

METALS TREATMENT AT SUPERFUND SITES BY ADSORPTIVE FILTRATION

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FOREWORD

The Superfund Innovative Technology Evaluation (SITE) Program was authorized in the 1966 Super-fund Amendments. The purpose of the Program is to assist the development of hazardous waste treatment technologies necessary to implement new cleanup standards which require greater reliance on permanent remedies. A key part of EPA's effort is its research into our environmental problems to find new and innovative solutions.

The Risk Reduction Engineering Laboratory (RREL) is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community,

The SITE Program is part of EPA's research into cleanup methods for hazardous waste sites around the nation. Through cooperative agreements with developers, alternative or innovative technologies are refined at the bench-and pilot-scale level then demonstrated at actual sites. EPA collects and evaluates extensive performance data on each technology to use in remediation decision-making for hazardous waste sites.

This report documents the University of Washington's studies of the use of adsorptive filtration for removing inorganic contaminants from the liquid phase. The research project assessed the ability of coated sand media to remove soluble and particulate metals simultaneously and the ease with which the media could be regenerated.

Copies of this report can be purchased from the National Technical Information Service, Ravensworth Bldg., Springfield, VA, 22161, 703-487-4600. You can also call the SITE Clearinghouse hotline at 1-800-424-9346 or 202-382-3000 in Washington, D.C. to inquire about the availability of other reports.

E. Timothy Oppelt, Director
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INTRODOCTION

This project evaluated an inexpensive, innovative approach for removing inorganic contaminants from the liquid phase at Superfund sites. In the process, called adsorptive filtration, metals are collected by attachment to a thin layer of ferrihydrite (iron oxide) that has been immobilized on the surface of sand grains. Since iron oxide is known to be a good adsorbent for heavy metals, it was hoped that the modification of the surface of the sand would allow the grains to adsorb soluble heavy metals as they passed through a column packed with the media. At the same time, it was anticipated that the grains would perform comparably to plain sand as a filter media for collecting particulate metals. Finally, for the system to be effective, it would have to be easily regenerated. That is, once the media was saturated with metals, it would have to be possible to release and concentrate the metals for further processing and, possibly, recovery.

The research project characterized various aspects of the adsorptive filtration process. Specifically, the goals of the research were to assess the ability of the coated sand media to remove soluble and particulate metals simultaneously as water containing those species passed through a column packed with iron oxide coated sand, and to assess the ease with which the media could be regenerated. In this report, the technology is described in a general way, and then the results of the experimental, pilot-scale program to test the technology's applicability Superfund remediation efforts are presented.

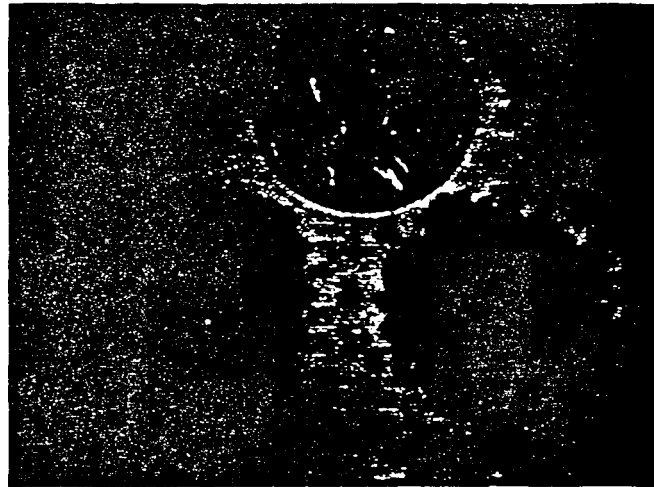
TECHNICAL DESCRIPTION OF THE TECHNOLOGY

Conventional technology for removing metals from solution involves precipitation of the metals as oxides, hydroxides, or sulfides, and then separation of the particulate metals by settling, usually aided by a coagulant such as iron hydroxide. This approach has several practical limitations, some of which are exacerbated when the metals are present in complex matrices such as commonly is the case for solutions at Superfund sites. Among these limitations are that precipitation is ineffective if the metals are complexed or if they are present as anions (e.g., CrO_4 , SeO_3 , AsO_4), and that those metals which do precipitate may form small particles that do not settle readily. As a result, large settling basins may be required to collect the metals, usually followed by a sludge thickening operation. Additionally, polymeric coagulant aids are frequently required for solids separation to be effective.

Adsorption is the binding of chemical species on the surface of suspended particles. If the adsorbent (solid surface) is chosen carefully and the solution chemistry is adjusted appropriately, adsorption-based

Despite the high affinity of ferrihydrite for metals, its use as an ion exchange medium has not been **successfully** developed because its physical properties (it is a bulky, flocculant material with extremely low hydraulic conductivity) are not conducive to such a process. To overcome these problems, a means was developed by which the ferrihydrite could be coated onto the surface of sand.* Simply precipitating ferrihydrite in the presence of sand generates a partial coating, but this coating is very thin and patchy, and it is relatively easily lost by abrasion or acid attack. However, a much more concentrated and resilient ferrihydrite coating can be produced by mixing sand with an acidic, iron-containing solution, and heating the mixture to complete dryness. Photographs of the uncoated sand used in the current study and of a typical batch of coated sand at various magnifications are shown in Plates 1 through 3. Once the coated sand grains are rinsed, the coating is stable to the mild abrasion that is typically encountered during filter backwashing, and it is very resistant to acids.

'Plate 1. Visual appearance of the uncoated and coated sand.



When the coated sand is placed in a column and a solution containing metals is passed through it, the ferrihydrite can adsorb the dissolved metals rapidly and efficiently. That is, the ion exchange properties of the iron oxide remain viable during the coating process, though the ion exchange capacity of coated ferrihydrite is reduced compared to that of ferrihydrite in a freely suspended state. The loss of this ion exchange capacity is at least partially offset by the fact that, at the same time that the surface of the coated sand is acting as an ion exchanger, the bulk media can perform the function of **a normal** granular media sand filter, i.e., it can remove precipitated metals and other particulate matter.

After some period of time, either the coating reaches its maximum capacity to remove metals or the filter requires backwashing. At this time, an acidic backwashing solution can be applied to recover the metals from the column and regenerate the column for further use. Because the ferrihydrite is trapped on the sand particles, only the contaminant metals and not the ferrihydrite are released. Thus, the need to dispose of large amounts of iron oxide with the metal sludge, one of the main drawbacks of **a** conventional treatment process, is eliminated. Furthermore, the regeneration solution could potentially be used repeatedly, so that over time the metals concentrations in it build up to quite high values, making subsequent metal recovery an economic possibility.

In sum, there are six essential **aspects of adsorptive** filtration that combine to make it **a** potentially valuable and widely applicable technology:

- Ferrihydrite is **a** strong metal adsorbent that can be regenerated by changing pH.
- * Ferrihydrite can be coated onto sand, retaining much of its ion exchange activity.
- * Ferrihydrite can adsorb some metal complexes that are not removed from solution by conventional precipitation.
- * Many metal oxyanions that cannot be treated by conventional precipitation can adsorb onto ferrihydrite.
- A column of coated sand acts as a filter as well as an adsorbent.
- The technology appears to be applicable over **a wide** range of contaminant concentrations.

METHODOLOGY

The project consisted primarily of pilot-scale testing of the ferrihydrite-coated sand. The experiments performed addressed the kinetics of adsorption and regeneration, the adsorption capacity of the media for both soluble and particulate metals, the effects of various organic contaminants on metals removal by the media, the long-term stability of the adsorbent, and the metal concentrations achievable in the

Finally, as noted above, a few tests were run with a solution collected from a Superfund site where conventional treatment is currently being applied.

General Procedures for Column Tests

The central component of the test apparatus a set of **Plexiglas** columns filled with iron oxide coated sand. The columns were 1.8 cm ID by 120 cm high. They were packed to a depth of 88 cm, so that each contained 250 mL (bulk volume) of the coated sand. The rest of the pilot-scale set-up consisted of automated instruments for maintaining pH of the influent water, pumping water through the column, and regenerating the column at fixed intervals. A schematic diagram of the experimental setup is shown in **Figure 1**. Samples were collected automatically at frequent intervals and were analyzed for metal content. In some cases, soluble and particulate metals were distinguished, based on filtration through a membrane filter with 0.45 μm pores (Millipore type HA). Headloss across the bed was also monitored.

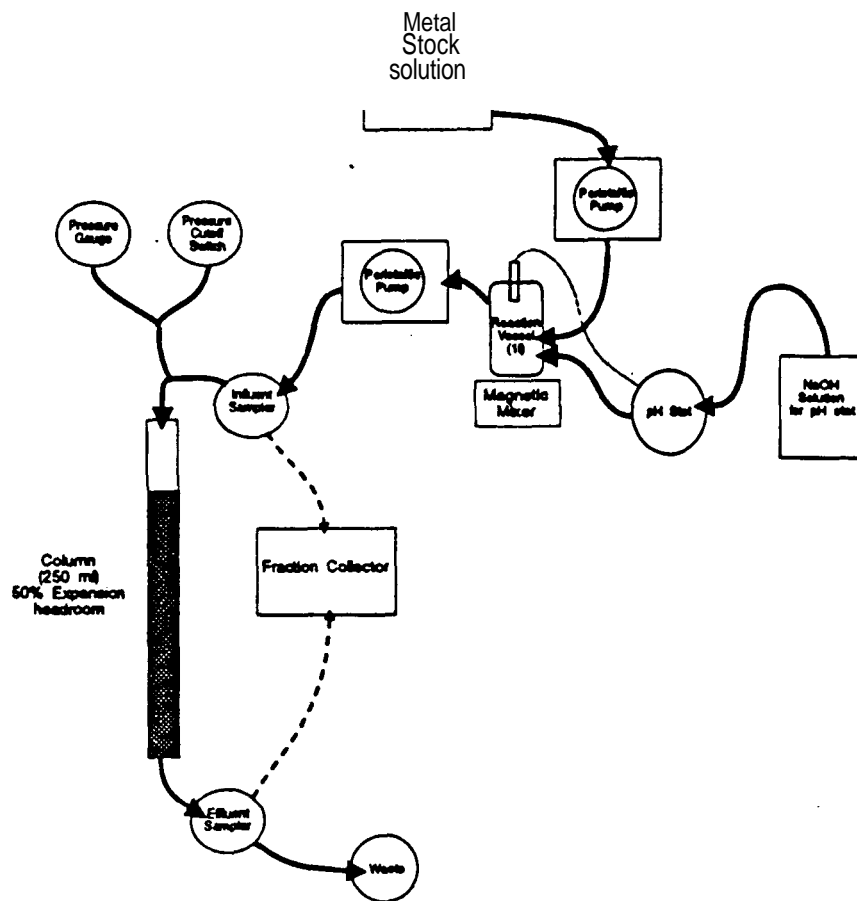


Figure 1. Schematic of setup used to determine breakthrough **curves** for the synthetic waste runs.

Terminology

For the purposes of this report, a single 'run' is defined as the period between any two regeneration steps. The columns were sometimes, but not always, backwashed in the middle or at the end of a run. In those cases where the column was backwashed one or more times during a single run, the **influent** solution that entered the column between backwashing steps is referred to as a 'batch' of influent. Thus, in some runs, only one batch of influent was treated (the column was backwashed and regenerated at the end of one treatment cycle), and, in others, several batches of influent were treated (the column was backwashed after each treatment cycle, but was not regenerated until several treatment cycles had been completed).

System Performance in Runs with Solutions Containing Only One Metal

The packed columns were used in several adsorption tests with influents containing only a single metal (Cd, Cu, or Pb) at a concentration of 0.5 **mg/L**, which was almost all soluble in all cases.

Media Capacity

The results from several runs investigating the effect of solution pH on sorption capacity are summarized in Table 2, and typical breakthrough curves for influents with 0.5 **mg/L** of a single metal are presented in Figures 2 through 4. The total amounts of metal adsorbed at the points of 50% breakthrough and at the end of the run are included in Table 2 and are typically several hundred to a few thousand mg of metal per liter of packed bed. The gross density of IOCS in the packed bed was 1670 g/L, so 1000 mg of metal per liter of packed bed corresponds to 600 mg of metal per kilogram of IOCS. The adsorption density can then be computed based on the iron content of the media, given in Table 1; 1000 mg of metal per liter of packed bed corresponds to 28 mg/g of Fe for Media I and 19 mg/g Fe for Media II.

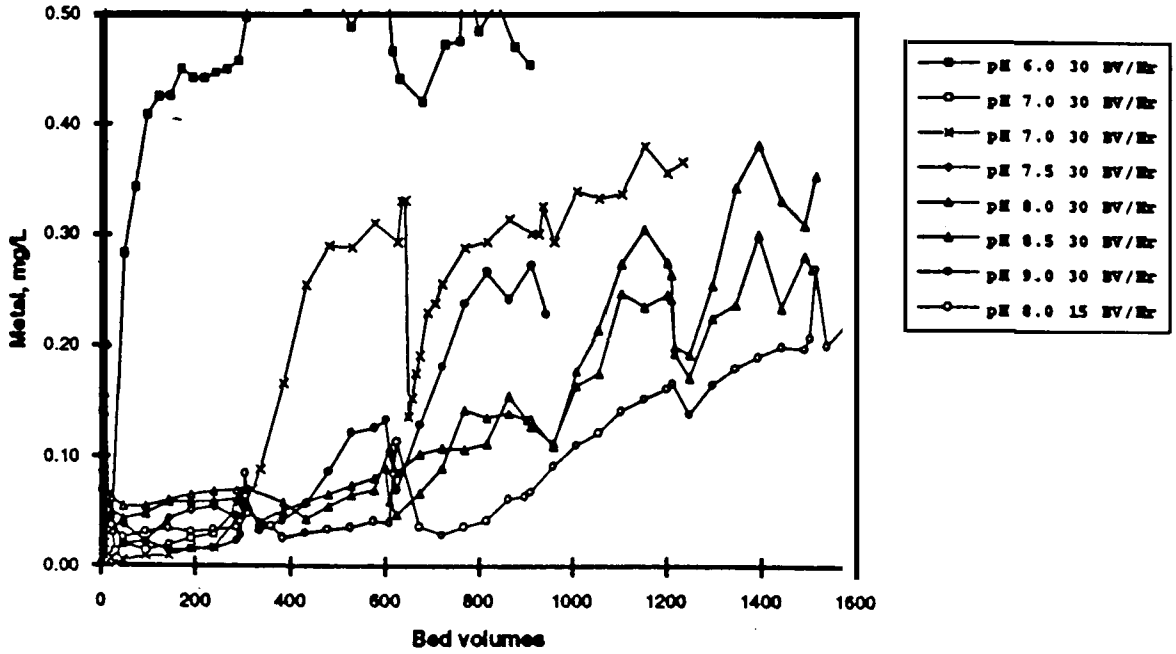


Figure 2. Breakthrough curves for 0.5 mg/L copper influent showing total metal in effluent as a function of bed volumes of water treated at various pH values. Several flow rates were used as indicated in legend.

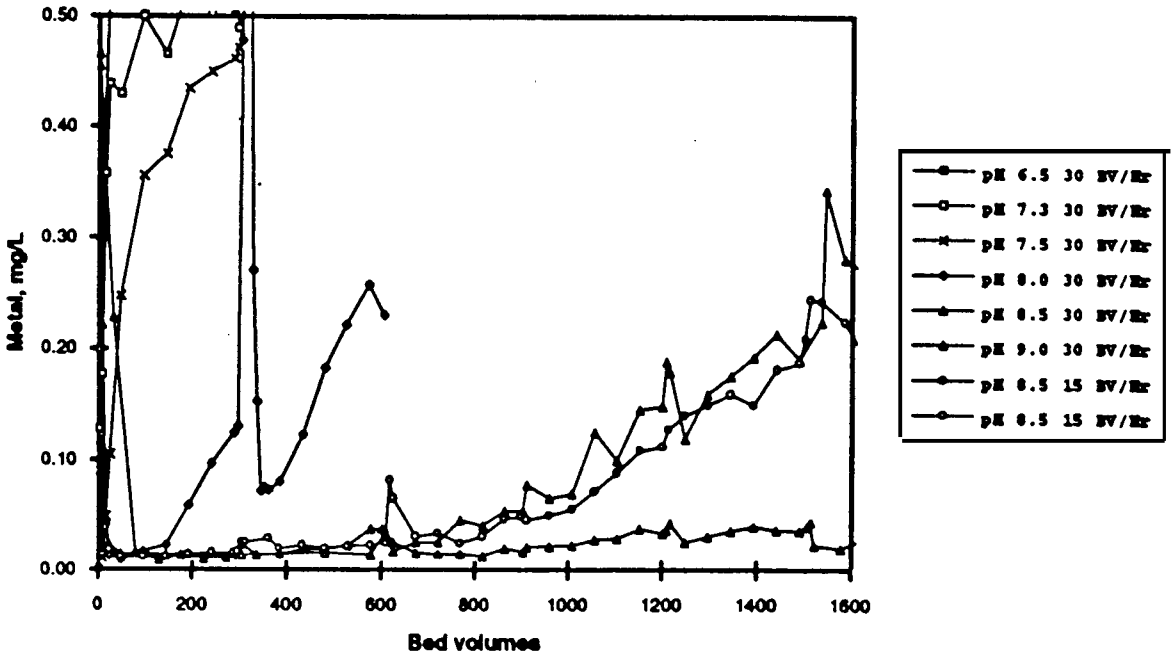


Figure 3. Breakthrough curves for 0.5 mg/L cadmium influent showing total metal in effluent as a function of bed volumes of water treated at various pH values. Several flow rates were used as indicated in legend.

steadily from pH 6.5 to pH 8.0, and then decreased again when pH was increased to 6.5 **and 9.0**. For Cd, capacity increased steadily to pH 6.5. When the pH was increased to 9.0, adsorption of Cd onto the walls of the plastic influent container prevented any significant amount of Cd from entering the column, so pH 6.5 was chosen as the highest value to study in this phase of testing. Sorption of Pb was quite good at pH 7.0, **and no** systematic variation of pH was conducted for the Pb runs.

Regeneration Kinetics

Several tests were conducted in association with these runs to evaluate regeneration kinetics. In these tests, regeneration consisted of recirculating 500 mL (2 empty bed volumes) of a pH 2.0 solution through the column for 30 minutes and analyzing the metal concentration in the solution every 5 minutes. This was followed by passing another 500 mL of pH 2.0 solution through the column in a single pass. After each 100 mL of this solution passed through the column, a subsample was collected and analyzed. **The** results for one such run for each metal are shown in Figures 5 and 6.

The metal concentration in the recirculation fluid increased rapidly at first and then only slowly thereafter. Based on these results, **it** appears that, if time were critical, a recirculating period as short as 10 minutes would release **a large** fraction of the available metal. Similarly, any releasable metal remaining on the media **after the first** step was released to the first 100 mL of the next batch of pH 2.0 fluid passing through the column.

Although the performance of the system during this set of experiments indicated that the media had substantial capacity to remove soluble metals, the capacity was somewhat smaller than hoped for, **and**, as noted above, **a** different batch of media (Media II in Table 1) was used in the remainder of the testing.

System Performance in Runs with Cu, Cd, and Pb Present in Influent

System s with 0.5 mg/l Cu, Cd, and Pb

In the first runs with Cu, Cd, and Pb present simultaneously in the influent, all at a concentration of 0.5 mg/L, the influent was adjusted to pH 8.5 and was fed at a rate corresponding to a 2-min **empty** bed detention time. However, the effluent pH fluctuated **significantly** and often dropped below 8.0 due to exchange of H⁺ ions for the adsorbing metal ions. When the influent pH was adjusted to 9.0, the effluent pH was stable and near that of the influent, and 7000 bed volumes of influent were treated effectively (Figure 7). The metal concentrations in the effluent were increased gradually during the run, with virtually no short-term fluctuations. Headloss was usually under 5 psi at the beginning of a run and increased gradually thereafter. When the headloss reached around 10-13 psi, the column was backwashed to removed particulate matter that had been trapped. This process was successful, in that the pressure drop through the column was reduced after backwashing and the metal removal efficiency was at least as good, and often better, after backwashing compared to before.

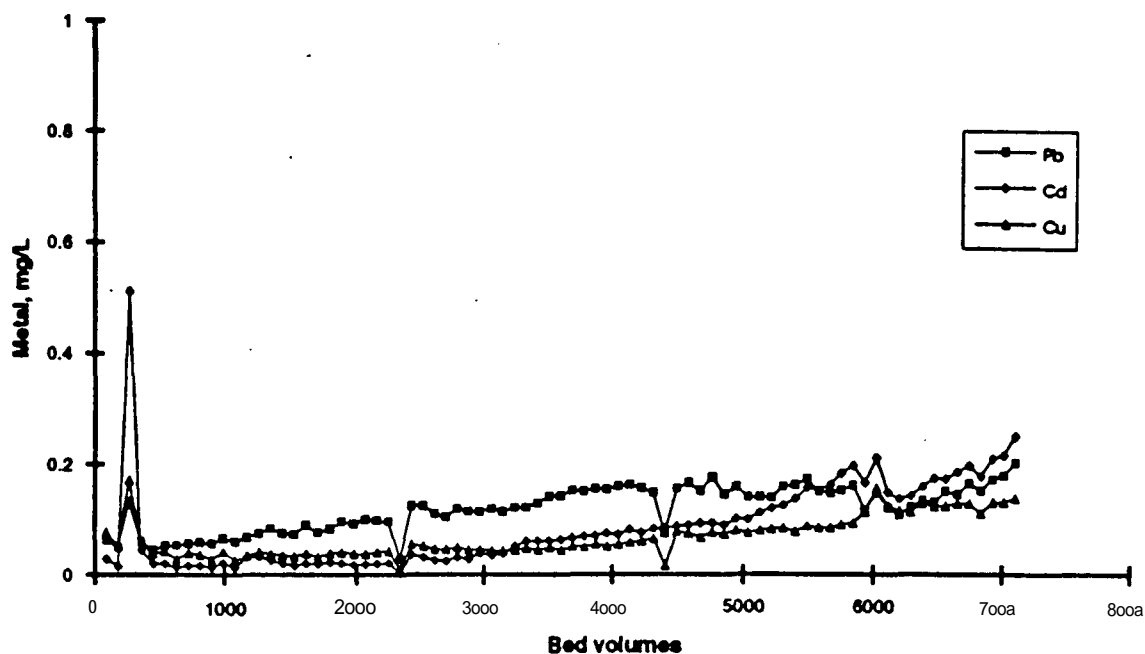


Figure 7. Breakthrough curves for Pb, Cd, and Cu using Media II. The influent concentration was 0.5 mg/L for each metal. EBDT=2 minutes, pH=9.0.

table 3. Conditions for Runs 14 to17. These runs were performed using batches containing all three metals (Pb, Cd, and Cu) each at 5 mg/L concentration.

Run	PH	Batches	EBOT	BV Treated
14	8.6	3	2 min.	831
15	8.9	3	4 min.	772
18	8.7	1	4 min.	199
17	9.3	1	1 min.	178

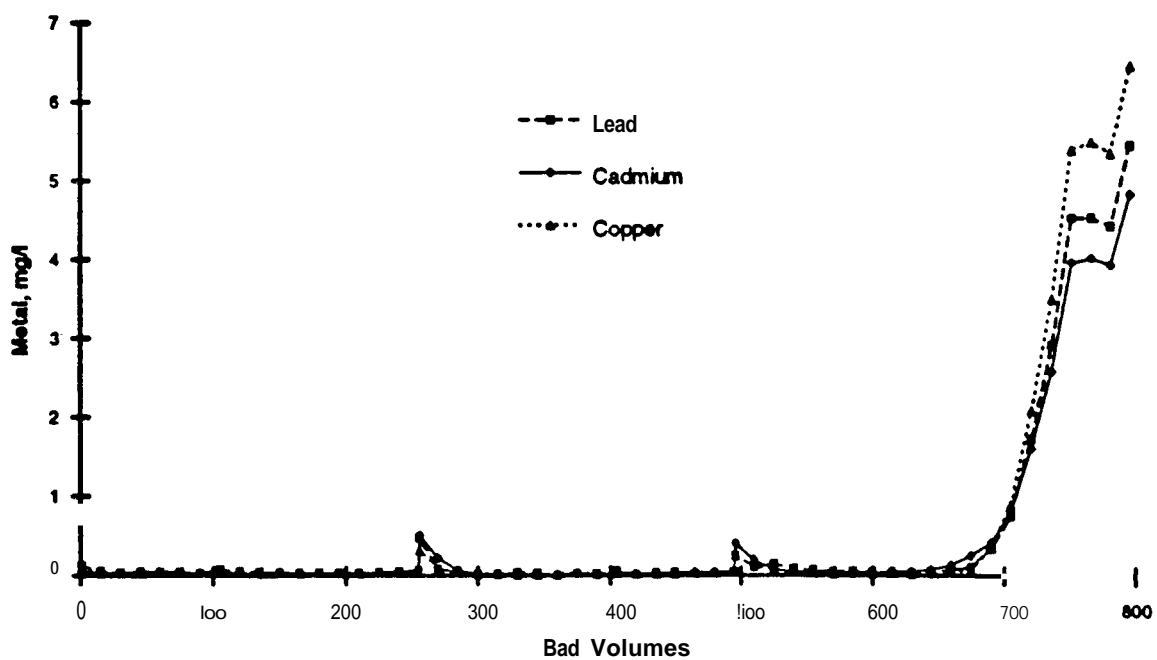


Figure 8. Breakthrough curve for Run 14. Influent contained Cd, Cu, and Pb at 5 mg/L each. EDBT=.2 min, pH=9.0.

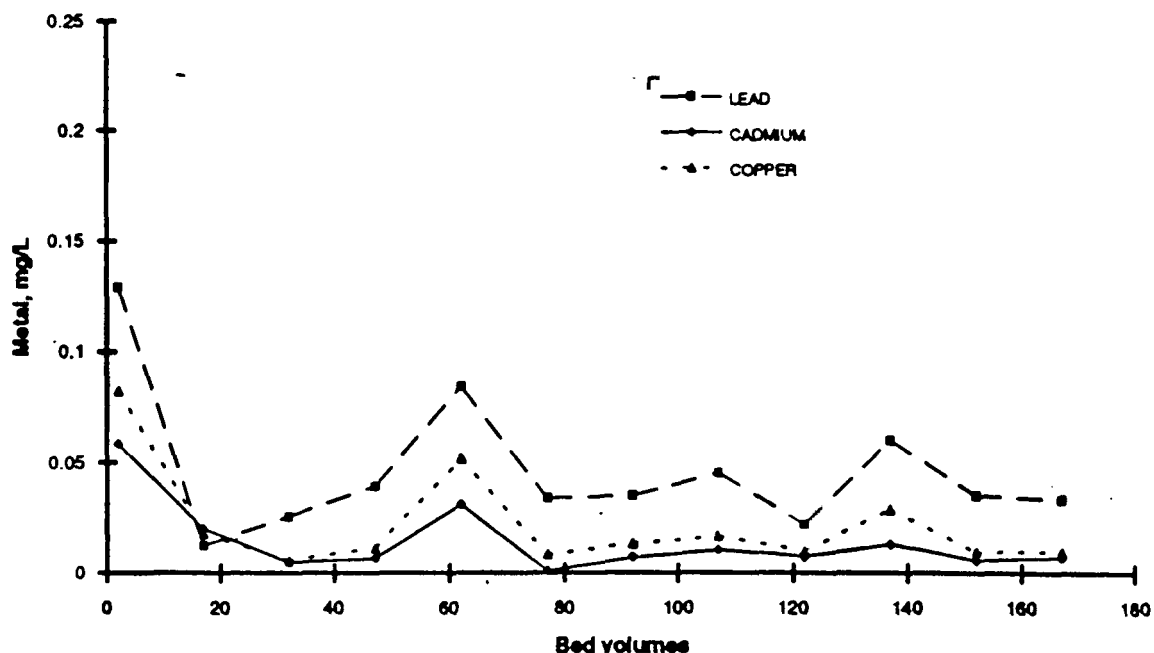


Figure 11. Breakthrough curve for Run 17. Influent contained Cd, Cu, and Pb at 5 mg/L each. EDT=2 min, pH=9.0.

During each run, effluent was sampled until the pressure drop across the column reached a pre-determined value, usually either 20 or 25 psi. At that point, an automatic shut-off switch was activated, and flow to the column was terminated. In Runs 14 and 15, the column was then backwashed with pH 9.0 water, and flow was re-initiated. As noted earlier, influent to the column at that point was identified as Batch 2. A similar sequence occurred when the pressure reached the target value again, and Batch 3 was treated. When the pressure reached the maximum allowable value after treatment of Batch 3, the column was backwashed and then regenerated with water adjusted to pH 2.0.

Since the total influent concentration during Runs 14-17 was considerably greater than the soluble influent concentration, it is apparent that a significant fraction of the metal in the influent precipitated prior to entering the column. The total concentrations (corrected for background) of all the metals in the effluent were well below 0.1 mg/L until about 150 to 200 bed volumes had been treated (a 6- to 12-hour period), at which point particulate metals began breaking through the column. Removal of soluble metal was always significant throughout these runs. Typical removal efficiencies for soluble metals in the influent were 80% for Cu, 90% for Pb, and 98% for Cd, and typical overall removal (comparing total effluent and total influent) were 99% or greater for all three metals (Table 4).

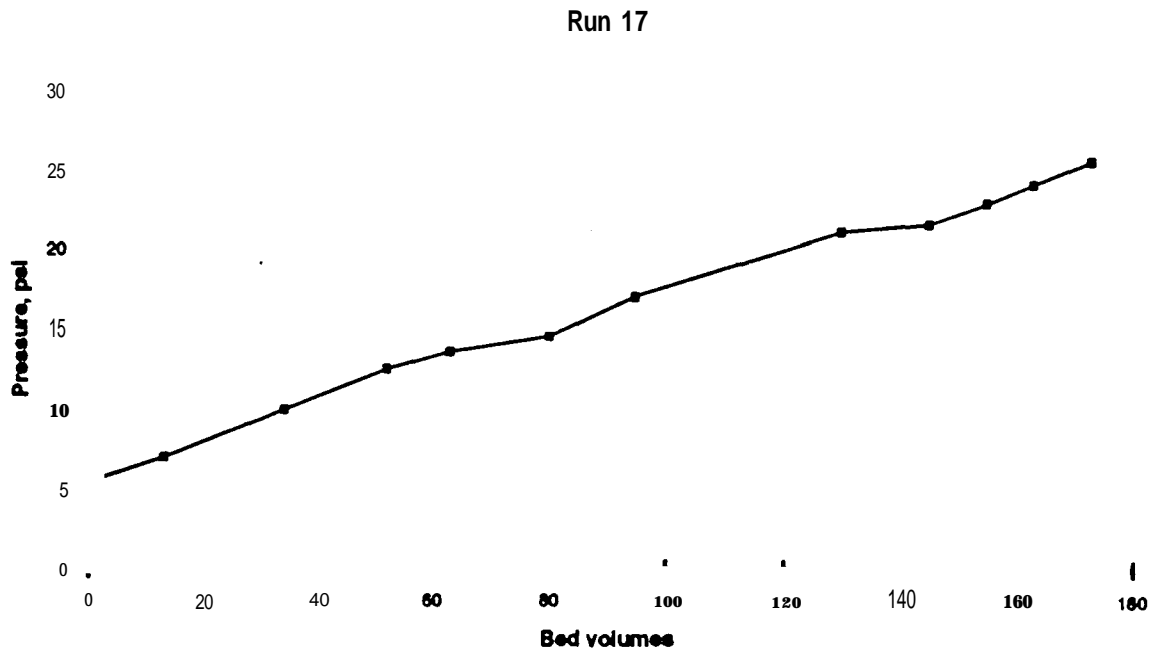
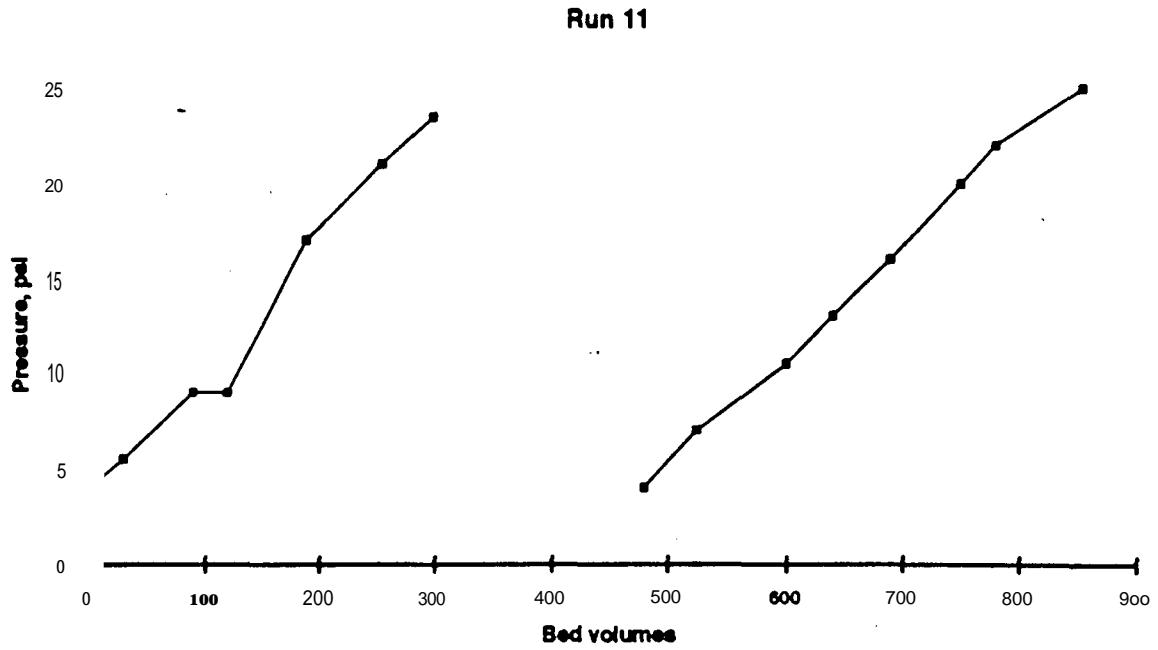


Figure 12. Headloss buildup during Run 11 and 17 as a function of influent volume treated. Run conditions: $P_b=C_d=C_d=5\text{mg/L}$; Run 11 EBDT=2 minutes; Run 17 EBDT=1 minute.

Table 5. Recovery of metals from the column after various treatments after Run 15. All values are mg/L unless indicated otherwise.

Metal, Batch #	Cumulative Particulate Metal Removed	Metal Recovered by Back-washing	Cumulative Soluble Me Removed	Metal Recovered by Regeneration	Total Metal Recovery Efficiency (%)
Pb, 1	80.7	35.4	29		
Pb, 2	63.0	67.3	36		
Pb, 3	<u>163.9</u>	<u>150.1</u>	<u>37</u>		
	307.6	252.7	102	161.1	101
Cd, 1	119.0	29.0	47		
Cd, 2	41.4	54.3	85		
Cd, 3	<u>158.8</u>	<u>135.9</u>	<u>77</u>		
	319.2	219.2	209	234.1	86
Cu, 1	109.3	46.2	5.5		
Cu, 2	85.1	84.7	12.3		
Cu, 3	<u>201.4</u>	<u>164.0</u>	<u>11.0</u>		
	395.8	294.9	28.8	59.8	84

Regeneration

The maximum metal concentration attainable in the regenerant solution is a function of pH and is important because it controls what can ultimately be done with the regenerant. The higher the concentration, the more likely it is that the metal values can be recovered, turning the process into a resource recovery technology, rather than just a treatment technology. The upper limit to this concentration is imposed by the solubility of the metals and the fact that the regeneration efficiency decreases when the regenerant becomes highly concentrated.

The regeneration protocol was typically to circulate 2 bed volumes of water adjusted to pH 2.0 through the column for two hours, although in some cases a larger volume of solution was used. After two hours, another, equal volume of acidified water was passed through the column and was not recirculated. The metal concentration in the recirculation fluid increased rapidly at first and then only slowly thereafter. The kinetics of regeneration after Run 15 are shown in Figure 13. Based on these results, it appears that a recirculating period as short as 10 minutes would release a large fraction of the available metal. Metal concentrations in the first and second regenerant solutions were as high as 3000 and 500 mg/L after the 5 mg/L runs.

Anion Removal

Five runs were conducted to evaluate the removal of As and Se from model solutions by the coated sand. In this case, the influent was adjusted to pH 3.5, but conditions were otherwise similar to those for removal of cationic metals. The run conditions are summarized in Table 6, and the results of several runs are shown in Figures 14 and 15. In runs 18 through 20, oxyanionic forms of both As and Se were present in the influent simultaneously, and both were removed quite efficiently from solution. System efficiency was characterized by a classical, S-shaped breakthrough curve, with significant Se or As appearing in the effluent after about 200 to 300 bed volumes of solution had been treated. The removal pattern was remarkably consistent, regardless of the metal (As or Se) being treated and its oxidation state (+3 or +5 for As; +4 or +6 for Se) (Figure 14). The latter result was particularly surprising, since selenate (SeO_4^{2-}) is generally much more difficult to remove from solution than is selenite (SeO_3^{2-}). To confirm this result and to minimize the possibility of any oxidation-reduction reaction involving selenium, Run 21 was conducted with selenate as the only metal anion in the influent. Consistent with the prior results, about 1000 mg Se was removed from solution per liter of packed bed prior to any significant breakthrough. However, when 100 mg/L sulfate was added to the influent, it apparently competed effectively with the selenate for binding sites on the iron oxide coating, and breakthrough occurred much sooner (Figure 15).

Table 6. Conditions for Run 18-22 using As and/or Se influent at 5 mg/L each. Media II was used for these runs.

Run #	Metals	PH	EBDT	Bed volumes treated.
18	Arsenate, Selenite	3.5	2 min.	1289
19	Arsenate, Selenite	3.5	2 min.	773
20	Arsenite, Selenate	3.5	2 min.	750
21	Selenate only	3.5	2 min.	438
22	Selenate, 100 mg/L SO ₄	3.5	2 min.	454

Effects of Other Contaminants on Removal of Cu, Pb, and Cd

Tests with complexed metals

Figures 16 and 17 show the breakthrough curves for the metals when complexed by ammonia and EDTA, respectively. Only Cd and Cu were tested with ammonia present as a complexing agent, since the ammonia did not maintain Pb in a soluble form. All three metals were present in the influent when EDTA was used as the chelating agent.

Substantial amounts of ammonia-complexed metal can be sorbed by the iron-coated sand. The breakthrough curves for Cd and Cu are almost identical. About 1500 mg of each metal can sorb per liter of media before the effluent concentration exceeds a few tenths of a mg/L, and about 4000 mg of each metal can sorb per liter of bed before the effluent concentration reaches 4 mg/L. Regeneration of this column using a total of 16 bed volumes of regenerant solution at pH 2.0 recovered 93% of the sorbed Cd and 100% of the Cu.

When the metals were complexed with EDTA, they broke through the column almost immediately. The capacity of the media to remove metals under these conditions is not significant either at pH 10.0 or at pH 4.5, and the adsorptive filtration process would not be applicable for treatment of waters containing **EDTA-complexed** metals.

In situations where complexed metals need to be treated, tests investigating the behavior of the complex will be required.

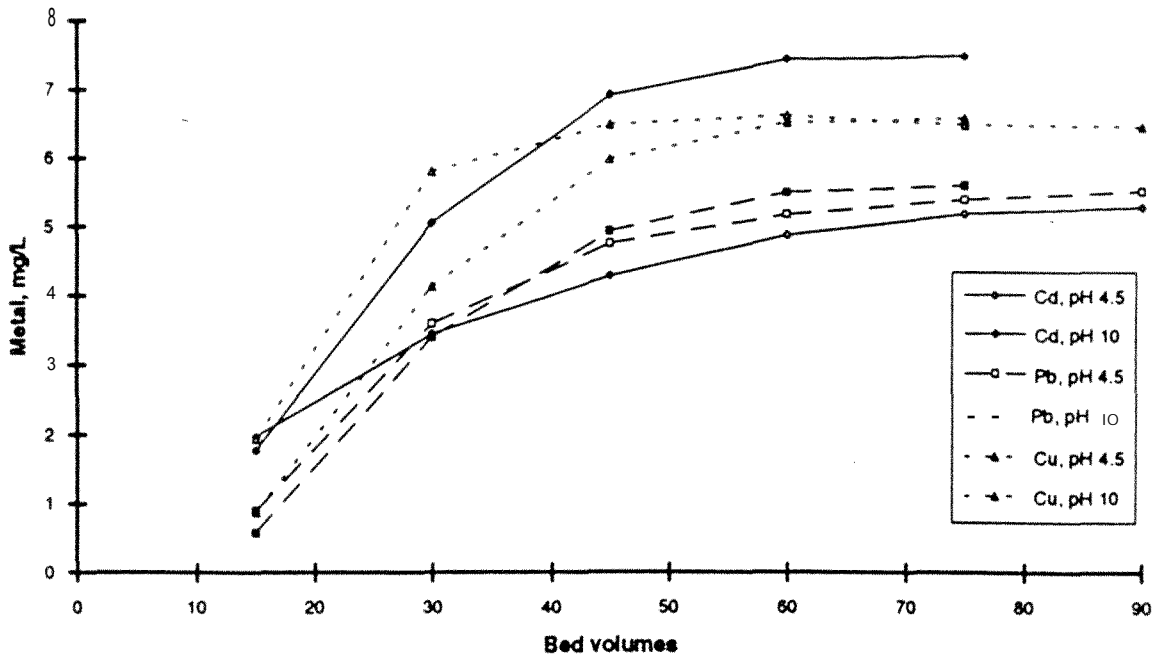
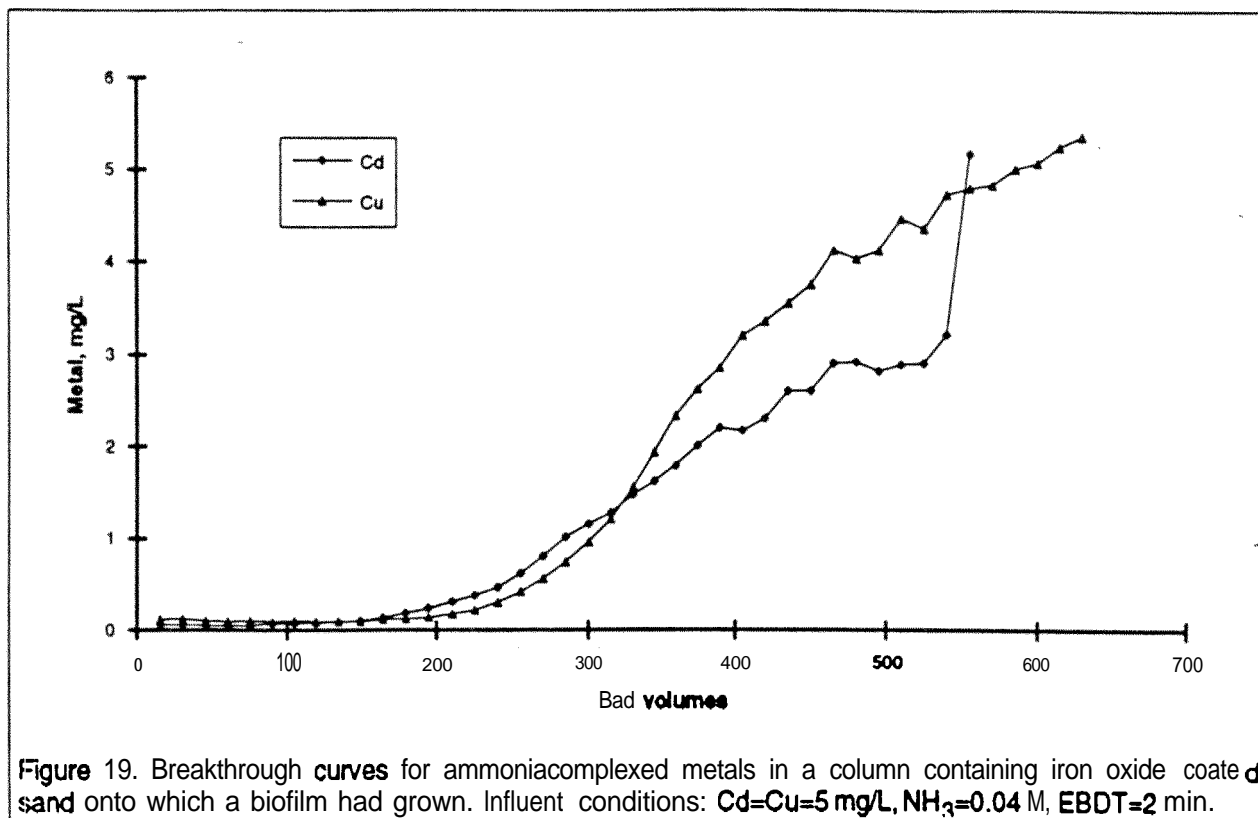


Figure 17. Effluent breakthrough curves for EDTA-complexed metals. Runs were completed at pH 4.5 and pH 10, as indicated. Influent conditions: Cd=Cu=Pb=5 mg/L, EDTA:metal ratio = 1.25:1 (1.84×10^{-4} M EDTA), EBDT=2 min.

Effects of organic surfactants.

Sodium lauryl sulfonate is a surfactant that might interfere with the adsorptive filtration process by interacting either with the metals or the surface of the media. Figure 18 shows the column performance in the presence of 0, 15, and 30 mg/L of this surfactant, along with enough ammonia to keep the metals in solution. Tests with higher concentrations of the surfactant could not be conducted due to its limited solubility. However, 30 mg/L is a higher concentration of surfactant than one would expect in most wastewaters where the adsorptive filtration process might be used, and Figure 18 indicates that this concentration had no noticeable effect on metal sorption. Computed regeneration efficiencies were 117% for Cd and 97% for Cu.

process as a result of biogrowth is unlikely to be a severe problem. Regeneration efficiencies were 94% for Cd and 105% for Cu.



Effects of oily substances on adsorptive filtration.

One test was conducted in which the media was exposed to motor oil, in order to simulate a situation where, by accident, a large amount of some oily substance entered an adsorptive filtration column. Normally, such substances would be removed upstream of the column. To investigate a worst-case scenario, a damp sample of the coated sand was exposed to a 10% by volume mixture of SAE 30 motor oil in water and was then packed into a column. Oil remained attached to the media, and air bubbles were trapped in the column. When the influent was applied, severe channeling was observed, and breakthrough occurred almost immediately. The coated sand was then removed from the column and cleaned by rinsing it twice in isopropanol. The cleaned sand was returned to the column, and the standard ammonia-complexed influent was applied. As shown in Figure 21, the media performed reasonably well, but a little more than half of the sorption capacity was lost. It is not known whether this loss was due to residual oil on the media, which might be removed by more strenuous cleaning efforts, or whether it reflects a permanent loss of capacity.

Evaluation of Options for Residuals Management

One of the major factors affecting the value of this technology is the ultimate disposition of the regenerant solution. An experimental evaluation of that issue was not conducted as part of this project. However, based on the high metal concentrations achieved in the regenerant with relatively little effort, it is likely that some recovery and reuse will be feasible in most cases, even if only by treating the sludge as an ore.

Treatment of Real Superfund Solutions

Once reasonable operating parameters for the technology were established, a real waste from a Superfund site was collected and treated in one of the columns. The untreated water at this site contains tens of mg/L of ferrous iron in addition to a few mg/L Zn and less than 1 mg/L of several other metals. It is treated by conventional precipitation/ coagulation at pH around 8.0 at the site, and, since the ferrous iron is oxidized and precipitated in the process, the metals are exposed to a large amount of iron oxide in the process. As a result, a significant fraction of the metals that can adsorb onto iron oxide do so in the treatment process. The treatment process at the site is slightly unconventional, in that conventional precipitation/ coagulation is usually carried out at pH 10 or greater. However, operation at that pH would be problematic with this particular water, since it contains high concentrations of Ca and alkalinity, causing massive amounts of CaCO_3 to precipitate when the pH is raised to 9.0. Fortunately, the combination of metal precipitation and (probably most importantly) adsorption onto iron oxide removes most of the metals from the soluble phase, so treatment at pH 8.0 is adequate.

We chose to treat the effluent from the precipitation/coagulation process being used on site. The upper practical limit imposed on the treatment pH in the on-site process also applied to the adsorptive filtration process. That is, we were constrained to operate the test system at pH near 8.0, well below the pH that would have been optimal for metal removal. On the other hand, the use of our process on this water represents a realistic test of whether adsorptive filtration can remove a substantial amount of metal from a solution that has been treated optimally by more conventional methods.

The water was therefore treated as received, at pH 8.0 with Zn as the only metal present in significant quantities. The total and soluble Zn concentrations in the samples collected were in the ranges 0.6 to 4.0 and 0.3 to 0.6 mg/L, respectively. The treatment set-up for these tests was more automated than that for previous tests, as shown by the schematic in Figure 21. As shown in Figures 22 through 24, typical total and soluble Zn concentrations in the effluent were around 0.2 and <0.1 mg/L, respectively. Regeneration kinetics for one of these runs is shown in Figure 25. The build-up of headloss during treatment of this solution followed the same pattern as was observed for treatment of the synthetic solution (Figure 26).

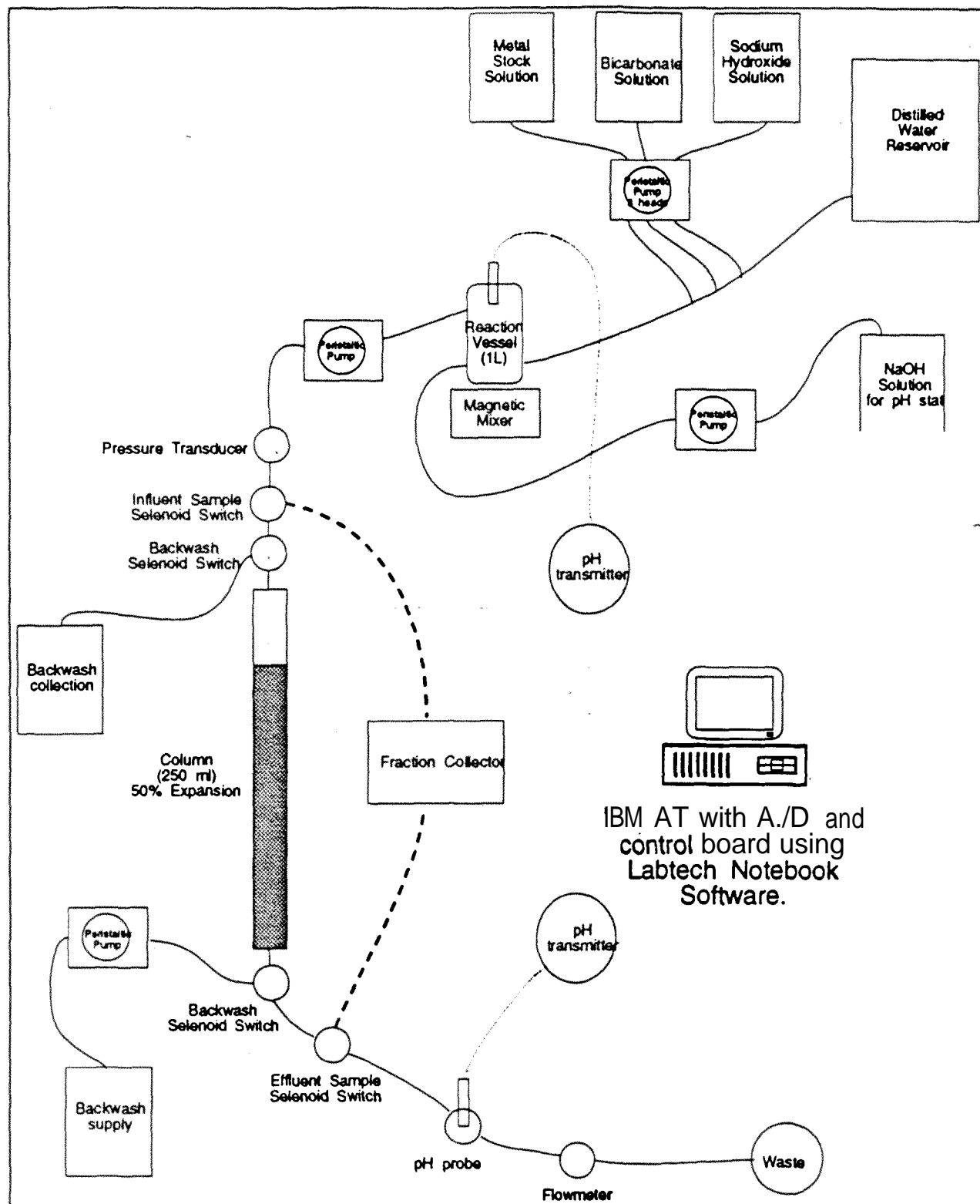


Figure 21. Schematic diagram of setup used for automatic treatment runs using Superfund site solution s.

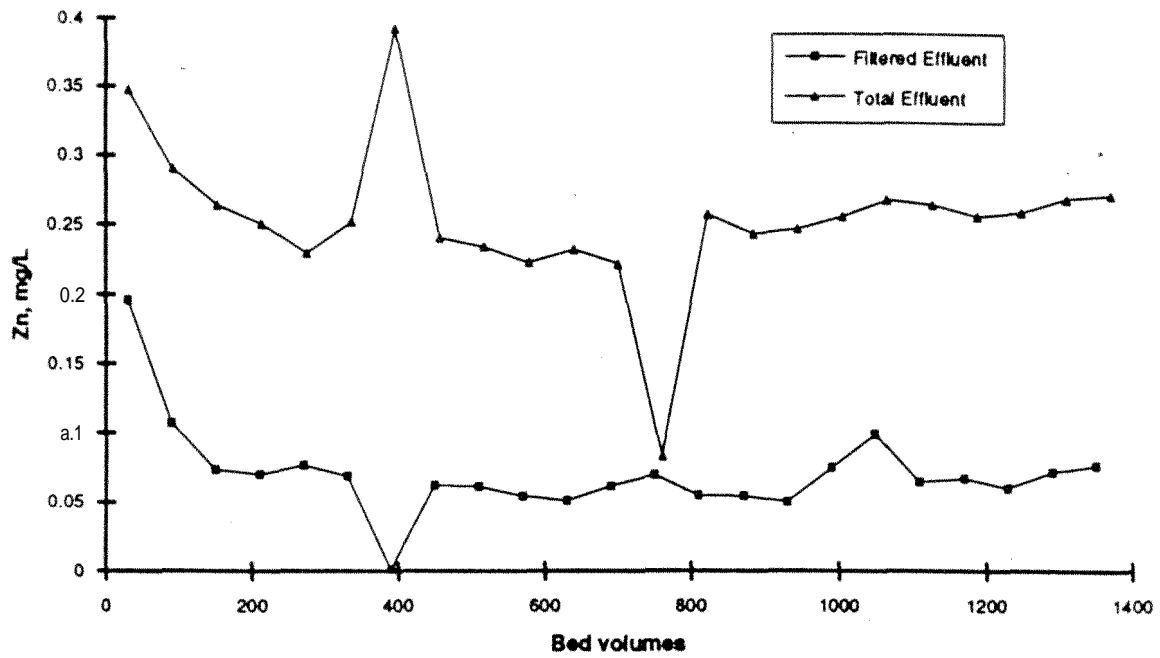


Figure 24. Effluent zinc concentration for Western Processing Run 4 as a function of bed volumes treated.

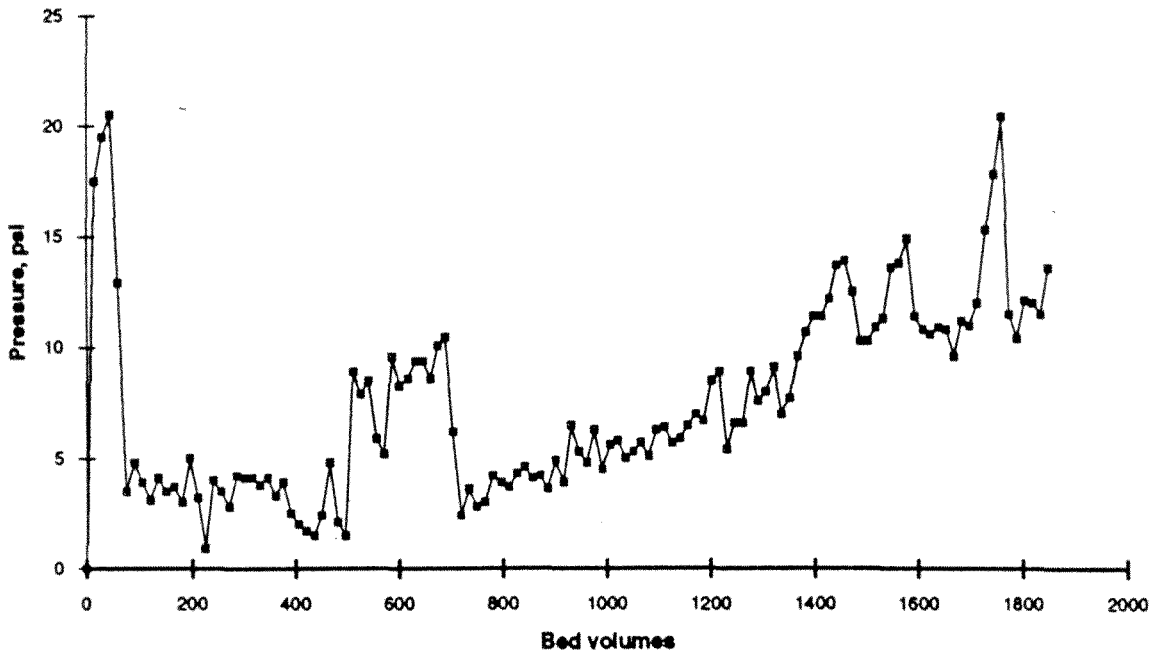


Figure 26. Headloss buildup during Western Processing Run 2.

CONCLUSIONS

In conclusion, simultaneous sorption and filtration of Cu, Cd, and Pb are feasible using iron oxide-coated sand under reasonable engineering conditions. Total and soluble effluent concentrations of less than 100 $\mu\text{g/L}$, and sometimes considerably less, are achievable. The media can be backwashed to recover most of the particulate metals, and regenerated by exposure to an acid solution to recover the remaining particulates and most of the adsorbed metals. The regenerant solution typically contains metal concentrations a few hundred times as concentrated as the influent. In tests with 5 mg/L of each of three metals in the influent, filtration limited process performance more than sorption did. It should be recognized that this outcome is not generalizable: the limiting factor in any application would depend on the specific operating conditions and chemical composition of the influent solution. Modifications to the influent, such as adjusting solution pH or adding a polymeric filter aid, and modifications to the operation, such as adjusting the hydraulic loading rate, would certainly affect the relative importance of headloss and effluent concentration limits. However, there was no indication that such factors could prevent adsorptive filtration from serving as a viable treatment technology.

The solutions investigated contained one to three heavy metals, at total heavy metal concentrations ranging from 0.5 to 15 mg/L. These solutions were treated successfully at empty bed contact times

ABBREVIATIONS

BV	Bed Volume
EBDT	Empty Bed Detention Time
EDTA	Ethylene Diamine Tetra-acetic Acid
IOCS	Iron-Oxide-Coated Sand
SDS	Sodium Dodecyl Sulfonate (also called Sodium Lauryl Sulfonate)