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MARTIN MARIETTA

Mercury Removal from Aqueous Mixed Waste

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OAK RIDGE NATIONAL LABORATORY

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Chemical Technology Division

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MERCURY REMOVAL FROM AQUEOUS MIXED WASTE

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ACRONYMS AND ABBREVIATIONS

DOE	Department of Energy
EPA	Environmental Protection Agency
GE	General Electric Company
ICPP	Idaho Chemical Processing Plant
ESPIP	Efficient Separations and Processing Integrated Program
MWIP	Mixed Waste Integrated Program
INEL	Idaho National Engineering Laboratory

ABSTRACT

Large volumes of mercury-contaminated wastes are stored on U.S. Department of Energy (DOE) sites. The mixed wastes contain sufficient radioactivity and hazardous materials that they must be handled under both the Atomic Energy Act and the Resource Conservation and Recovery Act. New, inexpensive, and improved separation methods are needed for treating a wide variety of mixed wastes at many DOE facilities. Volatile mercury should be removed from aqueous wastes before potential water evaporation and thermal treatment. For some solids, innovative methods such as selective leaching are being developed and there is a need for secondary treatment or regeneration of the leachate liquids.

Laboratory work was performed in order to investigate the possibility of using inexpensive sulfur-impregnated, activated-carbon pellets (Mersorb®) to remove mercury from aqueous waste. The desired goal was to generate engineering-scale data so that the mercury could be separated (removed) from aqueous streams or reliably accounted for in the development of overall treatment strategies for mixed wastes.

Laboratory studies demonstrated that mercury could be removed to levels below the current Environmental Protection Agency toxic characteristic level (0.2 ppm) when Mersorb was used under a variety of operating conditions. When comparing the use of the inexpensive Mersorb with the more expensive ion exchanger, Duolite GT-73, the Mersorb had favorable process economics; however, further testing and economic analysis is required before making final conclusions.

The target wastes were selected by obtaining mixed waste inventories for several DOE sites, evaluating the wastes against a set of seven criteria, and by contacting Mixed Waste Integrated Program representatives at the sites to discuss tentative target wastes.

1. INTRODUCTION

The goal of this project was to develop treatment processes to remove mercury from mixed waste. Processes applicable to liquid/aqueous waste are sulfur-impregnated activated carbon and ion exchange using resins and membranes. To help focus development activities on realistic process variables, target wastes for the study were selected from U.S. Department of Energy (DOE) mixed waste inventory. The liquid wastes were (1) the Idaho Chemical Processing Plant (ICPP) sodium-bearing acid waste (about 1.5 million gallons) and (2) leach solutions containing mercury present as the Hg^{2+} cation from acid treatment of solid wastes.

The long-term goal is to prepare for full-scale demonstration of the process on actual mercury-contaminated mixed waste. The demonstration may or may not be coupled with a Mixed Waste Integrated Program (MWIP) thermal treatment demonstration. This work addresses need statements listed in *Call for Technical Task Proposal FY95*, distributed by the Office for Research and Development and Office of Demonstration, Testing, and Evaluation. Specifically, Need Statements ES-1 (Radionuclide and/or Toxic Component Removal) and ES-5 (Aqueous Processing) under the Efficient Separations and Processing Integrated Program (ESPIP) are addressed. The project directly addresses MWIP's need for mercury processing as outlined in their *Technical Area Status Report for Chemical/Physical Treatment*.

This summary report describes fiscal year 1994 activities for the removal of mercury from aqueous waste. Leaching studies of mercury from solid waste were carried out by the Environmental Sciences Division at Oak Ridge National Laboratory and are reported elsewhere.

1.1 Selection of Target Wastes

The goal was to identify target wastes suitable for the development of two technologies for the removal of mercury from liquids. The technologies to be developed were sulfur-impregnated activated carbon sorption and mercury ion exchange using resins and membranes. The selection process for target wastes was as follows:

1. Mercury-containing mixed waste inventories were obtained for several DOE sites.
2. Each item on these inventories was evaluated against a set of seven criteria.
3. Contacts were made with MWIP representatives at all of the sites. Where tentative target wastes were identified, further contacts were made to ensure that the inventory information was still valid

and that the MWIP mercury control development work would be complementary to any other plans for treatment or disposal.

The target waste selected for process development was the ICPP sodium-bearing liquid waste. About 1.5 million gallons of this waste, which contains over 1 molar (M) acid, is stored at the Idaho site. Mercury separation technology for this waste should also be useful for the acid leach solutions from leaching treatment of noncombustible solid waste.

The waste was selected based on the following set of criteria.

1. Volume currently stored: Is the volume relatively large compared to other mercury-containing mixed wastes?
2. Volume currently generated: Is there a potential for large volumes to be accumulated in the future?
3. Storage risk or hazard: Is the current inventory in an unstable or dangerous situation, such as leaking containers? Is there a political situation?
4. Candidate for declassification: Would mercury removal make a significant difference in the management or disposal of the waste?
5. Characteristics suitable for selected technologies: Is the waste amenable to mercury separation by one of the two technologies to be investigated?
6. Similar wastes at several sites: Is this waste important at more than one site?
7. Current technologies: Does satisfactory separation technology already exist for the waste?

1.2 Experimental Approach

The specific objectives of the experimental portion of the project were to investigate the capability of sulfur-impregnated activated carbon to remove mercury from acid solutions. This was to be accomplished by studying the effect of (1) pH, (2) sorbent to liquid ratio, (3) mass transfer versus kinetic control, (4) competing ions, and (5) mercury loading on the sorbent in batch tests.

After completion of batch tests, column studies were to be performed to investigate design parameters. As a nonexperimental activity, commercial ion exchange resins were identified and literature data were compiled regarding suitability for mercury removal from acid aqueous waste.

2. MATERIALS AND METHODS

2.1 Target Waste Stream

The ICPP has about 1.5 million gallons of radioactive liquid waste that consists primarily of the content of six tanks of high-sodium-containing acid liquid. Average acidity [from nitric acid (HNO_3)] is 1.4 *M*. Mercury levels range from 100 to 860 mg/L (as Hg^{2+}), and the average value is 476 mg/L. Contaminants that may affect mercury removal efficiency are present in the following average concentrations (in mg/L): aluminum, 15,000; cadmium, 84; chloride, 773; iron, 1475; lead, 213; manganese, 744; nickel, 140; and undissolved solids, 1900. A peer review committee recommended three possible treatment options for treating this waste. In all three, the waste would at some point be fed to the fluid-bed incinerator and be volatilized into the off-gas system. Removal of mercury as a pretreatment for any of three processes would be beneficial.

2.2 Surrogate Waste Preparation

Two types of surrogate wastes were used in this study. The first was a simple solution of mercuric nitrate [$\text{Hg}(\text{NO}_3)_2$] prepared from either 1000- or 10,000-ppm standards diluted with deionized water. In some cases, crystalline $\text{Hg}(\text{NO}_3)_2$ was directly dissolved in deionized water. The acidity of this surrogate waste was adjusted with HNO_3 or sodium hydroxide (NaOH) to achieve the desired pH. The second surrogate waste, which simulates the sodium-bearing liquid waste, was prepared based on a formulation obtained for the ICPP waste.

2.3 Mersorb® Pellets

Sulfur-impregnated, granular, activated carbon was obtained from Nucon International, Inc. (Columbus, Ohio). The pellets had a diameter of 3 mm and a length of 3 to 8 mm. Nucon's technical data sheet lists sulfur content as 13% and mercury capacity as 85% of the theoretical value, which translates to a "real" capacity of 0.71 g mercury per gram of pellets. To get a mean value for the pellets' average volume and external surface area, the length and diameter of 50 pellets were measured; the average pellet volume was 35 mm^3 and the external surface area was 60.9 mm^2 . The average pellet weight was 0.0378 g.

2.4 Equipment

The jar mill studies were conducted using a US Stoneware (Mahwah, N.J.) variable speed jar mill; 1-L Pyrex® glass bottles were used as jars. An orbital shaker (VWR, Oak Ridge, Tenn.) and 125-mL Erlenmeyer glass flasks were also used in the initial friability testing. The column studies were performed in Kontes (Vineland, N.J.) liquid chromatography columns. The columns had a diameter of 48 mm and the length could be varied by adjustable plunger-type end caps. The feed was supplied to the bottom of the column with a variable speed and flow Masterflex® pump (Cole Parmer Instrument Co., Niles, Ill.). All surfaces in contact with the liquid, except for pump tubing, were glass or Teflon®.

2.5 Methods of Analysis

Mercury concentration in the aqueous liquid was measured using an 1100B atomic absorption spectrometer (Perkin-Elmer, Norwalk, Conn.) equipped with a cold-vapor-injection system (Model FIAS 400, Perkin-Elmer) and automatic sampler (Model AS 90, Perkin-Elmer). Argon was used as gas carrier and 3% (v/v) hydrochloric acid (HCl) was used as liquid carrier. The reducing agent was 1.1% (w/v) stannous chloride (SnCl_2) in 3% HCl. Typically, 4 mL of aqueous sample was filtered and 1 mL of the filtrate was diluted with 4 mL of preservative solution [0.1% (w/v) potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) in 5% (v/v) HNO_3]. The preserved sample was diluted in steps with preservative solution to a final mercury concentration of 1 to 20 ppb. Standards were prepared by diluting in steps with preservative solution from a 1000-ppm primary standard to final concentrations of 1, 10, and 20 ppb. Acidity was measured with pH paper with a 0.4 pH-unit accuracy.

3. RESULTS AND DISCUSSIONS

3.1 Batch Experiments

Friability studies were carried out on a jar mill and in Erlenmeyer flasks on an orbital shaker. The absorbance of the aqueous solution was monitored with time, and it was determined that the orbital shaking caused the carbon pellets to break down slightly. Thus, the jar mill was chosen as contactor for the batch experiments. The agitation speed for the orbital shaker and the jar mill was 150 and 81 rpm, respectively.

3.1.1 Effect of Agitation in Batch Experiments

Three tests were made to investigate the effects of jar mill speed on the uptake rate of mercury from 100 mL solution containing 100 ppm mercury at pH 2. Jar mill speeds tested were 11, 22, and 38 rpm with an excess of pellets (5g). The Mersorb pellets were capable of reducing mercury concentrations to less than 0.2 ppm (see Fig. 1). The initial mercury uptake rate followed first-order kinetic behavior (which was expected) described by the equation

$$\log[\text{Hg}^{2+}] = -0.4343kt + \text{constant}, \quad (1)$$

where k is the apparent reaction rate and t is the time. The linearity described in Eq. (1) may easily be observed in Fig. 2. As in noted in the figure, the data fall on a straight line for the initial data collected. The calculated apparent reaction rate at 11 rpm was 2.3 h^{-1} , and between 6.3 and 7.1 h^{-1} for the higher jar mill speeds. The clear increase in apparent reaction rate when the jar mill speed was increased from 11 to 22 rpm indicates that mass transfer limiting condition existed around the pellets at the lower agitation rate. The minor difference in apparent reaction rate at the higher jar mill speeds was attributed to experimental error. From this result it was determined that a jar mill speed of about 22 rpm would be used for the remainder of the study to avoid external (to the pellets) mass transfer limiting conditions.

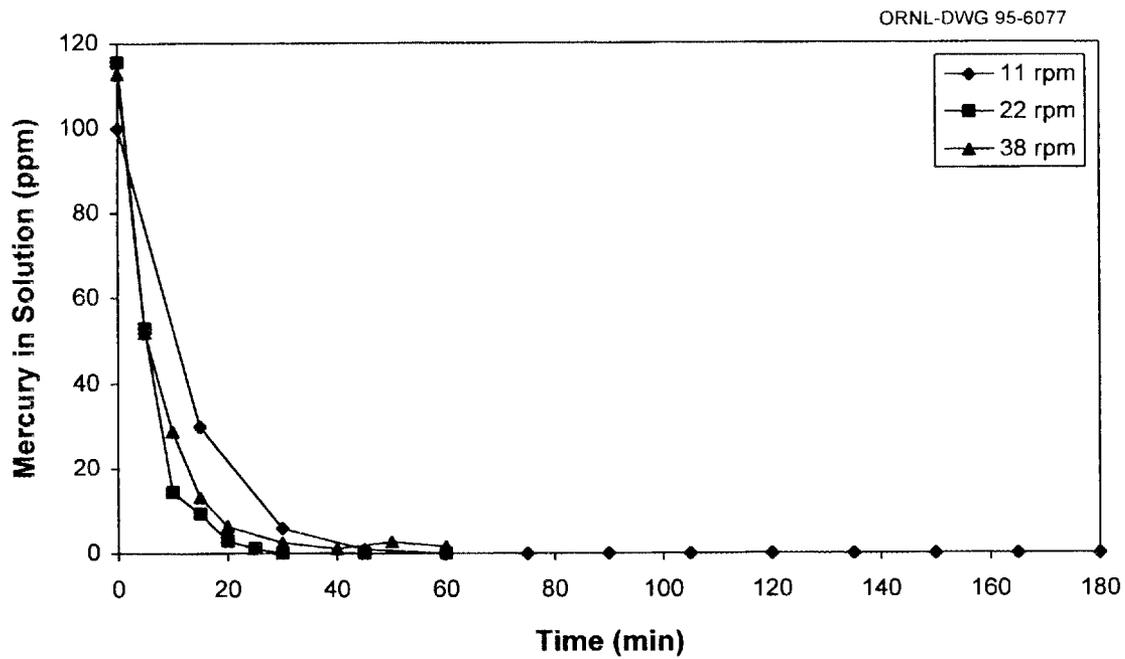


Fig. 1. Mercury uptake at various jar mill speeds in batch experiments.

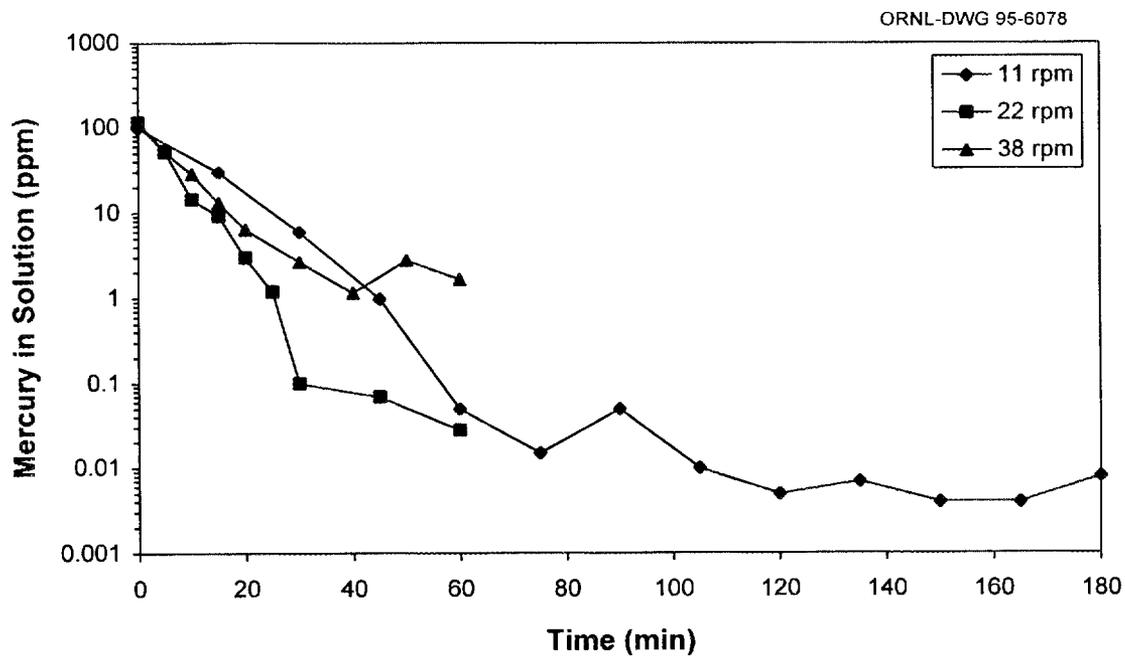


Fig. 2. Linearity in the study indicates first-order reaction rate.

3.1.2 Effect of Solution pH

The effect of pH on mercury uptake was investigated for three initial pH levels (pH 2, 3, and 4). The overall mercury uptake was about the same for all three experiments, which were conducted with 100 mL of solution with 10 ppm initial $\text{Hg}(\text{NO}_3)_2$ concentration. Mercury levels decreased to less than 0.5 ppm in 30 min contact time (see Fig. 3). The amount of Mersorb pellets was 5 g.

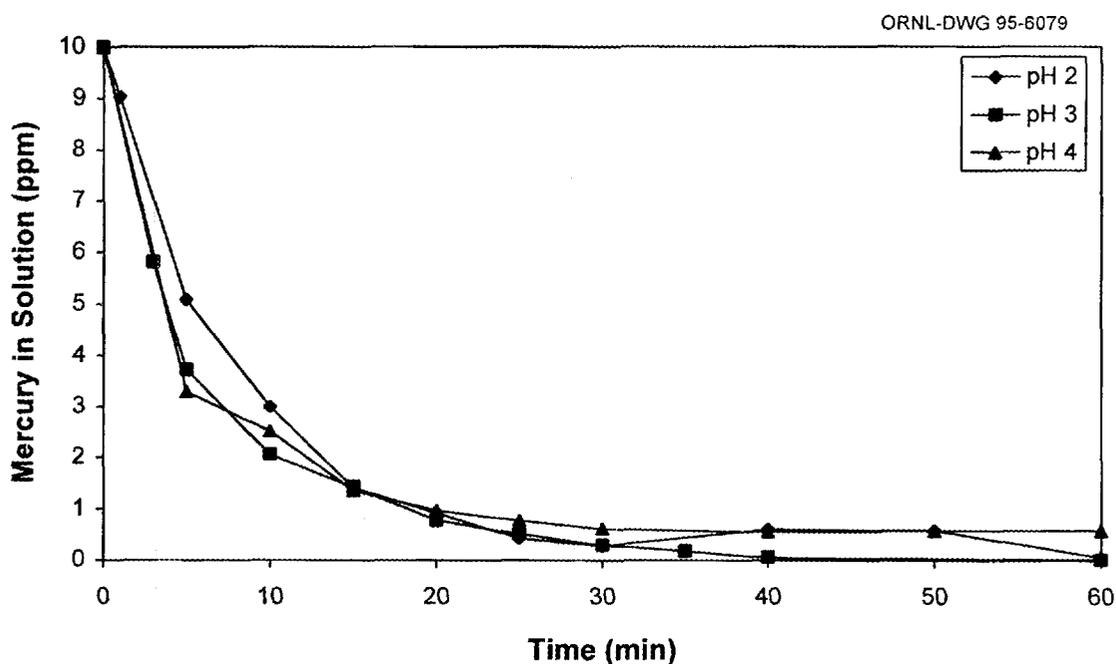


Fig. 3. Effect of pH on mercury uptake rate.

3.1.3 Effect of Successive Treatments

Mercury uptake rate at various mercury pellet saturations was studied at pH 2 by contacting two known amount of pellets with three successive mercury-containing solutions (100 mL). The results showed that the mercury uptake rate decreased as the Mersorb became saturated (see Fig. 4 and 5). As can be seen in the figures, faster uptake rates were observed in the jar containing 2 g of pellets (compared with the jar containing 1 g of pellets).

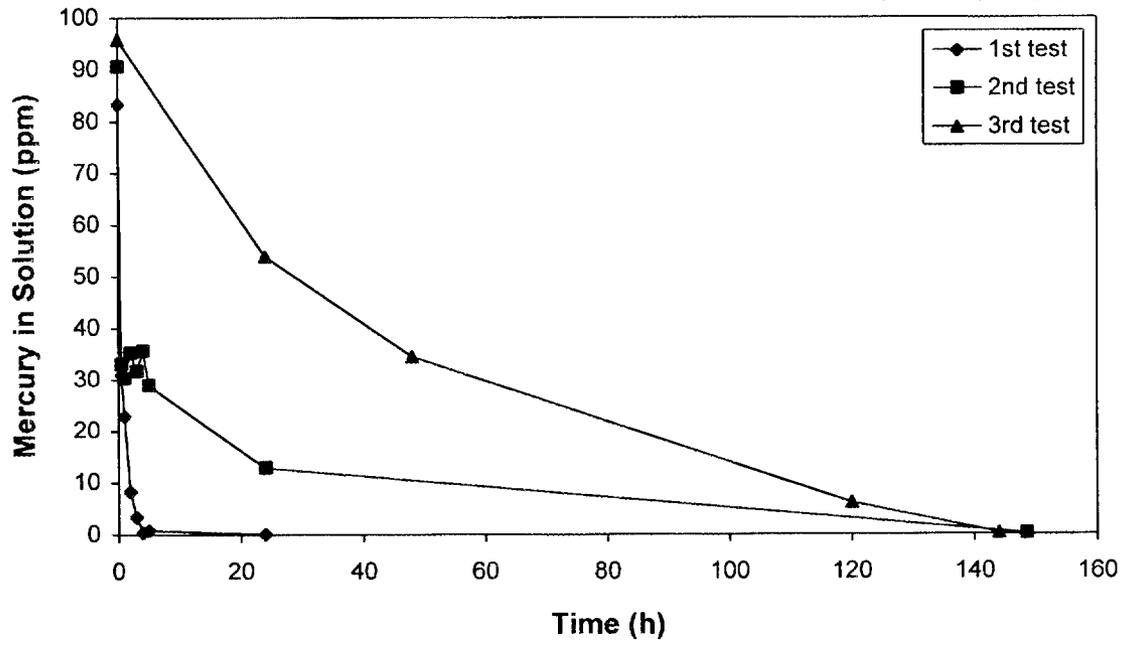


Fig. 4. Successive uptake of mercury on 1 g of pellets.

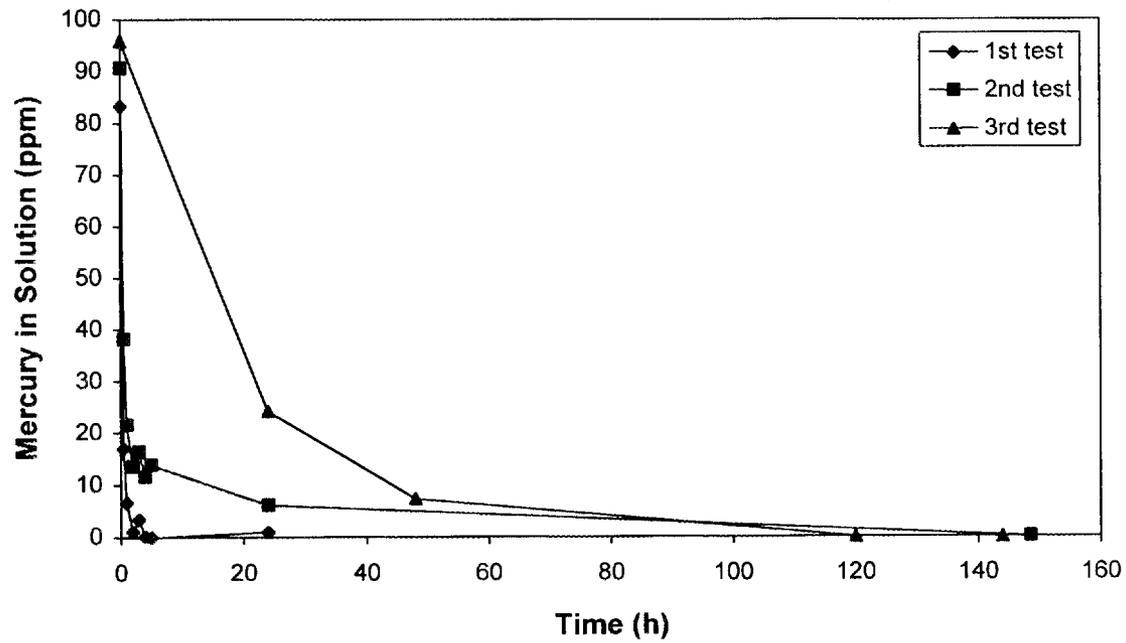


Fig. 5. Successive uptake of mercury on 2 g of pellets.

3.1.4 Mercury Capacity of Sorbent

Mersorb saturation loading (or capacity) at low pH (pH 2) was conducted with various mercury concentrations and Mersorb amounts. The saturation loading was, on average, 0.04 g Hg per gram of dry pellets. At a pH of 8 the loading increased to 0.12 g Hg per gram of dry pellets. These results correspond to 5.6% and 16.9% of the theoretical capacity, respectively, which agrees well with experimental data obtained from the manufacturer.

3.1.5 Experiments with Simulated Process Waste

Surrogate waste was prepared to simulate the ICPP waste. The surrogate waste description was obtained from Idaho National Engineering Laboratory (INEL). Using two liquid to Mersorb ratios, mercury uptake from 100-mL solution was monitored for the ICPP surrogate waste and for a well-defined $\text{Hg}(\text{NO}_3)_2$ solution. Compared with the $\text{Hg}(\text{NO}_3)_2$ solution, the mercury loading on the pellets was reduced by 50% when the ICPP surrogate waste was used (see Figs. 6 and 7). This result was anticipated because the ICPP surrogate waste contained competing ions such as iron, lead, cadmium, and nickel.

The ICPP waste has a pH of less than 1. Because the manufacturer of Mersorb does not recommend using the product for streams with a pH of less than 3, pH was adjusted to various levels in the ICPP surrogate waste. It was found that the initial mercury concentration of 325 ppm could be reduced by 93% to 97% if NaOH was added to adjust the pH to neutral (see Fig. 8). This finding may be an important waste pretreatment consideration.

3.2 Column Experiments

Large-scale separations of mercury from solutions would likely be done by passing the contaminated stream through columns packed with Mersorb pellets. A small laboratory column was designed and constructed to obtain mass transfer data and mercury capacity for columns. The column length (and thus the amount of pellets) could be adjusted and the solution was pumped through the bed by a variable-speed pump.

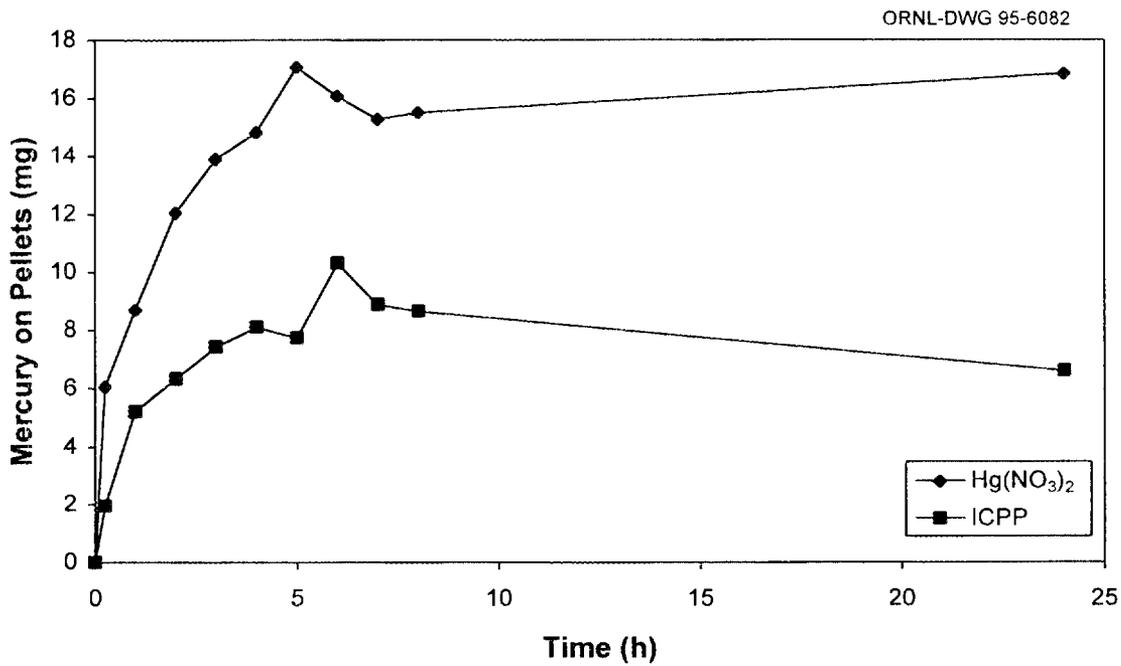


Fig. 6. Mercury loading on 0.5 g of pellets using two simulated wastes.

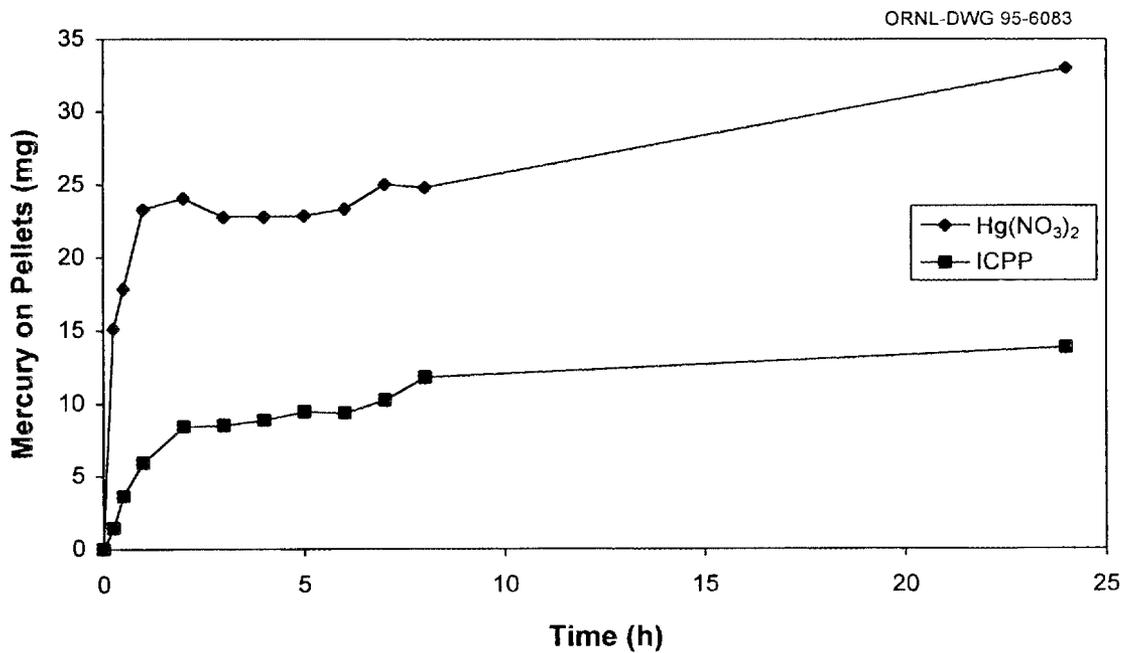


Fig. 7. Mercury loading on 0.9 g of pellets using two simulated wastes.

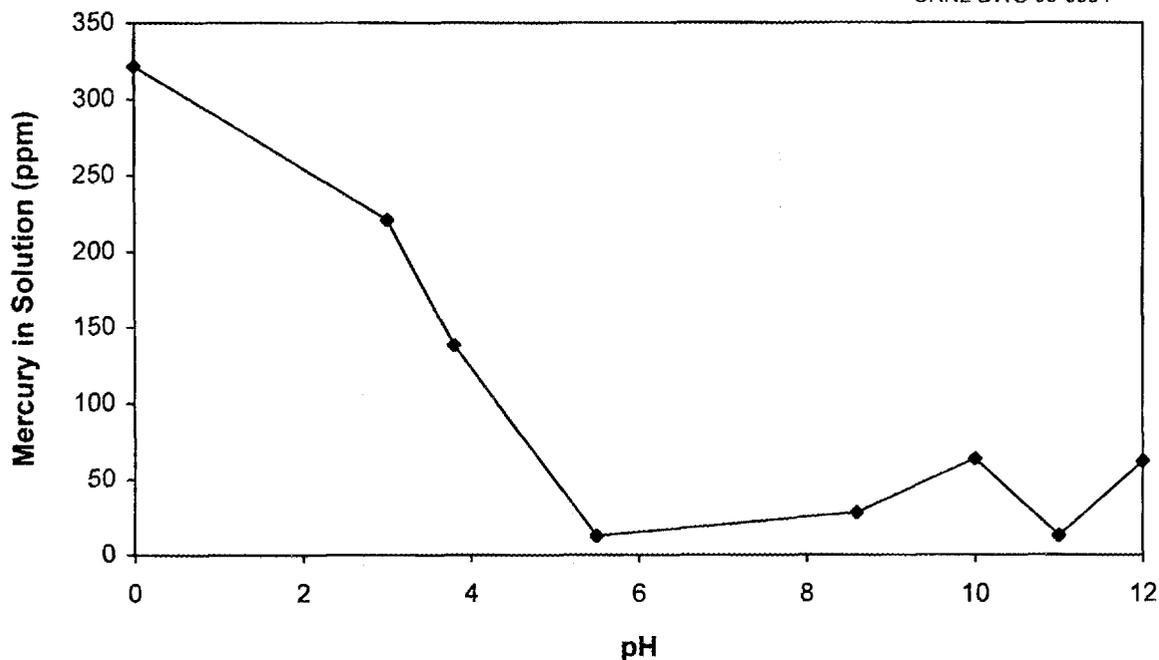


Fig. 8. Mercury removal from ICPP surrogate waste by pH adjustment.

3.2.1 Theory

A sorption column in operation has three distinctive zones:

1. the saturated zone, which is close to the feed inlet;
2. the mass transfer zone (or sorption zone) in which active sorption of the solute occurs; and
3. the unsaturated zone, which is essentially free from the solute and the sorbent has its original sorption capacity.

The mass transfer zone is mobile during the course of the operation; it is positioned at the inlet of the column at start-up and moves toward the outlet with time. The length of the mass transfer zone depends on the fluid flow and sorption kinetics. The mass transfer zone length is calculated from breakthrough curves (obtained by monitoring effluent concentration during continuous column operation) as in the following example:

Column length = 2 m, column diameter = 0.5 m → bed volume = 0.39 m³

From breakthrough data, we know:

Bed volumes of feed passed through column at 5% breakthrough = 50

Bed volumes of feed passed through column at 95% breakthrough = 60

Thus, the mass transfer zone length = $[(60 - 50)/60]*2 = 0.33$ m

Typically, sorption columns are designed to operate until 5% breakthrough is noticed in the effluent. In the above example this occurred after 50 bed volumes of feed had been passed through the column. At that point, about 1.67 m of the column was saturated, indicating an overall capacity of 83%. In general, the shorter the mass transfer zone length, the more efficiently the sorption column is used.

3.2.2 Effect of Column Length

The first column experiment was carried out with a bed depth of about 2.5 cm. The feed solution concentration was 1090 ppm mercury and had a pH of 2. The feed flow rate of 7 mL/min was a factor of 10 lower than typical process flow rates but was chosen as a conservative first attempt. The first fraction of effluent, consisting of 6.5 bed volumes, had a mercury concentration of 222 ppm, indicating immediate breakthrough. Another piece of information gained from this experiment was that the length of the mass transfer zone was longer than the total length of the column and thus larger than 2.5 cm.

To improve mercury removal and to find the mass transfer zone length, a second column experiment was performed with a bed length of 7.6 cm. From the results of this experiment it was concluded that the mass transfer zone length was about 6.2 cm at a liquid superficial velocity $[(\text{volumetric feed rate})/(\text{cross-sectional column area})]$ of 0.0068 mm/s. A mass balance on this test showed that at exhaustion the column had reached 5.8% of the theoretical mercury capacity, which is consistent with the results of the jar mill tests at this pH. As previously reported, the capacity increases with solution pH. This result may be used to design large-scale columns operating at similar liquid superficial velocities. The initial effluent that exited the column contained 20 ppm mercury, which is 100 times higher than the Environmental Protection Agency's (EPA) limit (0.2 ppm). The column length was consequently

increased (to 12.6 cm) in the next experiment, which resulted in a tenfold decrease in the initial effluent concentration from the column. The results of the three experiments are shown in Fig. 9.

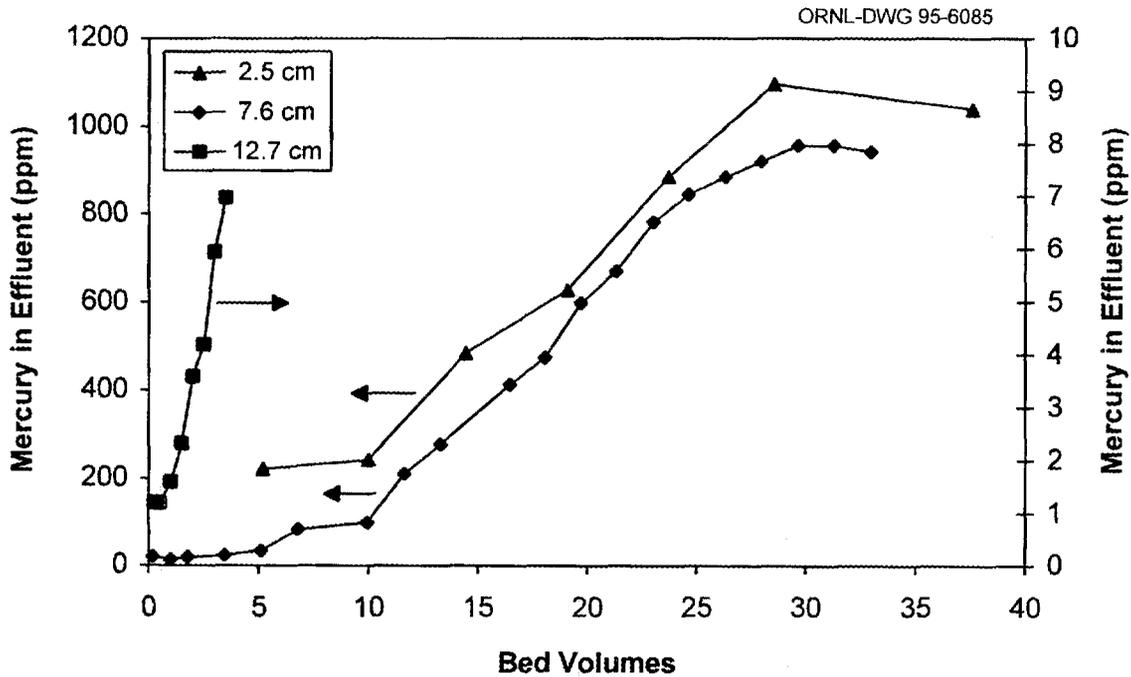


Fig. 9. Effect of column length on mercury removal.

3.2.3 Effect of Feed Concentration

Feed concentrations with 625 and 975 ppm mercury were tested at a higher liquid superficial velocity (0.014 mm/s) in 12.6-cm columns (see Fig. 10). The bed capacities for mercury in these two experiments were (at 5% breakthrough) 15 and 9 bed volumes, respectively, and the initial effluent concentrations were about 5 and 10 ppm mercury, respectively. These results may directly be applied to large scale-column design.

3.3 Aiming for EPA's Toxic Characteristic Level

EPA's toxic characteristic level (0.2 ppm) was reached in a column test with a bed length of 56.5 cm. This column experiment worked so well that it was shut down after 127 bed volumes of feed (350

ppm, pH 3) had passed through the column. The effluent at shutdown contained 0.025 ppm mercury. Various liquid superficial velocities were tested throughout the experiment with essentially no change in the effluent concentration. A mass balance over the column indicate that 45 g mercury was sorbed in the column. This corresponds to 11% of the theoretical capacity, which compares well with the other data collected.

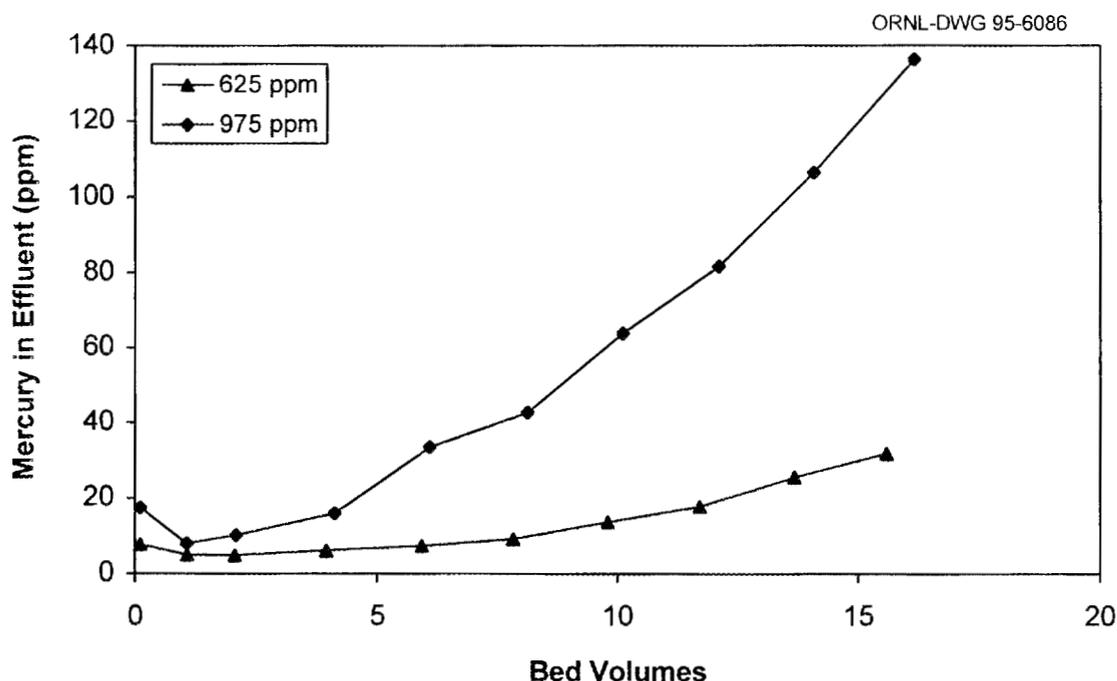


Fig. 10. Effect of various mercury feed concentrations.

3.4 Assessment of Engineering Design Data for Ion Exchange Operations

Several commercially available ion exchange materials are possibilities for use in separating mercury from aqueous media. The specificity and capacity of these materials vary in general with pH and the presence of particular competing ions. As part of the MWIP Mercury Control project, information has been collected on these materials and evaluated to determine whether sufficient data are available for engineering design and feasibility studies. Table 1 gives the list of materials that were evaluated.

The first three items in Table 1 appear to be nearly identical materials, that is, a macroporous, weakly acidic polystyrene/divinylbenzene cation resin with thiol functional groups. This material has

been tested extensively at the Savannah River Site and our assessment is that sufficient information exists on this resin for engineering designs for additional applications. A summary assessment of this material is the in the following.

Table 1. Ion exchangers for mercury separations

1. Duolite GT-73 (Rohm and Haas)	Thiol functional group
2. Purolite S-920 (Purolite)	Thiol functional group
3. Ionac SR-4 (Sybron Chemicals)	Thiol functional group (prepared by hydrolysis of isothiuronium group)
4. Ionac SR-3 (Sybron Chemicals)	Isothiuronium functional group
5. Ionac SR-5 (Sybron Chemicals)	Iminodiacetic function group
6. HiPAC SPE (Chromatochem)	Silica-based aminomercaptan chelation resin
7. Diphonix (Eichrom Industries)	Gem-diphosphonic acid resin
8. NASA Lewis Research	Co-polymer of polyvinyl alcohol and polyacrylic acid
9. SuperLig® (IBC Advanced Technol.)	Organic ligands chemically-bonded to silica gel (not truly ion exchange)

Another type of ion exchanger is Ionac SR-3 (Sybron Chemicals) . This exchanger contains an isothiuronium group, a powerful sequestrant for mercury. This exchanger can be used in a pH range of 0 to 6 and is said to separate mercury regardless of its ionic form. According to the manufacturer, it has been shown to effectively sorb methylmercury.

Contacts with Eichrom Industries indicated that Diphonix resins are not suitable for mercury separations; thus, this ion exchanger was not studied further.

Contacts with IBC Advanced Technologies indicated that their SuperLig products, SuperLig 604 and SuperLig 618, should be investigated. IBC Advanced Technologies has submitted a proposal to supply these materials to ORNL for testing, with some training and support. The proposal is being considered for fiscal year 1995 funding.

3.4.1 Summary Assessment for Duolite GT-73 (Rohm and Haas)

3.4.1.1 Sources of Information

Bibler, J. P., Wallace, R. M., and Ebra, M. A., "Mercury Removal from SRP Radioactive Waste Streams Using Ion Exchange," *Waste Management '86 Proceedings* **2**, 471–73 (1986).

Osteen, A. B. and Bibler, J. P., "Treatment of Radioactive Laboratory Waste for Mercury Removal," *Water, Air and Soil Pollution* **56**, 63–74 (1991)

Ritter, J. A. and Bibler, J. P., "Removal of Mercury from Wastewater: Large-Scale Performance of an Ion Exchange Process," *Water Science and Technology* **25**, 165–72 (1992).

Haefner, D. R., "Treatability Study of Aqueous Land Disposal Restricted Mixed Waste Containing Mercury and Lead," pp. 14.5.1–8 in *Proceedings of 2nd International Symposium on Mixed Wastes*, Baltimore, Md. 1993.

3.4.1.2 General

Duolite GT-73 is a macroporous, weakly acidic polystyrene/divinylbenzene cation resin with thiol functional groups. Haefner states that Purolite S-920 is very similar and provides an alternative source of supply. Savannah River Site staff have tested GT-73 on several of their waste streams and are using it currently to treat condensate and sump waters generated during process demonstrations of the Integrated Defense Waste Processing Facility. Two beds are used in series, each containing 0.7 m³ of resin. The resin cost was reported by Savannah River Site as about \$17,000 per cubic meter. Savannah River Site staff have found that GT-73 effectively removes mercury in its +2, +1, and 0 valence states. The resin can be used over a pH range of 1 to 13.

3.4.1.3 Equilibrium Data

Bibler (1986) reported distribution coefficient values (K_d in mL solution/gram of dry resin at pH = 8) of 70,000 for Hg^{2+} , 3600 for Hg_2^{2+} and 8900 for Hg^0 . The saturation capacity for Hg^{2+} is reported by the manufacturer as 140 g/L and was confirmed by Bibler. In the 1992 paper by Ritter and Bibler a “stated operating capacity” of 30 g/L is mentioned, perhaps because of competitive sorption of other metals in the wastewater studied.

3.4.1.4 Kinetics

Haefner gives a breakthrough curve (up to about 50%) for a 12-mL bed and a flow rate of 2.4 mL/min. The bed length was 6.75 cm. At 5% breakthrough, 840 bed volumes of effluent had been collected, and at 50% breakthrough, 1050 bed volumes had been collected. The length of the mass transfer zone is calculated at 1.35 cm for the 5 to 50% portion, which can be projected to about 2.7 cm for the entire zone. The superficial velocity for these data was 0.022 cm/s, somewhat low compared with the usual range for industrial ion exchange operations of 0.08 to 0.5 cm/s but the same as that used at Savannah River Site for their 700-L beds.

3.4.2 Summary Assessment for Ionac SR-3 (Sybron Chemicals)

3.4.2.1 Sources of Information

McGarvey, F. X. and Hauser, E. W., “Removal of Mercury from Industrial Wastes as well as from Potable Waters,” *Proceedings of 6th International Conference on Chemistry for the Protection of the Environment*, Sept. 15–18, 1987, Torino, Italy.

McGarvey, F. X., “Selective Ion Exchange Resins in Gold Processes: Mercury Removal and Gold Recovery,” *95th Annual Convention, Northwest Mining Association*, Dec. 3–8, 1989, Spokane, Wash.

3.4.2.2 General

Ionac SR-3 is a selective chelating, macroporous polystyrene/divinylbenzene resin with isothiuronium functional groups. According to the manufacturer, this resin is useful over a pH range of 0 to 6 and recovers mercury regardless of its ionic form. It has been shown to effectively sorb methylmercury and finely divided elemental mercury. The resin cannot be regenerated by conventional methods.

3.4.2.3 Equilibrium Data

The mercury (Hg^{2+}) capacity given in the manufacturer's literature is 119 g/L, which is slightly lower than that for the thiol resins (140 g/L). Distribution coefficient values were not found.

3.4.2.4 Kinetics

No breakthrough curves were found. The manufacturer recommends flow rates in the range of 0.08 to $0.33 \text{ m}^3/\text{m}^3\cdot\text{s}$ (or 5 to 20 bed volumes per hour). Personnel at the Sybron Technical Center recommend a minimum bed depth of 71 cm. They believe the mass transfer zones are about 10 cm.

3.4.3 Cost Analysis

Clearly, process economics will be much more favorable for Mersorb if it is applied to solutions at the higher pH; even at the lower pH, however, it may be competitive. This possibility can be illustrated by comparing sorbent costs with Duolite GT-73 ion exchanger. Mersorb costs about \$3 per pound, and even when loaded to only 3% of theoretical capacity, the cost per gram of mercury sorbed is about \$0.28. According to Savannah River reports, Duolite GT-73 costs about \$17 per liter and has a capacity of about 30 g of mercury per liter of resin; thus, Duolite GT-73 costs about \$0.56 per gram of mercury sorbed. It is assumed that neither sorbent is regenerated. A complete economic analysis would consider many other process costs, but the sorbent costs cited here indicate that Mersorb may well find some applications in treating DOE mixed wastes.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

From results of bench-scale laboratory experiments, the following conclusions were reached:

1. Sulfur-impregnated, activated-carbon pellets (Mersorb®) can be used to remove mercury (Hg^{2+}) to below EPA's toxic characteristic level (0.2 ppm).
2. Mersorb works under acid conditions (pH 2), but its capacity is reduced about 50% compared with neutral conditions.
3. Competing ions in the target waste stream reduced Mersorb capacity with 50%.
4. Mersorb appears to be economical compared with the leading ion exchange resin.
5. Commercial ion exchange resin information was compiled, but specific design data were hard to locate.

4.2 Recommendations

It is suggested that future studies should include sulfur-impregnated activated carbon and the three most promising commercial ion exchange resins in laboratory column studies. A variety of superficial velocities should be studied for low pH feed, and complete breakthrough curves should be obtained. Batch (jar mill) experiments may be useful to investigate effects of competing ions. Cost information (including waste disposal cost) should be compiled before final recommendations are made.

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