Metal Recovery Systems: Development & Use of Cost Estimation Equations

By J. Schumann & S.K. Ong

The goal of this paper is to provide an easy way for environmental professionals to derive rough estimates of capital costs required to build waste recovery systems and the operating costs required to keep them running. Cost estimation equations were developed as part of a facility-specific cost estimate. These equations were normalized, based on flow rate (gal/min) and metal mass flow rate (metal loading, lb/day), to make them applicable to many situations.

Table 1
Summary of Flows & Concentrations During Sampling

	Volumetric Flow Rate gal/min*	Copper Conc. mg/L	Nickel Conc. mg/L	Copper Mass Flow lb/day	Nickel Mass Flow lb/day
Rinsewater	195	7	9.3	6.3	7.3
Acid wastes	0.34	890	420	1	0.5
Basic wastes	0.25	65	24	0.06	0.02
Cyanide	23	121	N/A	11.2	N/A
Total	—	—	—	**18.6**	**7.8**

* Mixed metal waste streams—includes copper, nickel, tin & lead.

The metal finishing industry generates a considerable amount of heavy metal wastes, much of which is disposed of as hazardous wastes. As hazardous waste disposal costs increase, more and more firms in the metal finishing industry are looking to methods that will allow recovery of metals for refinement or resale. By this approach, liability issues are avoided and, frequently, disposal costs can also be reduced. Environmental regulations administered through the Resource Conservation and Recovery Act (RCRA), governing heavy metal-bearing waste streams are quite specific on one matter—a spent material that is recycled or reclaimed is considered differently if disposed of by land-filling (40 CFR 261.1 (c)). This regulation has far-reaching impact on disposal of the spent material. Under the RCRA "cradle-to-grave" system of waste handling and disposal, the generator has permanent liability for all disposed hazardous wastes. Permanent liability is avoided if the waste material is recovered for reuse or resale. Building and operating a recovery plant, however, requires capital expenditure and yearly operating expenses, the magnitudes of which are difficult to determine.

Description of Facility & Waste Streams

The project that provides the basis for this article was originally completed for an active electroplating facility in the eastern United States. The facility employs standard electroplating techniques, resulting in the following distinct waste streams:

- A high-flow-rate, low-concentration rinsewater stream derived from rinse stations following each step in the plating process;
- A high-concentration, low-flow-rate acidic waste stream composed of dumped plating baths;
- A high-concentration, low-flow-rate basic waste stream from dumping of sodium hydroxide-based cleaner baths;
- A cyanide waste stream from dumped cyanide-based plating baths and cyanide rinses.

The waste streams are segregated by their respective chemistries. Dissolved metals in these streams are a mixture of copper, nickel, lead, tin and iron. The facility has an existing wastewater treatment plant (WWTP) that utilizes a lime-precipitation process to remove dissolved metals. The WWTP produces a hydroxide sludge containing a mixture of metals. The current sludge cannot be recycled and is disposed of as a hazardous waste at considerable cost.

In the spring of 1996, a snapshot sampling event was completed at the facility. Copper and nickel concentrations were determined, along with flow rates. The results of this sampling event are detailed in Table 1. From the concentration and flow rate data, metal mass loading rates in pounds metal/day were determined for each waste stream (Table 1). The rinsewater stream constitutes the majority of flow and metals loading at the facility. The cyanide stream contributes the majority of copper. The basic and acidic wastes, while concentrated, do not contribute large amounts of metals because of low flow rates. With the exception of the cyanide and basic streams, all waste streams were acidic. The last two columns of this table are for segregated flows, which will be covered below.

Metal Recovery Methods & Technology Screening

Mixing of metals within a waste stream renders the final treatment product useless to a recycler, inasmuch as no metal can be readily separated from the sludge in pure form.[1] If waste streams are segregated on the basis of individual metals, however, the final product of the treatment will be relatively pure, making it useful for recycling.[1] A technology capable of recovering dissolved metals is thus applied to a segregated waste stream from which each metal can be recovered for reuse or resale, and hazardous waste generation is reduced.[2]

Based on available literature and the following criteria, a preliminary screening of recovery technologies was conducted to determine which technologies were applicable to the facility. The screening criteria were:

- Technology recovers metals in a form that could be reused on site, or in a form acceptable to a secondary metals refiner

- Capable of meeting the current discharge permitted concentrations in the plant outfall
- Compatible with the chemistry of the waste stream to be treated
- Currently in commercial use

Because copper and nickel represent the largest quantity of metals at the facility, this project focused on their recovery. Based on the preliminary screening, three recovery technologies were selected for design and cost analyses. The three recovery technologies were ion exchange, segregated precipitation, and electrodeposition. A general description of these technologies, along with their application are described below. Detailed discussions of each recovery technology are covered elsewhere (see references).

Ion Exchange

Ion exchange (IX) removes metal ions from a dilute waste stream by exchanging them for nonhazardous ions. The exchange takes place on electrically charged sites within resin beads. When the sites on the resin fill up with exchanged ions, the IX column is taken offline for regeneration. Regeneration is accomplished by flushing the column with a concentrated acid. The resulting regenerated solution consists of the metal salt of the acid. The reactions at the IX resin surface are pH dependent, and resins have optimum pH ranges specific to their manufacture.[3] At this facility, IX can be applied to treat the rinsewater stream, as well as the acid and basic wastes if neutralization is first carried out. Ion exchange can also be used for copper recovery after cyanide destruction.

Segregated Precipitation

The goal of segregated precipitation (SP) is to form insoluble metal precipitates that can be sent to a refiner for metal recovery. This system is basically a standard hydroxide precipitation system applied to waste streams segregated by metal. The resulting sludge is relatively pure in a single metal, which allows metal recovery to be accomplished.[4] At this facility, SP can be applied to treat the rinsewater stream, and the acid and basic wastes, if neutralization is first carried out. Segregated precipitation can also be used for copper recovery after cyanide destruction.

Electrodeposition

Electrodeposition (ED) involves the application of electrical current to plate dissolved metals out of wastewater onto a cathode. It is carried out in tanks equipped with insoluble cathodes and anodes. In service, metal bearing wastewater is passed through the tanks. Current passed through the waste stream causes reduction of the metal ions, resulting in metal deposition on the cathode.[5] At the anode, various oxidation reactions take place, based on the chemistry of the waste stream. After a time, the cathode is removed and the deposited metal recovered. Electrodeposition can be used for metal recovery from the IX regeneration solutions.

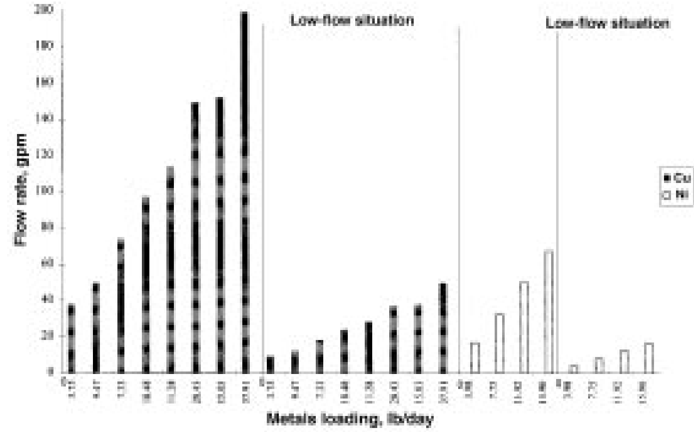

Fig. 1—Segregated flow rates and metals loading.

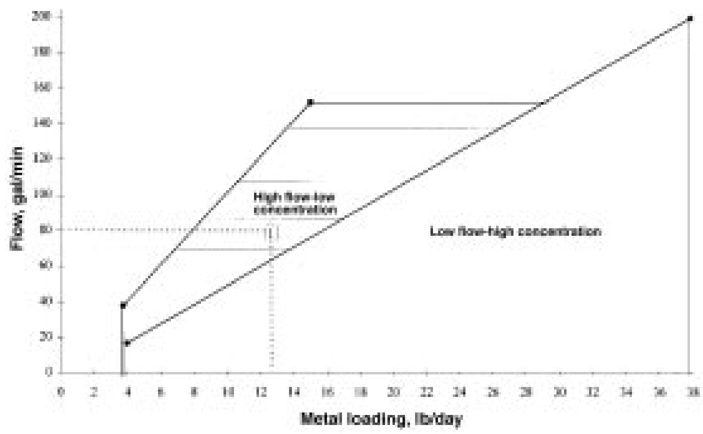

Fig. 2—Operating range for ion exchange systems.

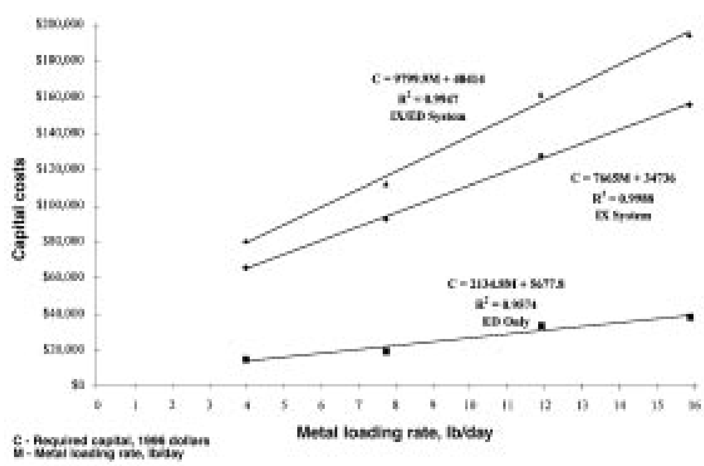

Fig. 3—Ion exchange required capital costs: low-flow, high-concentration, 4-17 gal/min.

Design

At the time of the sampling snapshot, only a few of the plating lines at the subject facility were operating. To bracket conditions in the facility and to provide information on trends in costs, designs were performed at several flow rates. The flow rates shown in Table 1 were overall mixed metal flows. To design recovery systems, the segregated flow rate and associated metals loading for each metal had to be determined. Segregating the overall flow rates was done by determining flows from each step of the plating process and which metal was used in that step. The resulting segregated flow rates were 73.8 gal/min and 32.9 gal/min for copper and nickel, respectively. The balance of the original overall flow rate went into a stream containing a mixture of lead, tin

Table 2—Design Assumptions

Assumption	Rationale & References
IX Design	
• Resin capacity for hydraulic loading was 2 gal/min/ft^3	• Value provided by ref.[9]
• Resin capacity for metals loading was 2.93 lb metal/ft^3 resin	• Value provided by ref.[3,9]
• Resin specified has optimum pH of 3-4	• Minimized pH adjustment
• Maximum pressure loss through resin specified as 70 psi	• Allowed use of less expensive piping while minimizing the required number of reactors
• Piping spec. as Sched. 40 or 80 PVC	• Based on pressure condition
• Sulfuric acid chosen as regenerant	• Relatively inexpensive
• IX reactors are coated carbon steel	• Minimized capital cost while allowing corrosion resistance
• Bag filters and strainers required prior to reactors	• Minimized risk of plugging the resin with particulates
ED Design	
• Cathodes were plates, or shot made of the metal to be recovered	• Allowed maximum surface area in a minimum space
• Anodes were graphite pellets	• Corrosion resistant material that maximized surface area
• ED tanks specified as fiberglass or polyethylene	• Corrosion resistant materials that minimized capital costs
SP Design	
• Batch operation of sludge dewatering	• Minimizes amount of equipment required
• Sludge thickeners sized for 1-2 day retention time	• Allows sludge to be accumulated and dewatered on a batch basis
• Inclined plate clarifiers specified	• Minimized footprint required in facility

and iron. From these segregated flows, several other flow rates and associated metals loads were extrapolated. Figure 1 shows the range of flows used in design.

In addition, to assess costs at low flows, designs were also performed at flow rates corresponding to 25 percent of the above-described segregated flows, with the same metals loadings. These flow rates and metal loadings (shown in Fig. 1) were then used for copper and nickel recovery system designs. Inclusion of the cyanide stream as a copper waste resulted in additional design flow rates for copper waste streams. The following systems were designed:

1. Separate IX systems for copper and nickel recovery, each including:
   - pH adjustment system
   - Resin columns, surge tank, pumps, valves and process piping
   - Batch neutralization systems for the acidic and basic wastes
   - Regeneration system
2. Separate IX systems for copper and nickel recovery, the same as described above, with addition of an ED system to recover metals from the regeneration solutions.
3. Separate SP systems for copper and nickel recovery, each including:
   - Batch neutralization systems for the acidic and basic wastes
   - Flocculation tanks, clarifiers and sludge thickeners
   - Surge tank, pumps, valves and process piping
   - One lime feeder, dissolving tank, filter press and sludge dryer for the combined copper and nickel recovery systems.
4. Separate SP systems for copper and nickel recovery, the same as Item 3, but with reuse of the facilities' existing filter press and sludge dryer. This system assumes the facility has an existing precipitation system and is upgrading to a recovery system.

Brief information on the basis of each system design is as follows.

General Issues

To allow metal recovery, it is necessary to segregate the waste streams into copper- and nickel-bearing wastes. For this, the waste piping system within the facility must be modified. For instance, instead of having one rinsewater pipe, a pipe for copper rinsewaters and one for nickel rinsewaters would be provided. Copper acidic and basic wastes must be kept in separate systems until they are processed for neutralization. Neutralization would be accomplished by mixing together copper acidic and basic streams together in a holding tank under controlled conditions. The facility does not generate a nickel basic waste. Therefore, nickel acidic wastes were stored in a separate holding system and bled into the nickel rinsewater stream.

IX Design

Table 2 lists the specific assumptions for the IX design. The main parameter for IX design was the volume of resin required. This volume was based on either the flow rate or on the metals loading, whichever required a greater volume. In the course of design, it was apparent that flow rate controlled the design in all cases except for low flow/high metals loading. Pumps were sized according to pressure requirements and flow rates. A pH adjustment system was included in the designs to adjust flows to this range. A regeneration system was also included. The IX system was stripped down with little automation beyond timers to start and stop the regeneration cycle.

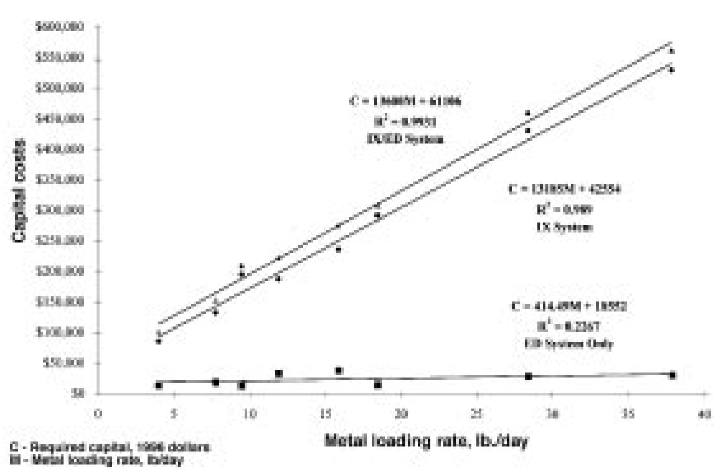

Fig. 4—Ion exchange required capital costs: low-flow, high-concentration, 17-200 gal/min.

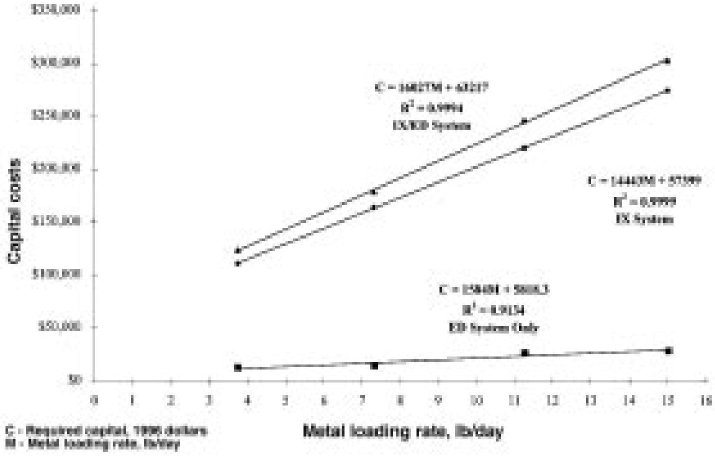

Fig. 5—Ion exchange required capital costs: high-flow, low-concentration, 9-38 gal/min.

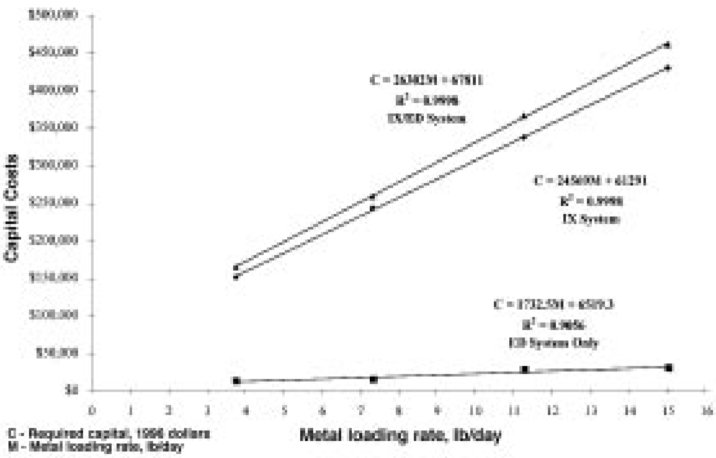

Fig. 6—Ion exchange required capital costs: high-flow, low-concentration, 38-152 gal/min.

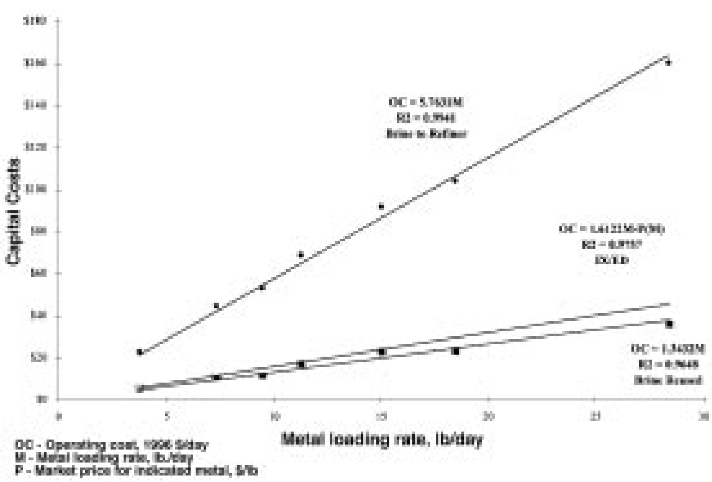

Fig. 7—Copper IX operating costs: flow rate 9.5 to 38 gal/min.

ED Design

Electrodeposition systems were designed to recover copper and nickel from the concentrated sulfate solutions produced during IX regeneration. Table 2 lists parameters used in the design. Sizing of cathodes and anodes was based on surface reaction rate constants derived from references.[6,7] The ED tanks were sized based on the volume of regeneration solution from the IX and the time required for plate-out.

SP Design

Table 2 lists assumptions that went into SP design. Because the facility already uses precipitation processes, some of the equipment could be reused, such as the sludge dryer and the filter press. By reusing equipment, capital costs may be greatly reduced. Reuse of the existing sludge dewatering equipment assumes that copper- and nickel-bearing sludges would be dewatered on a batch basis. Each waste stream (copper and nickel) required a dedicated clarifier. A new lime feeder system was included in the design.

Cost Estimates

Based on the design for each system, detailed cost estimates were prepared. Capital costs for installed systems were determined for each flow rate and associated metals loading. Table 3 lists assumptions for the capital and operating costs analyses. Costs were derived from literature and engineering cost estimation sources. Included in capital costs were piping for segregated waste streams, process piping, pumps, valves, meters, and electrical equipment, plus labor for installation. Engineering costs were based on the assumption that these systems would be designed in-house. Using an outside consultant to perform the engineering will raise costs. All costs were based on 1996 dollars.

Operating costs were determined from chemical consumption, power required to operate pumps and metal resale, if applicable. At the time of this project, the chosen secondary metals refiner indicated that, for the quantity of metals generated at this facility, the refiner would accept the metals wastes for no charge.[8] Acceptance charges vary by refiner and are therefore specific to each situation.

Development of Cost Estimation Equations

Because costs were specific to this facility, plotting the costs as a function of either metals loading or flow rates allowed development of normalized cost equations. A statistical analysis was performed on each data set to determine equations resulting in the best fit for the data. Plotting the data as a function of metal loading rates provided a better statistical fit than did flow rates. In most cases, it was determined that the data followed a linear relationship between costs and metals loading. The data were found to contain sharp discontinuities, however, corresponding to changes in flow rate. Cost equations also had to reference flow rate, which led to development of Figs. 2 through 12.

Estimation equations are valid over a certain range of flows (Figs. 2-12). To use the equations, the metal loading rate (lb metal/day) must first be determined. This rate can be estimated from the flow rate of a waste stream and the concentration of metal within the stream.

Capital cost equations include a fixed cost (represented by the y-intercept in the linear cost equations). This fixed cost represents the price that must be paid regardless of the volume of waste to be treated. Since operating costs consist of consumable items, a no-flow situation results in a zero operating cost situation (y-intercept of zero). Use of ED to recover metals after IX results in income from metals resale. This income is linked to the current market price of the metals.

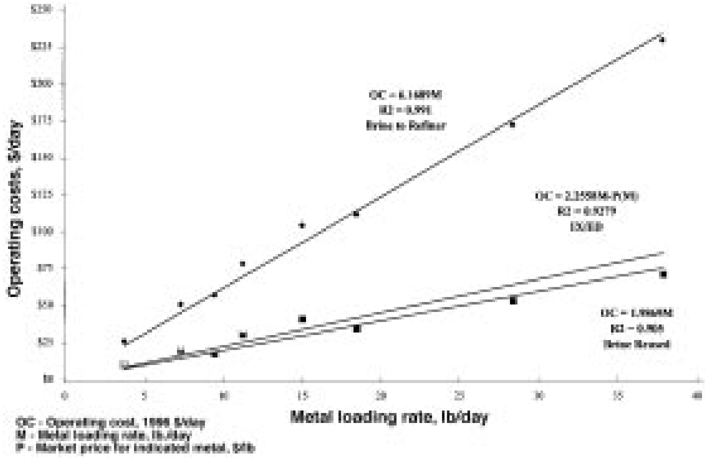

Fig. 8—Copper IX operating costs: Flow rate 38 to 200 gal/min.

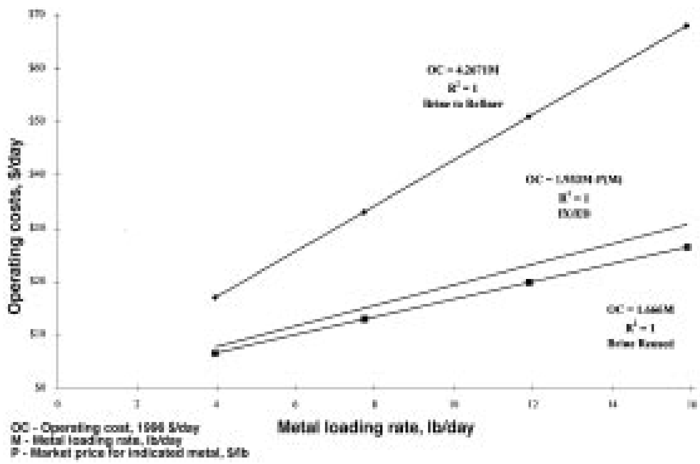

Fig. 9—Nickel IX operating costs: Flow rate 4 to 17 gal/min.

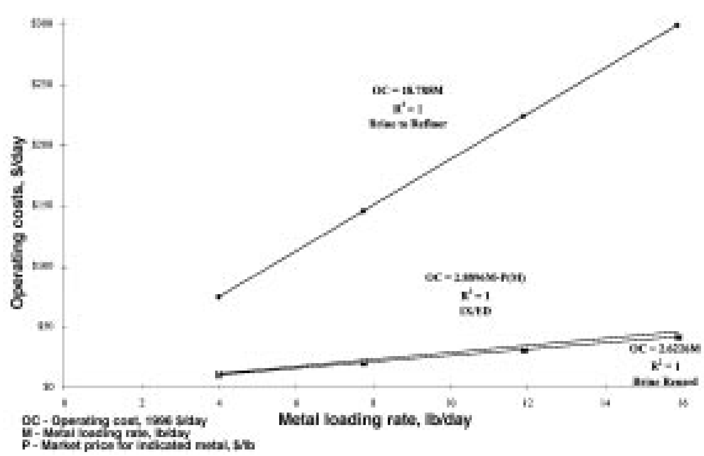

Fig. 10—Nickel IX operating costs: Flow rate 17 to 68 gal/min.

The operations cost equations for IX/ED contain a term to account for the sale price of metals.

Results

Ion Exchange (IX)

Capital

Capital costs for IX are a function of the mass of metal to be removed (metal loading rate) and flow rate, and are not highly dependent on the type of metal to be removed. Designs for IX were greatly affected by flow rate resulting from system hydraulics (flow-through resin beads). It was found that two distinct operating ranges for IX could be defined, as shown in Fig. 2. The low-flow-rate, high-concentration range corresponds to concentrated flow streams, as found in low-flow rinse streams and concentrated streams made up of plating baths. The high-flow rate, low-concentration range corresponds to a high-flow rate situation with low corresponding metal loads (indicative of dilute, high-flow rinsewater streams). This operating range required a greater number of columns for a given metal loading rate to process the volume of waste effectively.

To use the cost equations for IX, the operating range must first be determined from Fig. 2. For example, a metal load of 12 lb/day at a flow rate of 80 gal/min results in a high-flow, low-concentration situation (Point 1 in Fig. 2). Figures 3 through 6 show the cost estimation trends and equations for the operating ranges. Included in these figures are capital costs for an IX system complete with tanks, regeneration equipment, and all pumps, piping and electrical needs; the capital cost for an ED system and capital for the IX/ED system combined. As can be seen from these figures, for a given metal load, it is significantly cheaper to build and operate an IX system at a lower flow rate.

Operating Costs

Operating costs depend on the flow rate of the waste stream and the metal loading rate. Because recovered copper and nickel have different resale values per pound, operating costs must also take into account the type of metal. The IX system could be operated in three different schemes:

- Regeneration solutions could be shipped to a refiner directly,
- Solutions reused on site if the facility uses metal sulfate solutions, or
- Metals could be recovered from the regeneration solutions through use of an ED system.

Because each operating scheme has differing economics, equations were derived for each scheme. It was found, however, that the operating costs did not vary significantly as a function of the different operating ranges (as defined in the capital cost section).

Cost equations are shown in Figs. 7-10. The IX operating costs consist of resin replacement, power costs, and costs for chemicals such as regeneration acid and pH adjustment chemicals. Resin was assumed to require replacement every five years.[3] Volume of chemicals was calculated based on resin capacity and flow rates, while power costs were based primarily on required pump power.

The least attractive operating scheme was shipment of regeneration solutions to a refiner. The nearest refiner to this facility requires shipment over a distance of 400 miles. Shipping the regeneration solutions to a refiner for disposal results in significant transportation costs, thereby rendering this method uneconomical.

Use of ED to recover metals from the regeneration solutions results in additional power costs, but little transportation expense. Recovery of metals for resale through ED allows at least a portion of the operating costs to be recouped.

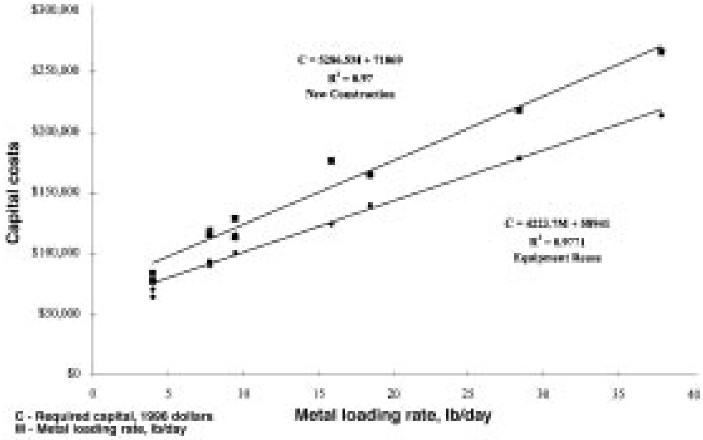

Fig. 11—Selective precipitation required capital costs, 4-200 gal/min.

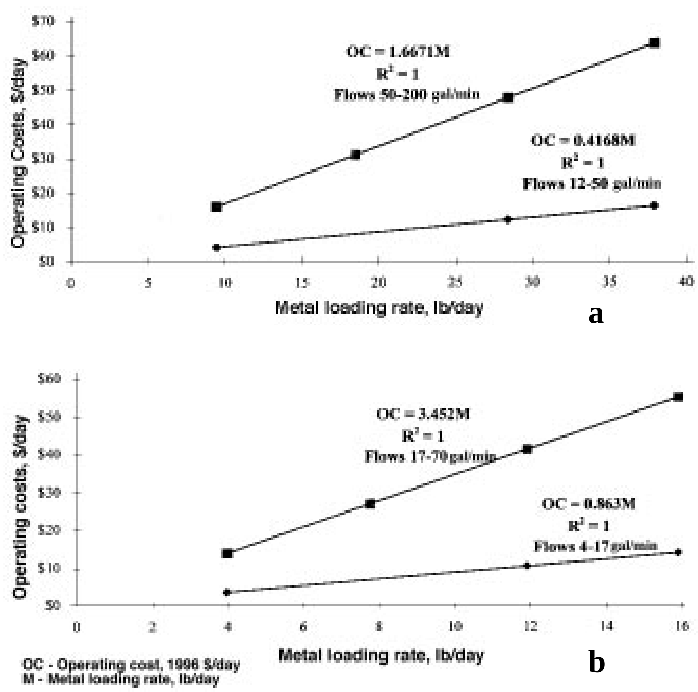

Fig. 12—SP operating costs: (a) copper; (b) nickel.

The cost effectiveness of the IX/ED system is linked to the current price of metals; therefore, the operating cost equations contain a term to account for the price of the metal. In these equations, a negative cost would result from income from metals sales greater than operating costs, thereby indicating a profit. Using the equations, the break-even price for the metals can be determined for a specific metals loading by setting the operating costs to zero and solving for the current price. For instance, nickel wastewaters in the 4-17 gal/min, 10 lb/day range had a break-even nickel price of $1.93/lb.

Reuse of regeneration solutions on site also greatly lowers costs (no transportation). The cost effectiveness of regeneration solution reuse, however, is also linked to the market price of metals. Because the study facility did not use sulfate solutions as plating materials, this aspect was not explored, and the operating cost equations do not reflect savings resulting from solution reuse.

Selective Precipitation (SP)

Capital Costs

The SP capital costs were well represented by a single linear equation over the flow rate range of 4 to 200 gal/min (see Fig. 11). Because SP systems consist of tanks, clarifiers and mixing equipment that constitute a less restrictive hydraulic situation than IX, SP costs are less dependent on flow rate. If the facility already uses precipitation, the existing lime feeder and sludge dewatering equipment can be reused, thereby lowering capital expense (see Fig. 11). Such SP systems will require separate clarifiers for each metal stream, but sludge can be dewatered and dried in batch processes by including a sludge thickener tank with 1-2 days' capacity.

Operating Costs

The SP operating costs consist of chemical use, power costs and transportation. Because sludges must still be shipped to a secondary metals refiner every 90 days, sludge transport constitutes a significant portion of operating costs. Equations for SP are summarized in Fig. 12. Operating costs for copper and nickel systems were more indicative of metals loadings and flow rates than of the metals themselves, inasmuch as no income was derived from the sludge.

Comparison of IX to SP

Capital Cost

IX systems require less capital cost at low flow rates than other systems for the same flow and metals loading. For example, at a metals load of 5 lb/day (10 gal/min), IX has a capital cost of $73,060 vs. $97,500 for SP. At higher flow rates, however, the situation is reversed. At 10 lb/day (20 gal/min), IX capital costs are $174,400 vs. $123,930 for SP. Figure 13 depicts this situation. As can be seen, capital costs for SP systems do not become cheaper than capital costs for IX systems until flow surpasses about 11 gal/min.

Operating Cost

To provide an example based on the time of the sampling snapshot, consider the case where nickel waste streams are flowing at 33 gal/min, with a total metals loading of 7.75 lb/day (Table 1). Using the appropriate operating cost equations from Figs. 10 and 12, an SP system would cost $26.75/day to treat those waste streams. If nickel was selling for roughly $3/lb, however, an IX/ED treating the same waste streams would actually generate a small profit of $0.85/day. As can be seen from this example, IX/ED can be operated more cheaply than SP. The IX/ED system would cost more to build, however, than a comparable SP system ($166,500 for IX/ED vs. $112,040 for SP). Operating costs are a function of many factors, such as metal resale and refiner acceptance charges. A comparison between IX and SP should be specific, therefore, to the operational situation. If a recovery system is desired, a facility-specific comparison should be made to determine which system will result in the lowest operating costs.

Conclusions

Overall, for a given metals load, it is significantly cheaper to build and operate a metals recovery system at a lower flow rate. Lower flow rates allow the size of equipment to be mini-

Table 3—Assumptions for Capital Costs

Assumption	Rationale & References
• Electrical costs were 20% of project	• Standard cost factor[10]
• Engineering costs were 5% of project	• Standard cost factor[10]
• Site preparation work (excavation, etc.) was 10% of total project costs	• Standard cost factor[10]
• Tanks are all plastic, costing $6.50/gal, including installation	• Cost factor derived from reference[11] for polyethylene or fiberglass tanks
• Plant waste piping required roughly 600 ft of 4Ó PVC pipe per segregated waste stream	• Value specific to the study facility
Assumptions for Operating Costs	
• Yearly costs based on 250-day working yr	• Standard for this facility
• Work day based on eight hr	• Standard for this facility
• Transportation to a refiner would require a 400-mile trip	• The refiner chosen for this analysis is located approx. 400 miles away
• Transportation cost was $122/ton-trip	• Value derived from ref.[6] and corrected for a 400-mile trip
• Metal recovery systems will not increase operator time and cost	• The facility already employs a full time WWTP operator, who would be available to operate recovery systems
• Pumps and motors were 70% efficient	• Allowed determination of power costs
• No refiner acceptance charges for sludges	• Value provided by ref.[8] for the volume of sludge produced by the study facility

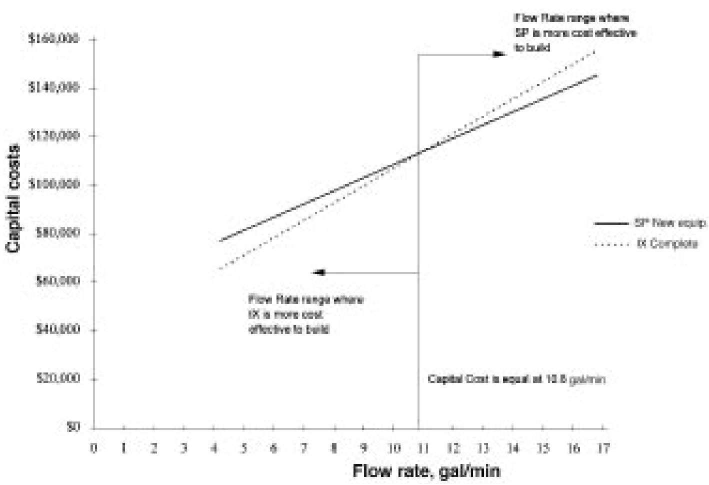

Fig. 13—Comparison of IX and SP capital costs.

mized, along with the volume of chemicals required for operation. Pump power is also minimized by reduction of flow rate; therefore, efforts to minimize wastewater generation will result in a reduction of costs.

From a capital cost standpoint, IX is applicable to low-flow waste streams as a result of the restrictive hydraulics of flow through the resin bed. Both capital and operating costs are dependent on both the metals loading and the flow rate. In all cases, it is cheaper to build and operate IX systems at low flow rates. Reusing the IX regeneration solutions on-site, or recovering metals through ED for resale represent the most cost effective operation. Use of ED allows part of the operating costs to be recouped.

Segregated precipitation is more applicable to higher flow rate waste streams from a cost standpoint. From this analysis, SP is not cost-effective for capital expenditure at flow rates less than 11 gal/min. In all cases, SP operating costs must include transportation of the sludges to a secondary metals refiner every 90 days to comply with RCRA requirements.

It should be noted that the cost estimation equations in this article are intended to give rough estimates in 1996 dollars. Because the situations governing waste generation are ultimately very specific to each facility, these equations are not intended to give a detailed, construction-ready cost estimate.

***Editor's note:** Manuscript received, February 1998.*

Summary of Abbreviations

RCRA—Resource Conservation and Recovery Act
WWTP—Wastewater Treatment Plant
C—Capital cost in dollars
OC—Operating costs in dollars/day
M —Metals load in lb/day
P—Market price of metal in $/pound

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