annual Meeting, February 25-27, 2002, Phoenix, Arizona, Pre-print 02-069, 5 p.

Carstensen, T. L. and Neira, M. P., 1997, Development of a Leachable Copper Resource Model for In Situ Mine Expansion: Society for Mining, Metallurgy, and Exploration, Annual Meeting, Denver, Colorado, February 24-27, 1997, Pre-print 97-84, 8 p.

Christensen, R. J., Danielson, Jr., D. A., Davidson, D., Hallford, D., Johnston, D., Scholes, P., Huff, R., Kreis, H., Raihl, A., LaSala, C. and Swan, S. A., 1991, In-Situ Mining with Oil Field Technology: Oilfield Review, January 1991, v. 3, p. 8-17.

Dahl, L. J., 1989, Methods of Determining the Geologic Structure of an Ore Body as it Relates to In Situ Mining; in In Situ Leach Mining: Proceedings: Bureau of Mines Technology Transfer Seminars, Phoenix, AZ, April 4, 1989 and Salt Lake City, UT, April 6, 1989, U. S. Bureau of Mines Information Circular 9216, p. 37-48.

Dhawan, N., Safarzadeh, M. S., Miller, J. D., Rajamani, R. K. and Moats, M. S., 2012, Insights into Heap Leach Technology: Society of Mining Engineers Annual Meeting, February 19-22, 2012, Seattle, Washington, Pre-print 12-119, 8 p.

Fletcher, J. B., 1971, In-Place Leaching at Miami Mine, Miami, Arizona: Society of Mining Engineers AIME Transactions, December 1971, v. 250, p. 310-314.

Fletcher, J. B., 1985, In-Situ Leaching at Miami; in SME Mineral Processing Handbook: Norman L. Weiss (ed.), Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 2, Section 14D, Chapter 3, p. 7-10.

Guilbert, J. M. and Park, Jr., C. F., 1986, The Geology of Ore Deposits: W. H. Freeman and Company, New York, 985 p.

Hoffman, D., McPheters, L. and Rex, T., 2012, Florence Copper Project: Economic Impact Study: Report prepared by the L. William Seidman Research Institute, Arizona State University, 132 p.

Hoag, C. K., 1996, Geology and Project Overview of the BHP Florence (Poston Butte) Porphyry Copper Deposit, Pinal County, Arizona; in Field Guide for a Transect from Florence to Miami, Arizona: Compiled by Stephen M. Richard, Guidebook for the Arizona Geological Society Spring Field Trip, April 20-21, 1996, p. 9-16.

Krahulec, K. A. 1997, History and Production of the West Mountain (Bingham) Mining District, Utah; in Geology and Ore Deposits of the Oquirrh and Wasatch Mountains, Utah: D. A. John and G. H. Ballantyne (eds.), Society of Economic Geologists Guidebook Series, v. 29, p. 189-217.

M3 Engineering and Technology Corporation, 2012, Rosemont Copper Project NI 43-101 Technical Report Updated Feasibility Study, Pima County, Arizona, USA: Prepared for Augusta Resource Corporation, August 28, 2012, 344 p.

M3 Engineering and Technology Corporation, 2013a, Florence Copper Project NI 43-101 Technical Report Pre-Feasibility Study, Florence, Pinal County, Arizona: Prepared for HDICuris, April 4, 2013, 285 p.

M3 Engineering and Technology Corporation, 2013b, Copper Flat Project Form 43-101F1 Technical Report Feasibility Study, New Mexico, USA: Prepared for Themac Resources, November 21, 2013, 312 p.

M3 Engineering and Technology Corporation, 2014a, Gunnison Copper Project NI 43-101 Technical Report Prefeasibility Study, Cochise County, Arizona, USA: Prepared for Excelsior Mining Corporation, February 14, 2014, 305 p.

M3 Engineering and Technology Corporation, 2014b, MacArthur Copper Project Amended NI 43-101 Technical Report Preliminary Economic Assessment, Lyon County, Nevada, USA: Prepared for Quaterra Resources, Inc. and Quaterra Alaska, Inc., January 17, 2014, 256 p.

Moose Mountain Technical Services, 2015, NI 43-101 Technical Report and Resource Estimate for the Van Dyke Copper Project, Miami, Gila County, Arizona: Prepared for Copper Fox Metals, Inc., January 30, 2015, 170 p.

O'Gorman, G., Michaelis, H. V. and Olson, G. J., 2004, Novel In-situ Metal and Mineral Extraction Technology: DOE Award Number: DE-FG26-03NT41937, Little Bear Laboratories, Inc., September 22, 2004, 62 p.

O'Neil, T., 1991, In Situ Copper Mining at Santa Cruz: A Project Update: Mining Engineering, v. 43, n. 8, p. 1031-1034.

Power, K. L., 1985, Ranchers Bluebird Mine; in SME Mineral Processing Handbook: Norman L. Weiss (ed.), Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, v. 2, Section 14D, Chapter 4, p. 10-15.

SGS Metcon/KD Engineering, 2013, Redhawk Copper, Inc. Copper Creek Project Preliminary Economic Assessment 25,000 TPD Mill with an Underground Mine for Development of the Copper Creek Resource: NI 43-101 Technical Report prepared for Redhawk Copper, Inc., Amended October 28, 2013, 467 p.

Sherer, R., 2011, The Florence Copper Project: Building a Next Generation Copper Producer: Mining Engineering, v. 63, n. 11, p. 62-65.

Sillitoe, R. H., 2005, Supergene Oxidized and Enriched Copper Deposits: Products of the Interplay between Ore Type, Time, Tectonics, and Climate: Geological Society of America Annual Meeting, Salt Lake, Utah, October 16-19, 2005, Geological Society of America Abstracts with Programs, v. 37, n. 7, p. 12.

Tetra Tech, 2011, Executive Summary Zonia Copper Project Preliminary Economic Assessment Update, NI 43-101 Technical Report, Yavapai County, Arizona, USA: Prepared for Redstone Resources Corporation, April 29, 2011, 16 p.

Tetra Tech, 2013, NI 43-101 Technical Report Open Pit Operations Feasibility Study Pumpkin Hollow Project, Yerington, Nevada: Prepared for Nevada Copper Corporation, November 14, 2013, 341 p.

United States Bureau Mines, 1994, Draft Environmental Assessment for the Santa Cruz In Situ Copper Mining Research Project: Twin Cities Research Center, Minneapolis, MN, August 25, 1994, 80 p.

U. S. Energy Information Agency, 2014, 2013 Domestic Uranium Production Report: U. S. Department of Energy, Washington D. C., May 2014, 24 p.

United States Congress, 1988, Copper: Technology and Competitiveness: Office of Technology Assessment, OTA-E-367, Washington D. C., U. S. Government Printing Office, September 1988, 272 p.

Weber, D. S., Barter, C. F. and Kreis, H. G., 2000, Hydraulic Testing for Identification of Fluid Movement Patterns at Santa Cruz in In-Situ Copper Mining Research Project, Pinal County, Arizona: SME Annual Meeting, February 28 - March 1, 2000, Salt Lake City, Utah, Pre-print 00-25, 6 p.

Weeks, R. E. and Millenacker, D. J., 1988, Environmental Permitting Considerations for True In Situ Copper Mining in the State of Arizona: Society of Mining Engineers Annual Meeting, Phoenix, Arizona, January 25-28, 1988, Pre-print 88-196, 8 p.