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# Biosorption of Metal Contaminants Using Immobilized Biomass—Field Studies

By T. H. Jeffers, P. G. Bennett, and R. R. Corwin

UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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## UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

| | | | |
|---|---|---|---|
| BV | bed volume | L/min | liter per minute |
| °C | degree Celsius | m | meter |
| cm | centimeter | *M* | molar mass |
| gal | gallon | meq | milliequivalent |
| gal/min | gallon per minute | mg | milligram |
| g/L | gram per liter | mg/L | milligram per liter |
| L | liter | min | minute |
| lb | pound | pct | percent |

# BIOSORPTION OF METAL CONTAMINANTS USING IMMOBILIZED BIOMASS—FIELD STUDIES

By T. H. Jeffers,[1] P. G. Bennett,[2] and R. R. Corwin[3]

## ABSTRACT

The U.S. Bureau of Mines has developed porous beads containing immobilized biological materials such as sphagnum peat moss for extracting metal contaminants from waste waters. The beads, designated as BIO-FIX beads, have removed toxic metals from over 100 waters in laboratory tests. These waters include acid mine drainage (AMD) water from mining sites, metallurgical and chemical industry waste water, and contaminated ground water. Following the laboratory studies, cooperative field tests were conducted to evaluate the metal adsorption properties of the beads in column and low-maintenance circuits, determine bead stability in varied climatic situations, and demonstrate the beads' potential as a viable waste water treatment technique. Field results indicated that BIO-FIX beads readily adsorbed cadmium, lead, and other toxic metals from dilute waters; effluents frequently met drinking water standards and other discharge criteria. The beads exhibited excellent handling characteristics in both column and low-maintenance circuits, and continued to extract metal ions after repeated loading-elution cycles. Based on laboratory and field data, cost evaluations for using BIO-FIX technology to treat two AMD waters were prepared. Operating costs for BIO-FIX treatment, which ranged from $1.40 to $2.30 per 1,000 gal of water treated, were comparable with chemical precipitation costs.

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## INTRODUCTION

The search for new and innovative technologies to remove toxic metals from dilute waste waters has focused attention on the metal binding capacities of various biological materials. Peat moss, yeast, algae, bacteria, and various aquatic flora (*1-6*)[4] are among the hundreds of materials identified as potential metal sorbents. Although these materials have shown promise for waste water treatment applications, their use has been limited, particularly in treating acid mine drainage (AMD) waters. Biosorption systems often require the addition of nutrients, and maintenance of a healthy microbial population may be difficult because of metal toxicity. In addition, liquid-solid separation of the metal-laden biomass and treated water is cumbersome. Nonliving biomass adsorbs metals as effectively as living biomass (*7-8*), but material-handling problems such as liquid-solid separations still exist.

Researchers have recognized that immobilizing nonliving biomass in a granular or polymeric matrix improves biomass performance and eases separation of biomass from solution (*9-11*). The U.S. Bureau of Mines has pursued this approach by immobilizing biomass in porous polysulfone beads designated as BIO-FIX beads. BIO-FIX beads are prepared from readily available raw materials and can be used in conventional hydrometallurgical processing equipment such as packed and fluidized-bed columns.

Laboratory studies have demonstrated that BIO-FIX beads have considerable potential for utilizing biosorption as a waste water treatment technique (*12*). However, as previous researchers have noted, transfer of biotechnology processes from the laboratory to the field has been slow (*13*). To facilitate commercial adoption of BIO-FIX technology, field tests were conducted at four sites. A main objective of these tests was to evaluate bead performance during on-site treatment of AMD and other waste waters using commercially available column systems. A second objective was to determine the applicability of using two Bureau-developed low-maintenance systems for treating AMD waters in remote areas. To ensure credibility and successful transfer of the technology, each test was conducted in close cooperation with private industrial firms or government agencies. This work was done in support of the Bureau's goal to control and mitigate the effects of mine drainage and liquid wastes.

## BIO-FIX BEAD CHARACTERISTICS

The characteristics of BIO-FIX beads have been thoroughly documented in previous publications (*12, 14*). In summary, the beads function as cation exchangers employing an adsorption mechanism analogous to ion-exchange resins. When the beads are contacted with waters containing metal ions, the ions pass into the bead interior. As the metal ions contact active sites on the biomass, they are extracted and tightly held. This process continues until all of the active sites are occupied. At that time, the beads are contacted with a dilute acid solution that strips the metal ions from the biomass, and thus the beads are regenerated for further use.

### ADSORPTION PROPERTIES

The cation exchange capacity (CEC) of beads containing immobilized sphagnum peat moss was determined by the method of Kunin (*15*) to be 4.5 to 5.0 meq of cation per gram of dry beads. This compares favorably with ion-exchange resins, which typically have CEC's of 0.5 to 5.5. The bead adsorption kinetics are also favorable; the majority of the equilibrium sorption occurs in the first 20 min of contact. Tests also showed that the beads are most effective when treating solutions with pH's between 3 and 8, where essentially complete metal removal is usually attained.

Mining and mineral processing waste waters often contain significant amounts of calcium and magnesium ions. Many ion-exchange resins readily adsorb these ions, which decreases their capacity for the targeted heavy-metal ions. Adsorbed calcium and magnesium ions are initially extracted by BIO-FIX beads, but are steadily displaced by heavy-metal ions as the loading cycle progresses. Laboratory tests indicate that a typical metal affinity series for the beads is Al > Cd > Cu > Zn > Fe > Mn > Ca > Mg. This displacement phenomena increases the capacity of the beads for heavy-metal ions at the expense of innocuous common ions.

### ELUTION PROPERTIES

Efficient removal of loaded metal values from BIO-FIX beads is necessary to ensure the long-term use of the beads for repeated extraction-elution cycles. Mineral acids, including sulfuric, nitric, and hydrochloric, are effective eluants. Sulfuric acid is generally the eluant of choice since the sulfate matrix is more compatible with

[4]Italic numbers in parentheses refer to items in the list of references at the end of this report.

subsequent processing of metal-enriched strip solutions using chemical precipitation, evaporation, and solvent extraction techniques. Greater than 90 pct of the loaded metals are eluted in the first 15 min of contact using 20 to 30 g/L $H_2SO_4$. Following acid elution, the beads are rinsed for 20 min with a 15-g/L $Na_2CO_3$ solution to neutralize any residual acid.

### PHYSICAL PROPERTIES

BIO-FIX beads display excellent chemical and physical stability. In cyclic loading and elution tests, the beads extracted over 95 pct of the zinc, manganese, and cadmium from an AMD water for 200 load-strip cycles without any decrease in metal sorption capacity. Further evidence of bead stability was demonstrated by exposing the beads to varied climatic conditions. After 152 days of outdoor exposure, during which time the beads were repeatedly frozen, thawed, dehydrated, and exposed to sunlight, the beads showed no signs of physical deterioration or decrease in metal extraction capability. Upon rehydration or thawing, the beads continued to extract metal ions. For example, zinc and manganese extractions from an AMD water were identical for a control set of beads as well as for sets of beads exposed to the conditions described above, averaging over 96 pct.

## TREATMENT OF WASTE WATERS FROM VARIOUS SOURCES

After the basic properties of BIO-FIX beads were determined, laboratory tests were conducted on nearly 100 waste waters to determine the types of waters most applicable to BIO-FIX treatment. The waters were tested in cooperation with mining operations, consultants working with clients, and Federal and State agencies. Specific waters investigated included AMD waters from metal and coal mining operations, metallurgical processing waters such as rinse waters and filtrates from neutralizing operations, contaminated ground waters, electronic industry effluents, and waste water treatment facility effluents. The most common metal contaminants present in these waters were cadmium, lead, zinc, copper, iron, manganese, and nickel. However, up to 20 additional metals were occasionally encountered. Contaminant concentrations ranged up to about 50 mg/L, while the solution pH's ranged from 0.5 to 13. A few of the waters contained organic contaminants such as mineral oils and aromatic hydrocarbons in addition to the heavy metals. Table 1 presents a summary of these results for five waters. Analytical techniques employed for metal determinations in these and subsequent tests included graphite furnace atomic absorption and inductively coupled plasma.

**Table 1.—Metal concentrations, in milligrams per liter, before and after treatment of dilute waste waters with BIO-FIX beads**

| Type of water | Cd | Cu | Fe | Mn | Ni | Pb | Zn |
|---|---|---|---|---|---|---|---|
| AMD: | | | | | | | |
| Head . . . . . . . . . . . | 0.05 | 0.14 | 0.03 | 6.1 | 0.22 | ND | 11.0 |
| BIO-FIX effluent . . . | <.01 | <.01 | <.01 | .03 | .03 | ND | .07 |
| Ground water: | | | | | | | |
| Head . . . . . . . . . . . | ND | 1.4 | .90 | .90 | ND | 0.35 | 16.5 |
| BIO-FIX effluent . . . | ND | .11 | .02 | .04 | ND | .03 | .69 |
| Industrial water: | | | | | | | |
| Head . . . . . . . . . . . | 1.06 | .40 | <.01 | 3.62 | 16.8 | .21 | 6.5 |
| BIO-FIX effluent . . . | .03 | .01 | <.01 | <.01 | .03 | .01 | .02 |
| Plating rinse: | | | | | | | |
| Head . . . . . . . . . . . | 1.2 | .45 | 8.0 | .22 | 42.1 | .15 | 9.6 |
| BIO-FIX effluent . . . | <.01 | .02 | <.01 | <.01 | .03 | <.01 | .02 |
| Precipitate effluent: | | | | | | | |
| Head . . . . . . . . . . . | .22 | .17 | .05 | 21.6 | ND | ND | 1.7 |
| BIO-FIX effluent . . . | <.01 | <.01 | <.01 | .19 | ND | ND | .03 |
| NDWS . . . . . . . . . . . . | .01 | 1.0 | .3 | .05 | ([1]) | .05 | 5.0 |

ND Not determined.
NDWS National Drinking Water Standard.
[1]No Drinking Water Standard.

Several trends were observed during these tests. One important conclusion was that the type or source of a waste water was not an important factor affecting its treatability. As identified in earlier screening tests, the type of metal contaminants, concentrations of contaminants, and pH dictated the degree of success in treating a particular water. Heavy-metal cations were readily extracted from pH 3 to pH 8 waters, and metal concentrations were generally reduced to the low microgram-per-liter range when the initial starting concentrations were less than 50 mg/L. These effluents frequently met National Primary and Secondary Drinking Water Standards (*16*). Metals were removed from both sulfate and chloride solutions, and the presence of organics up to a level of about 50 mg/L did not hinder metal extraction. Finally, because of their ability to remove metals from very dilute solutions, BIO-FIX beads were very effective as a secondary or polishing system following primary treatment.

# FIELD TESTS

Field testing of BIO-FIX bead technology was conducted at four sites. Two contacting systems were selected for the field studies. The first system utilized standard ion-exchange columns, while the second system consisted of low-maintenance circuits developed for treating AMD problems in areas where frequent access is difficult.

## COLUMN CIRCUIT

Column tests utilizing BIO-FIX beads were conducted to treat two AMD waters. The three-column circuit consisted of a lead-load column, a scavenger column, and an elution column. Each column measured 15.0 cm ID by 138 cm high and contained 14.3 L of beads. During continuous operation, the lead and scavenger columns were loaded in series. Meanwhile, the third column, which had been loaded in an earlier cycle, was eluted. At the end of a loading cycle, the scavenger column became the lead column, the eluted column became the scavenger column, and the lead column was eluted. A schematic of the circuit is shown in figure 1.

Elution and regeneration of the loaded beads was accomplished by sequentially passing 1 BV of 30 g/L $H_2SO_4$, 1 BV of wash water, and 1 BV of 15 g/L $Na_2CO_3$ through the column. Acid displaced from the column was saved as the product eluate, while the displaced rinse water and sodium carbonate solutions contained only minor amounts of metal and were later reprocessed with the feed waste water.

### Treatment of Taconite Operation Water

The first field test with the column circuit was conducted to remove several metals from a pH 5.5 AMD water emanating from sulfide waste rock piles at a taconite operation. The water contained, in milligrams per liter, 3.4 Ni, 0.18 Co, 0.06 Cu, and 0.21 Zn. Because of the proximity of this site to several lakes and important recreational areas, stringent discharge requirements ranging from 0.13 mg/L Ni to only 0.01 mg/L Co were imposed by state regulatory agencies.

Over 1,200 gal of water were processed during the field test to determine the effects of solution flow rate and solution volume per cycle on effluent quality. Total solution resident time in the loading columns (lead and scavenger columns) ranged from 14.2 to 43.4 min, and 30 to 70 BV of solution were processed each cycle. A summary of results for several cycles is presented in table 2.

**Table 2.—Metal adsorption from taconite AMD water**

| | Residence time, min | Volume treated, BV per cycle | Metal concentration, mg/L | | | |
|---|---|---|---|---|---|---|
| | | | Ni | Co | Cu | Zn |
| AMD head | NAp | NAp | 3.4 | 0.18 | 0.06 | 0.21 |
| Effluent | 15 | 40 | .33 | .06 | .03 | .10 |
| | 20 | 40 | .03 | .01 | .02 | .01 |
| | 20 | 50 | .03 | .01 | .03 | .01 |
| | 30 | 70 | .18 | .03 | .02 | .03 |
| Discharge criteria | NAp | NAp | .13 | .01 | .03 | .05 |

NAp Not applicable.

The results show that all discharge criteria were achieved when 40 to 50 BV of solution were processed per cycle and the total solution residence time was 20 min. Over 98 pct of the targeted metals were extracted in cycles conducted at these conditions. The results were especially encouraging since the temperature of the water processed was only 1° to 3° C and the air temperature was at or below freezing during the tests. When the residence time was decreased to 15 min or the volume of water was increased to 70 BV per cycle, 86 to 93 pct of the metals were still extracted, but effluent quality deteriorated.

Product eluates produced during the test contained metal concentrations as great as 150 times those of the initial feed concentrations. These eluates were further processed by precipitating the metals with magnesium oxide or evaporating the eluate to yield a residue. Precipitation produced approximately 1.3 lb of precipitate per 1,000 gal of waste water processed, while evaporation produced 0.9 lb of residue per 1,000 gal of waste water. These residues consisted primarily of magnesium and

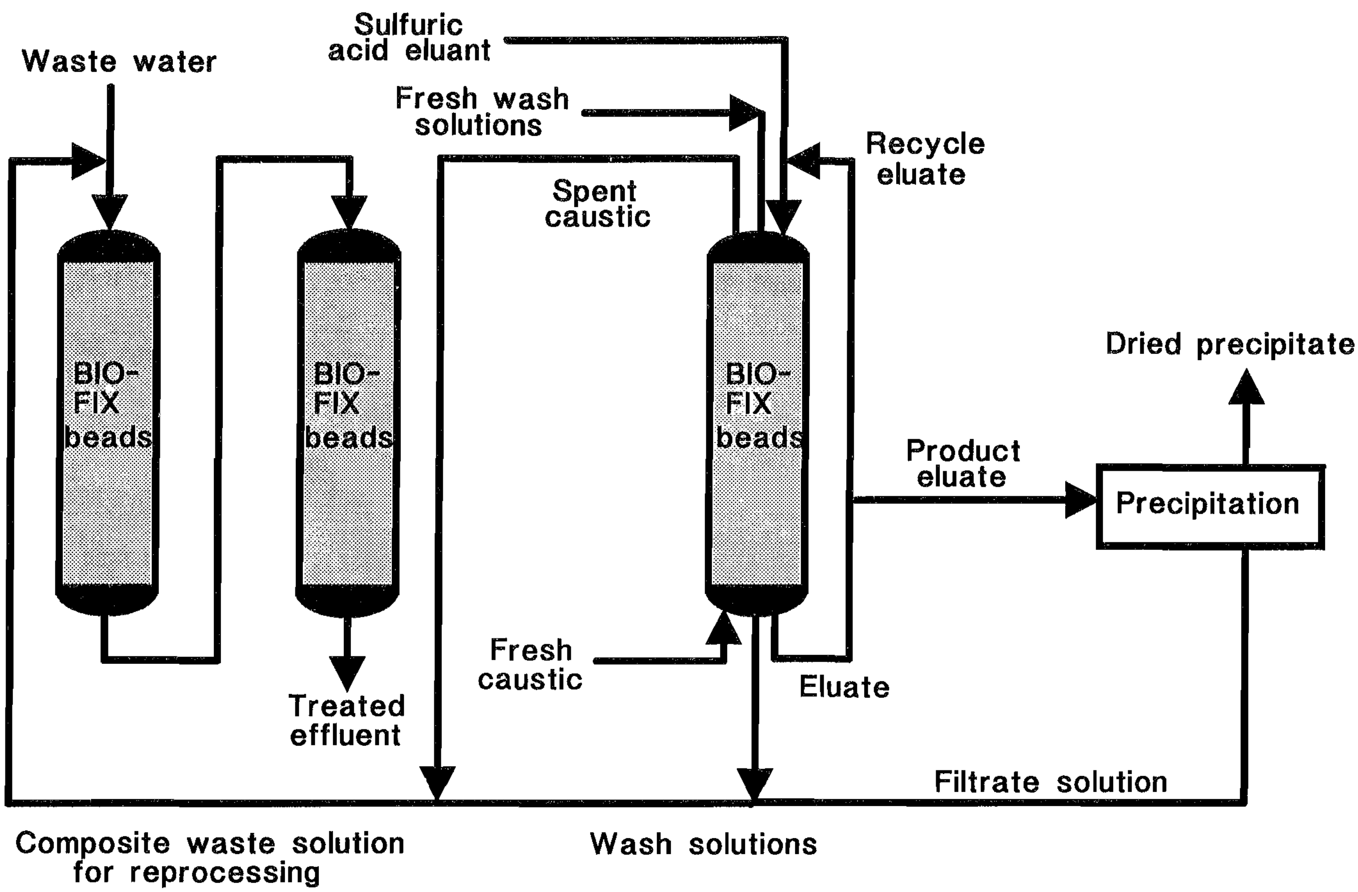


**Figure 1.—Schematic of continuous BIO-FIX bead column circuit.**

calcium sulfates, while nickel, cobalt, copper, and zinc constituted only 2 to 3 pct of the total weight. The filtrate solution from the precipitation procedure was returned to the column circuit for reprocessing.

Subsequent to the field operation, a private environmental firm, working in cooperation with the Bureau, operated a BIO-FIX column circuit at the same site for about 3 months. The circuit employed three columns containing 284 L of beads per column. Operating parameters were similar to those employed during the earlier Bureau test, i.e., 40 BV of solution were processed per cycle, and the total solution residence time in the loading columns was about 20 min. During the pilot-plant campaign, over 3.8 million L of water were processed, and the discharge criteria for nickel, cobalt, copper, and zinc were consistently achieved. The results were essentially identical to the Bureau's results, and verified that BIO-FIX technology is a viable treatment technique for this AMD water.

### Treatment of Zinc Mining Operation Water

The three-column circuit was also utilized to remove zinc, iron, and manganese from AMD water at an active zinc mining operation. The pH 6 water contained, in milligrams per liter, 18 to 24 Zn, 18 to 36 Fe, and 22 to 28 Mn. The mine operators treat about 2 million gal of AMD water per day at this site by lime precipitation. This treatment produces large volumes of sludge and yields effluents that frequently exceed the zinc discharge requirement of 0.75 mg/L Zn. Currently, no specific criteria are required for iron or manganese at this location.

Laboratory studies in a BIO-FIX bead column circuit prior to the field test indicated that effluents met the zinc discharge standard when 60 BV of water were processed per cycle and the solution residence time was 5 to 8 min in each column. In addition, iron and manganese effluent concentrations were reduced to $<0.5$ mg/L. However, during the processing of over 15,000 L of solution in the field, the water contained heavy loads of suspended solids including precipitated iron and finely ground ore. When the columns were operated in a downflow mode, the suspended solids packed the interstitial spaces between the beads, and channeling of the solution resulted. Upflow operation of the circuit was possible, but heavy ore particles inhibited effective fluidization of the beads. As a result, the zinc discharge requirement was achieved for only 15 to 20 BV of solution per loading cycle. Average metal extractions for 20 BV of water were 90 to 95 pct for zinc, iron, and manganese, but dropped to 50 to 60 pct for each metal when 40 BV were processed per cycle. Previous laboratory and field tests had indicated that solutions containing up to 3 pct solids could be processed with BIO-FIX beads in column circuits. However, the solids encountered in those cases were finely disseminated precipitates, primarily iron hydroxides. Although the quantity of suspended solids in the current field work were within the permissible operating range, the heavier ore particles could not be handled, and effective column operation was not achieved.

## LOW-MAINTENANCE CIRCUIT

Many AMD sites consist of numerous small seeps scattered over remote areas that discourage deployment of an active treatment system with its associated labor costs and logistics problems. Often the seep flows are cyclic and periodically dry up. Typical flow rates may vary from 5 to 50 gal/min. To address this problem, two low-maintenance systems were developed. These systems utilize porous bags of BIO-FIX beads placed in a trough or bucket circuit through which the AMD water flows by gravity. Individual systems are placed at each seep, and loaded bags are periodically removed and replaced with fresh bags of BIO-FIX beads. The bag replacement frequency is dependent upon the solution's metal concentration and flow rate.

Most of the seeps intended for treatment with a trough system are situated so that a hydraulic gradient is present. The trough system utilizes the hydrostatic head of the waste water to force water down and then up through consecutive BIO-FIX bags as it progresses down the trough. As water flows up through the bags, the beads are fluidized, ensuring complete contact of solution and beads. The flow of the waste water is countercurrent to the replacement of BIO-FIX bags. Periodically the bag at the head of the trough, which is the bag most fully loaded with metals, is removed from the system, leaving a vacant cell. The bag immediately below is moved up into the vacant cell. This procedure is repeated for each of the cells until a bag of freshly eluted beads is positioned into the last cell. The bags in the end of the trough act as scavenger bags to ensure complete removal of any residual metal ions. A simplified sketch of the trough system is depicted in figure 2.

The bucket system works in a similar manner. Beads are enclosed in cylindrical polypropylene bags and are placed in tightly sealed buckets. The buckets are connected by flexible plastic hose and water flows down a gradient from bucket to bucket and up through each bag of beads. Distribution plates are placed in the buckets to ensure uniform contact of beads and waste water. This configuration, shown in figure 3, essentially imitates a series of small columns. The procedure for periodically removing and regenerating the beads is similar to that used for the trough system.

An important consideration in utilizing BIO-FIX beads in porous bags was selection of a suitable bag material. Several potential materials were evaluated to determine physical strength, chemical resistance to acid and caustic solutions, and wetting characteristics. Polymax B,[5] a fine-mesh filter media woven from polypropylene fibers, met all the above criteria. Bags fabricated from Polymax filter media were resistant to tearing, freeze and thaw conditions, and sunlight, and no decrease in strength was noted after immersion in 1*M* $H_2SO_4$ or 1*M* $Na_2CO_3$.

### AMD Water—Abandoned Silver Mine

The first field test using a low-maintenance system was conducted in cooperation with the U.S. Forest Service to remove iron from a pH 6.5 water draining an abandoned silver mine. Although the water flow rate was only about 1 L/min, the water was targeted for remediation since it flowed directly into a small stream used as a source of drinking water for a local community. In addition, iron precipitates had accumulated to a depth of several centimeters near the mine entrance and inhibited growth of vegetation in the vicinity. Because of seasonal changes, the iron concentration of the water ranged from 20 to 60 mg/L, while the discharge standard was 1 mg/L Fe. The trough employed at this location consisted of 16 compartments containing a total of 96 L of beads. The trough measured 2.1 m long by 0.3 m wide by 0.3 m high. During the 11-month test, 2,300 L of beads were removed, regenerated, and placed back in the trough, and approximately 450,000 L of water were treated. In spite of heavy snows and cold temperatures experienced during the test, the only problem encountered was failure of a caulking material used to position the individual weirs in the trough. After correcting this problem, the iron discharge requirement was consistently achieved. In addition, the beads filtered out precipitated iron, and a clear effluent was produced.

### AMD Water—Abandoned Zinc Mine

A second long-term field test was conducted using both the trough and bucket systems to treat a pH 4.1 water emanating from an abandoned adit. The mine water contained, in milligrams per liter, 0.05 Cd, 1.5 Cu, 5.5 Fe, 0.06 Pb, and 5.5 Zn, and flowed at a rate of about 100 gal/min. Cooperating agencies for this test included the U.S. Forest Service, the State of Utah, and several local environmental agencies. The immediate area is

[5]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

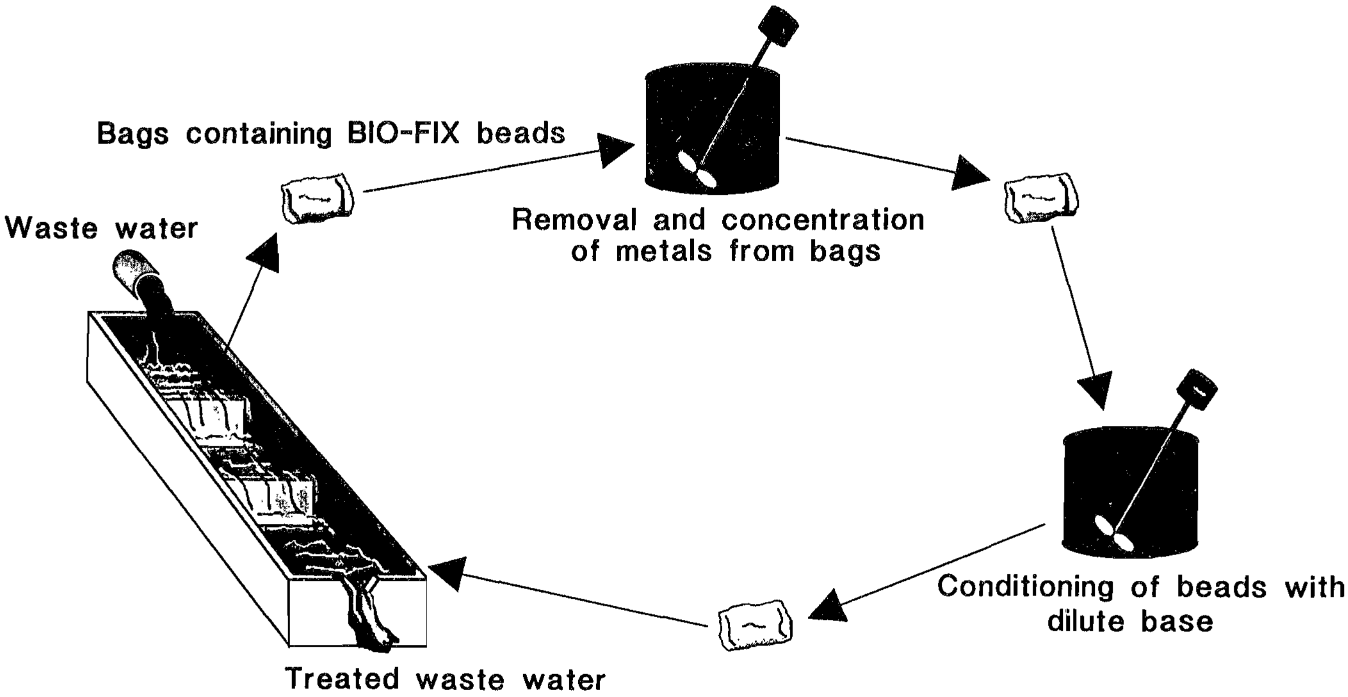


Figure 2.—Low-maintenance trough system.

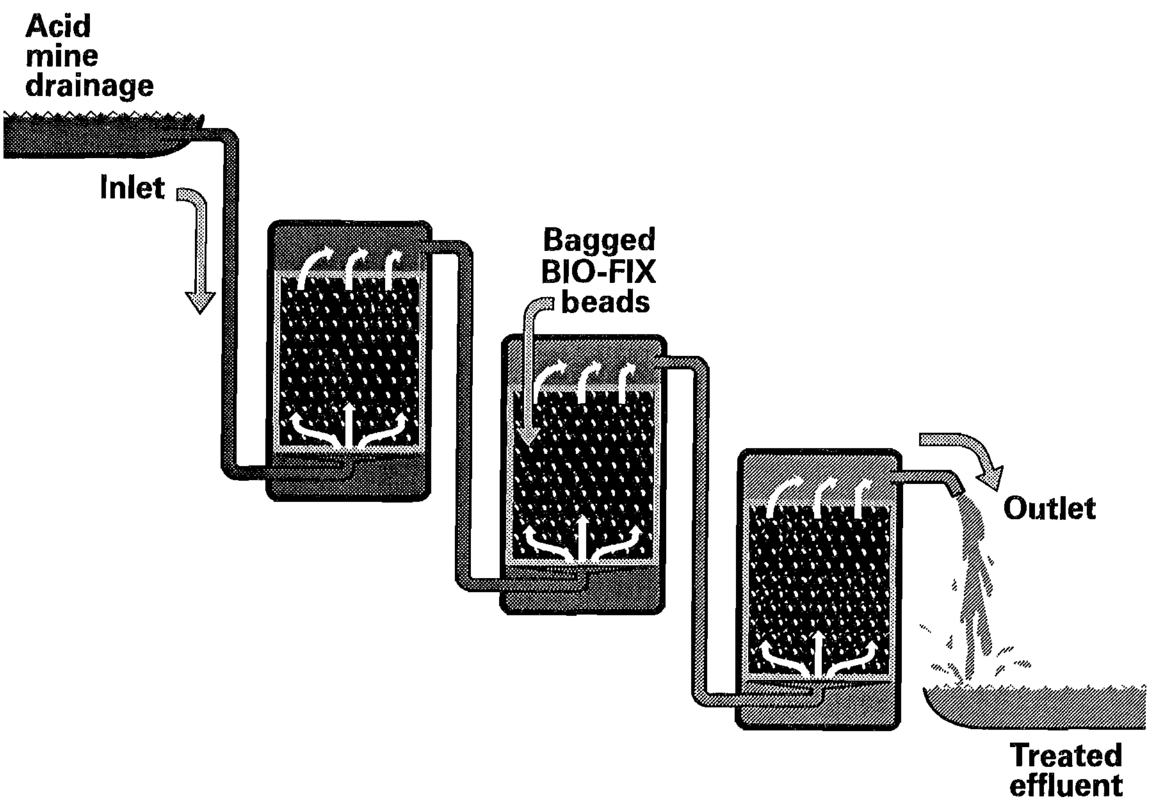


Figure 3.—Low-maintenance bucket system.

mountainous and sustains heavy recreational use. Iron compounds have precipitated along the creek, detracting from the area's aesthetic value, while the heavy metals have impacted aquatic wildlife. The water is also used as a source of drinking water.

During the first 3 months of the test, the trough employed at this site consisted of 16 compartments containing a total of 88 L of BIO-FIX beads, while the bucket system utilized 8 bags of beads containing 11 L of beads each. The solution flow rate to each circuit was identical, and was varied from 0.3 L/min to 1 L/min to determine the effect of flow rate on adsorption efficiency. The bead replacement frequency was also identical for both systems. Fifty percent of the beads were removed from each circuit and regenerated once weekly. A total of 150,000 L of water were treated during this phase of the testing.

In the second test phase, the bead replacement rate was varied. During this period, the trough and bucket systems each contained 66 L of beads, and the flow rate to each circuit was 0.4 L/min. Initially, 33 pct of the beads were removed from each circuit once a week, and later, 33 pct of the beads were replaced once every 2 weeks. About 28,000 L of water were treated while investigating this parameter. Results of the flow rate and bead replacement rate tests are summarized in table 3. Results shown represent averages obtained during a period of several months.

Effluent analyses indicated that both low-maintenance systems removed significant amounts of the targeted metals. All drinking water standards were met for each circuit at flow rates of 0.3 or 0.5 L/min when 50 pct of the beads were replaced once a week. Aquatic wildlife standards were met for iron and lead in each circuit, and the bucket system met the aquatic standard for copper. Little difference in effluent quality was noted between flows of 0.3 or 0.5 L/min. An average of 85 to 89 pct of the metals were adsorbed at each flow. However, effluent quality deteriorated, and only 48 to 57 pct of the metals were adsorbed when the flow rate was increased to 1 L/min.

Performance in both circuits was adversely affected when the bead replacement interval was increased to once every 2 weeks. At a flow rate of 0.4 L/min, over 85 to 88 pct of the metals were removed by beads in each circuit at a 1-week interval, and drinking water standards were achieved for cadmium, copper, lead, and zinc. By contrast, only 68 to 81 pct of the heavy metals were adsorbed at a 2-week replacement interval, and drinking water standards were met for only copper, lead, and zinc.

No definitive conclusion was reached regarding the relative effectiveness of the two circuits. Although some differences in effluent quality were obtained in tests at similar conditions, overall metal adsorption rates were similar. For example, at a flow rate of 0.5 L/min, the respective adsorption rates of the trough and bucket circuits were 90 and 91 mg of metal per liter of beads per day.

Product eluates produced during the low-maintenance tests were subjected to precipitation with magnesium oxide. Although the waste water flow rates and bead replacement frequencies varied, 1.5 to 1.6 lb of dried precipitate were obtained per 1,000 gal of waste water treated. The precipitates consisted mainly of magnesium and calcium sulfates, and approximately, in percent, 6 Fe, 5 Cu, 10 Zn, and 1 Cd and Pb.

**Table 3.—Metal adsorption using low-maintenance circuits**

| | Flow rate, L/min | Bead replacement interval, weeks | Metal concentration, mg/L: Cd | Cu | Fe | Pb | Zn |
|---|---|---|---|---|---|---|---|
| AMD head | NAp | NAp | 0.047 | 1.5 | 5.5 | 0.057 | 5.5 |
| Drinking water standard | NAp | NAp | .01 | 1.0 | .3 | .05 | 5.0 |
| Aquatic wildlife standard | NAp | NAp | .001 | .012 | 1.0 | .003 | .1 |
| PHASE 1[1] | | | | | | | |
| Trough effluent | 0.3 | 1 | 0.006 | 0.081 | 0.06 | 0.001 | 1.2 |
| | .5 | 1 | .007 | .067 | .10 | .001 | 1.4 |
| | 1.0 | 1 | .017 | .27 | .81 | .015 | 4.3 |
| Bucket effluent | .3 | 1 | .004 | .005 | .06 | .001 | 1.8 |
| | .5 | 1 | .003 | .001 | .10 | .001 | 1.4 |
| | 1.0 | 1 | .022 | .49 | 1.3 | .025 | 4.7 |
| PHASE 2[2] | | | | | | | |
| Trough effluent | 0.4 | 1 | 0.003 | 0.02 | 0.88 | 0.001 | 1.0 |
| | .4 | 2 | .017 | .44 | 1.3 | .008 | 2.3 |
| Bucket effluent | .4 | 1 | .003 | .02 | .09 | .001 | 1.4 |
| | .4 | 2 | .012 | .03 | .2 | .001 | 2.1 |

NAp Not applicable.
[1]Flow rate was varied.
[2]Bead replacement interval was varied.

# PROCESS ECONOMICS

Preliminary economic evaluations for using BIO-FIX beads to remediate two AMD waters were prepared by the Bureau's Process Evaluation Group. One water (designated LDT) containing 3.5 mg/L Zn, 2.3 mg/L Mn, and 0.02 mg/L Cd had a pH of 6.9 and flowed at an average rate of 1,706 gal/min. The second water (designated SKG) containing 11.3 mg/L Zn, 6.4 mg/L Mn, and 0.06 mg/L Cd had a pH of 3.8 and had an average flow rate of 260 gal/min. Treatment plants for both waters were designed to remove over 98 pct of the metal contaminants and produce effluents containing <0.05 mg/L Zn, <0.05 mg/L Mn, and <0.01 mg/L Cd. Data utilized to design the treatment plants were generated in the field and during extended laboratory processing of the subject waters. Both plants utilized a three-column BIO-FIX bead circuit as described in the "Column Circuit" section. Operating procedures regarding waste water flow rate, water processed per cycle, and bead elution and regeneration were also similar to those described in earlier sections.

## CAPITAL COSTS

The capital cost estimate was of the general type called a study estimate by Weaver and Bauman (*17*). This type of cost estimate is usually within 30 pct of the cost to build the described plant; however, factors such as changes in material costs can have a significant impact on the accuracy. Capital costs included fixed capital such as the BIO-FIX beads and processing equipment, as well as working capital and startup costs. The estimated total capital cost for an operation to treat the LDT water was $3.37 million, based on third quarter 1991 costs (Marshall and Swift index of 935.1). The total capital cost for a plant to treat the SKG water was $0.61 million, again based on third quarter 1991 costs.

## OPERATING COSTS

Operating costs were based on 365 days of operation per year and included direct, indirect, and fixed costs. Specific items addressed were raw materials, utilities, labor, maintenance, payroll overhead, taxes, insurance, and depreciation. The estimated annual operating cost for a plant treating the LDT water was $1.26 million, or $1.40 per 1,000 gal of water treated. Annual operating costs for a plant treating the SKG water were $0.30 million, or $2.31 per 1,000 gal of water. The discrepancy in the costs for the two waters was due to the scale of operation. For comparative purposes, the estimated operating costs for facilities treating waters similar to the LTD water using conventional lime precipitation are $1.00 to $1.50 per 1,000 gal (*18*). Thus, the BIO-FIX bead cost of $1.40 per 1,000 gal is competitive with existing precipitation practice.

# SUMMARY AND CONCLUSIONS

Field tests demonstrated that BIO-FIX beads are a viable treatment option for removing toxic metals from AMD waters. In laboratory tests, the beads also proved effective for treating metallurgical processing waters, rinse waters, waters from neutralizing operations, and contaminated ground waters. Drinking water and aquatic wildlife standards were frequently met, and treated effluents generally contained <0.05 mg/L of the targeted metals. A three-column circuit utilizing equipment and techniques currently employed in ion-exchange operations was effective for BIO-FIX bead use. Conditions were established that resulted in >90 pct extraction of the heavy metals in contact times of 20 min or less. The only significant problem encountered during field operations was a heavy load of finely ground ore particles in one water. In this situation, the beads continued to adsorb metals, but column operation was hindered, and the bead loading capacity was diminished.

Two low-maintenance systems developed by the Bureau showed potential for treating low-flow AMD waters in remote areas. Although weekly maintenance of the systems was required, no external power was supplied, and the systems removed >85 pct of several toxic metals in areas subject to heavy snows and cold temperatures. Drinking water standards were frequently met for cadmium, copper, iron, lead, and zinc. These systems appear best suited for treating low-flow AMD waters in remote areas. Data indicated that low-maintenance systems could be designed for less frequent maintenance, depending on the volume of beads employed and metal concentrations of the water.

Field data obtained during operation of the column circuits were used in conjunction with laboratory data by the Bureau's Process Evaluation Group to determine estimated costs for two BIO-FIX bead treatment plants. Operating cost for a plant treating 260 gal/min of a zinc-manganese-cadmium AMD water was $2.31 per 1,000 gal of water treated. The cost dropped to $1.40 per 1,000 gal for a plant designed to treat 1,700 gal/min of a zinc-manganese-cadmium AMD water. These costs compare favorably with estimated costs for lime precipitation plants treating similar waters.

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