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WASTEWATER PRETREATMENT AND COMPLETE TREATMENT COST MODELS FOR SELECTED INDUSTRIES

The University of Oklahoma PH.D. 1979

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THE UNIVERSITY OF OKLAHOMA

GRADUATE COLLEGE

WASTEWATER PRETREATMENT AND COMPLETE TREATMENT COST MODELS FOR SELECTED INDUSTRIES

A DISSERTATION

SUBMITTED TO THE GRADUATE FACULTY

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By

KUNG-CHEH GEORGE LI

Norman, Oklahoma

1979

WASTEWATER PRETREATMENT AND COMPLETE

TREATMENT COST MODELS FOR

SELECTED INDUSTRIES

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WASTEWATER PRETREATMENT AND COMPLETE TREATMENT COST MODELS FOR SELECTED INDUSTRIES

CHAPTER I

INTRODUCTION

Public Law 92-500 (1), amending the Federal Pollution Control Act, as passed by Congress on October 18, 1972, and contains several points of direct interest to industry. The industrial cost recovery (ICR) and pretreatment of industrial wastes are of major importance. In many instances, companies with industrial wastes have the choice of treating their wastes themselves (on-site treatment) or tying into a publicly owned treatment works (POTW) system, after any pretreatment and paying the ICR and service charge to the municipal system. With the new PL 92-500 in full effect, it could be more advantageous for the industry, that the industry constructs and operates its own wastewater system. Thus, it is really necessary to carry out a research which can assist the industry in choosing the optimum strategy for municipal versus on-site treatment of its wastes.

The purpose of this research was intended to develop a set of industrial waste pretreatment and complete treatment cost models which correlates treatment costs with waste variables. By applying these cost models, the total cost of treatment of an industrial waste in its own treatment plant and in a municipal wastewater system can thus be compared. As a result, the industry can select a correct path to follow - either to treat its own wastes, to join a group treatment of industrial wastes, or to contact a municipality to accept, treat and dispose of its waste incurring in paying ICR and user charge after any pretreatment.

In addition, in response to the new Public Law 92-500 (Federal Water Pollution Control Act Amendments of 1972) and Public Law 95-217 (Clear Water Act of 1977) (2), there will be a substantial investment in waste treatment by private industry during the next ten years. These cost models should provide reasonable estimates of the initial investments involved in constructing and equipping these waste treatment plants.

Among major industries, the following industries have been considered the major consumers of natural resources, the major users of water, and the significant contributors to polluting discharge to the environment.

Petroleum Refining

Pulp and Paper

Electroplating

Organic Chemical Manufacturing

Inorganic Chemical Manufacturing

The above industries are also subject to Environmental Protection Agency (EPA) pretreatment regulations. The cost models developed by this study were essentially for these industries.

Based on the information provided by these cost models, this study discusses how these models can guide industries when confronted with common problems — to construct independent treatment plant, to join group treatment from several sites, or to participate in a municipal collection and treatment facilities.

There is an increasing awareness of cost effectiveness in industrial wastewater treatment. Through an evaluation of cost models developed, a discussion related to the sensitivity of the factors affecting treatment cost, and the cost-effective design of treatment processes is included.

CHAPTER II

PREVIOUS WORK

Many cost models have been proposed to describe the relationships between cost and waste variable for wastewater treatment plants. This chapter is a chronological account of this development.

One of the pioneering works to establish a cost model for wastewater treatment was made by Velz (3) in 1948. Velz attacked this problem by collecting data on costs from about 500 plants. The data was then statistically analyzed by the following model.

$$Y = aX^b \tag{2.1}$$

where

Y = unit construction cost per MGD

X = size of plant in MGD

a,b = constants

The data analyzed by Velz was only from the Northeastern and central United States, and as such was valid only in these areas.

In 1957, a similar study was made by Diachishin (4) in an effort to update the work of Velz. Diachishin

extended his data collection to include other areas of the country. Two predictive models were derived; the first to be used for primary treatment plants with approximately 35% BOD removal, and the second for trickling filters and activated sludge plants. Both of these two models also used the form of equation 2.1.

Three construction cost models were formulated by Thoman and Jenkins (5) in 1958. These cost models, concerned primary treatment, secondary treatment plants, and oxidation ponds, were computed for estimating cost per capita as a function of design population. The models were developed in the following form.

$$Y = aX^b \qquad (2.2)$$

where

Y = construction per capita

X = design population

a,b = constants

The characteristic feature of Thoman and Jenkins' work was to consider the regional diffrerences in the construction costs. To account for these differences, the United States was divided into twenty areas on a county line basis. Each area corresponded to one of the twenty cities used in obtaining the United States average Engineering News Records — Construction Cost Index (ENR-CCI).

In 1963, the multiple regression model was first used by Wollman (6) to estimate the operation and mainte-

nance costs. The predictive model used was of the following form.

$$Y = b_o + b_1X_1 + b_2Y_2 + b_3X_3 \qquad (2.3)$$

where

Y = the annual operation and maintenance cost per daily population equivalency (PE).

X_1 = treatment level in per cent of BOD removed

X_2 = per cent of total waste that is industrial

X_3 = population served by sewage system.

b_o, b_1, b_2, b_3 = constants.

In 1970, Butts and Evans (7) made a study on the treatment, construction and operation costs for 291 projects built in Illinois between 1957 and 1968. Least square linear regression technique was used to relate design population equivalents to either unit costs in terms of dollars per design population equivalents or total costs in terms of dollars. The cost models were categorized into two classifications for new schemes and for plant additions. Equations for estimating construction and operation costs were in the general two-variable cost function form.

$$Y = aX^b \qquad (2.4)$$

where

Y = either construction or operation costs

X = plant design capacity

a,b = constants.

In the analysis of the construction of plant addition, an assumption was made that costs are related to both the initial plant size and the size of the addition. The predictive model, therefore, was analysed by the following form.

$$Y = b_o X_1^{b_1} X_2^{b_2} \qquad (2.5)$$

where

Y = cost of new addition to old plant

X_1 = capacity of new addition

X_2 = capacity of existing plant

b_o, b_1, b_2 = constants

Shah and Reid (8) using multiple linear regression techniques analyzed the construction costs of waste treatment plants in 1970. Regression equations were developed by using all possible and reasonable combinations of explanatory variables to explain the response, unit cost of construction. The form of equation was,

$$Y = b_o + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 \qquad (2.6)$$

where

Y = construction cost per design PE or design MGD, in 1957-59 dollars

X_1 = Design PE

X_2 = Design flow in MGP

X_3 = Design BOD of the influent in mg/ℓ

X_4 = BOD removal efficiency

b_o, b_1, b_2, b_3, b_4 = constants

Along with the linear form, the following non-linear forms of the equations were also tested.

$$\ell n\, Y = b_o + b_1 \ell n X_1 + b_2 \ell n X_2 + b_3 \ell n X_3 + b_4 \ell n X_4 \qquad (2.7)$$

$$\frac{1}{\ell n Y} = b_o + b_1 \ell n X_1 + b_2 \ell n X_2 + b_3 \ell n X_3 + b_4 \ell n X_4 \qquad (2.8)$$

$$\frac{1}{Y} = b_o + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 \qquad (2.9)$$

The symbols in equations 2.7, 2.8, and 2.9 are the same as equation 2.6. The variables, X_3 and X_4, related to the BOD in influent and BOD removal efficiency, were found to be not significant statistically, in the estimation of construction costs of waste treatment plants studied. The following are some typical models developed by Shah and Reid.

1) Primary treatments:

$$\ell n\, Y = 12.42 + 0.3852\ \ell n\, X_2 \qquad (2.10)$$

2) Waste stabilization ponds:

$$\frac{1}{\ell n Y} = 0.1291 - 0.0044\ \ell n\ X_1 + 0.0073\ \ell n\ X_2 \qquad (2.11)$$

3) Standard rate trickling filter:

$$\ell n\ Y = 7.90 + 0.4007\ \ell n\ X_1 = 0.9568\ \ell n\ X_2 \qquad (2.12)$$

4) High rate trickling filter:

$$\ell n\ Y = 9.39 + 0.3357\ \ell n\ X_1 - 0.6443\ \ell n\ X_2 \qquad (2.13)$$

5) Activated sludge treatment plant:

$$\ell n\ Y = 8.53 + 0.4610\ \ell n\ X_1 - 0.7375\ \ell n\ X_2 \qquad (2.14)$$

where Y in equations 2.11, 2.12 and 2.13 are construction cost per design MGD in 1957-59 dollars, and other symbols as in equation 2.6.

In 1973, Maisden, Pingry and Whinston (9) made a study to develop models for estimating the operation costs of activated sludge plants. The general form of the cost models was

$$\ell n\ Y = b_o + b_1 \ell n X_1 + b_2 \ell n X_2 + b_3 \ell n X_3 \qquad (2.15)$$

where

Y = operation cost per MG

X_1 = plant capacity in MGD

$$X_2 = \frac{\text{Influent BOD - Effluent BOD}}{(\text{Effluent BOD})^2}$$

X_3 = percent of design capacity used by the plant.

By using the operation cost data for activated sludge plants throughout Indiana for the years 1965-69. The following operating cost model was developed.

$$\ell n\ Y = 1425.104 + 0.513\ \ell nX_1 + 0.151\ \ell nX_2 - 0.567\ \ell nX_3 \qquad (2.16)$$

All the above cost models for wastewater treatment were developed primarily for industrially developed countries. In 1976, Reid and Muniga (10) made a pioneering work in an attempt to produce effective models for water demand, wastewater disposal, and cost of water and wastewater treatment in developing countries. The stepwise regression techniques were used to establish the best predictive equations. Among the eight sets of models developed, the one for predicting construction, operation and maintenance costs of activated sludge in the developing countries was as follows:

$$\ell nC'_{ww.af} = 6.5907 - 0.3020\ \ell nX_{20} + 0.0021\ \ell nX_{21} \qquad (2.17)$$

$$\ell nC''_{ww.af} = 5.1250 - 0.3355\ \ell nX_{20} \qquad (2.18)$$

$$\ell nC'_{ww.as} = 5.7594 - 0.2645\ \ell nX_{16} + 0.2644\ \ell nX_{21} \qquad (2.19)$$

$$\ell nC''_{ww.as} = 4.9224 - 0.2754\ \ell nX_{16} + 0.0021\ \ell nX_{21} \qquad (2.20)$$

$$\ell nC'_{ww.la} = 7.2754 - 0.0035\ \ell nX_{16} - 0.3575\ \ell nX_{20} \quad (2.21)$$

$$\ell nC''_{ww.la} = 5.6075 - 0.0073\ \ell nX_{16} - 0.3902\ \ell nX_{20} \quad (2.22)$$

where

$C'_{ww.af}$ = per MGD construction cost in Africa in US $1,000.

$C''_{ww.af}$ = per MGD operation and maintenance costs in Africa in US $1,000 per year

$C'_{ww.as}$ = Per MGD construction cost in Asia in US $1,000

$C''_{ww.as}$ = per MGD operation and maintenance costs in Asia in US $1,000 per year

$C'_{ww.la}$ = per MGD construction cost in Latin America in US $1,000

$C''_{ww.la}$ = per MGD operation and maintenance costs in Latin America in US $1,000 per year.

In 1978, Dames and Moore (11)(12) presented two reports on the construction, operation and maintenance costs of the nation's municipal wastewater treatment plants. The cost data has been centered on two-dimensional log-log plots and two-variable linear regression. The form of the equations was the following.

$$Y = aX^b \quad (2.23)$$

where

Y = construction or operation and maintenance costs

X = design capacity or service population

a,b = constants

All the cost models aforementioned could be significant for domestic wastes, but cannot be said to apply to industrial wastes in general. It is because industrial wastes differ from domestic wastes in one or more of the following aspects (13).

1) Large fluctuations in the organic load as well as the volumetric load, requiring need for equalization.
2) Acidic or alkaline requiring neutralization.
3) Contains grease or oils.
4) Toxic substances such as (a) salts of lead, mercury, chromium, copper and other heavy metals, (b) cyanides, sulfides, and (c) bactericidal compounds, requiring need for pretreatment.
5) Odor - forming substances.
6) Extreme temperature, usually high, that may need cooling.
7) Deficiency in some essential biological nutrients.

Due to the complexity of characteristics and treatment processes of industrial wastes, it is necessary to establish their own cost models correlating the industrial waste treatment costs with related variables.

CHAPTER III

TECHNIQUE FOR FITTING MATHEMATICAL MODELS TO COST DATA

Regression Analysis

As mentioned before, the purpose of this study was to develop cost models which correlate the treatment cost with waste variables by summarizing a mass of cost data. Linear regression which fits equation to data and expresses a relationship between one or more independent variables to a dependent variable in a linear manner was therefore considered to be the most suitable method for cost models development.

The general form of models used in regression analysis can be written as the following:

$$y = b_o + \sum_{i=1}^{k} b_i X_i \qquad (3.1)$$

where

y = The dependent variables; such as:

(1) Capital cost of treatment facilities in $/1000 gpd

(2) Operation and maintenance cost of treatment facilities in $/yr/1000 gpd

(3) Capital cost of treatment facilities in $/ton of annual production

(4) Operation and maintenance facilities in $/yr/ton of annual production

X = The independent variable; such as:

(1) Volume of wastewater in MGD

(2) Volume of wastewater in gpd/ton of annual production

(3) Concentration of critical pollutant in influent in mg/l

(4) Concentration of critical pollutant in effluent in mg/l

(5) Efficiency of critical pollutant in per cent

b_i = The unknown parameters or coefficients.

The multiple linear regression analysis is used to find estimates of the unknown coefficients in the above linear model. The coefficients are determined to provide the minimum sum of square of differences between the observed Y's and this linear combination of the X values (14).

Generally, if we let the observations on the first individual be represented by

$$Y_1, X_{11}, X_{21}, X_{31}, \ldots, X_{k1}$$

Those on the second individual by

$$Y_2, X_{12}, X_{22}, X_{32}, \ldots, X_{k2}$$

and so on to the nth, or last, individual,

$$Y_n, X_{1n}, X_{2n}, X_{3n}, \ldots, X_{kn}$$

Then the required solution for $b_o, b_1, \ldots, b_k$ is obtained by solving for these coefficients in the following set of equations:

$$nb_o + b_1\Sigma X_{1i} + b_2\Sigma X_{2i} + \ldots + b_k\Sigma X_{ki} = \Sigma Y_i$$

$$b_o\Sigma X_{1i} + b_1\Sigma X^2_{1i} + b_2\Sigma X_{1i}X_{2i} + \ldots + b_k\Sigma X_{1i}X_{ki} = \Sigma X_{1i}Y_i$$

$$b_o\Sigma X_{2i} + b_1\Sigma X_{2i}X_{1i} + b_2\Sigma X^2_{2i} + \ldots + b_k\Sigma X_{2i}X_{ki} = \Sigma X_{2i}Y_i$$

$$- -$$

$$b_o\Sigma X_{ki} + b_1\Sigma X_{ki}X_{1i} + b_2\Sigma X_{ki}X_{2i} + \ldots + b_k\Sigma X^2_{ki} = \Sigma X_{ki}Y_i \qquad (3.2)$$

As inspection of data indicated the inappropriateness of fitting directly a linear relationship. In such cases the possibilities are to try an appropriate non-linear fit directly to the data or else to make an initial transformation of the data such that the relationship between the transformed data is also linear and the multiple linear regression analysis can be applied. Transformation selected to reduce complex models to linear ones could be logarithmic

and reciprocal. In this study, the following transformations of the original model were tested to establish the best cost model.

$$\ell n\ y = b_o + \sum_{i=1}^{k} b_i\ \ell n X_i \tag{3.3}$$

$$\frac{1}{\ell n\ y} = b_o + \sum_{i=1}^{k} b_i\ \ell n X_i \tag{3.4}$$

$$\ell n\ y = b_o + \sum_{i=1}^{k} b_i X_i \tag{3.5}$$

$$\frac{1}{y} = b_o + \sum_{i=1}^{k} b_i X_i \tag{3.6}$$

where

y = dependent variable

X_i = independent variable

b_i = Regression coefficients

Since the same data is used to compute several forms of regression model, the question is how to select the best fitting one. The answer is through the use of tools fundamental to statistical model building and regression analysis. Primarily, these are the inspection of correlation coefficient, the analysis of F-value, and the examination of residuals which will be shortly reviewed as follows.

Correlation Coefficient

Correlation coefficient (r) is a measure of the degree of the closeness of the relationship between variables. The correlation coefficient for a simple regression can be written mathematically as:

$$r^2 = \frac{\text{Explained Variation}}{\text{Total Variation}} = \frac{\Sigma(y_c - \bar{y})^2}{\Sigma(y - \bar{y})^2} \qquad (3.7)$$

where $\Sigma (y - \bar{y})^2 = \Sigma (y - y_c)^2 + \Sigma (y_c - \bar{y})^2$

	Sum of square about the mean	=	Sum of square about regression	+	Sum of square due to regression
or	Sum of square about the mean	=	Residual sum of square	+	Sum of square due to fitted equation

y = observation value of dependent variable

y_c = predicted value of y

$\bar{y}$ = arithmetic mean of observation values of y

The term r^2, the coefficient of determination, refers to the square of correlation coefficient. r^2 represents the fraction of the total variation accounted for by the fitted equation. The correlation coefficients are close to one, lead to the conclusion that the prediction equations are extremely good.

In dealing with more than two variables at a time, the partial correlation coefficient is necessary to be used to measure the linearity between observation of two variables with all other coefficients held as constants. The partial correlation coefficient is specifically desirable when one is interested in knowing the correlation between one independent variable and the response variable without taking into consideration the effect of remaining independent variables in the equation. The partial correlation coefficient of y and X_3 with X_2 held constants can be calculated in terms of simple coefficients as shown in equation 3.8.

$$r_{13.2} = \frac{r_{13} - r_{12} \cdot r_{23}}{[(1 - r_{12}^2)(1 - r_{23}^2)]^{1/2}} \qquad (3.8)$$

where

$r_{13.2}$ = partial correlation coefficient between y and X_3 when X_2 is held constant.

r_{12} = simple correlation between y and X_1

r_{13} = simple correlation between y and X_3

r_{23} = simple correlation between X_2 and X_3.

In multiple regression, the coefficient of determination, denoted by R^2, is also the explained variation over the total variation. The R^2 can take on values from 0 to 1, the latter representing a situation in which all the variation is explained.

Analysis of F-Value

The F-value is used to judge the "significance" of the value of R, because R^2 is, in fact, concerned only with the association between the variables and not with their dependence or independence. A significant F-value means that the regression coefficients explain more the variation in the data than would be expected by chance. Thus, the F-value is a measure of the equation's usefulness. The F-value can be compared with tabulated values to give a test of the hypothesis that the regression coefficient is zero against the alternative that the equation as a whole defines a significant relationship between variables. The value of the F-statistic is the ratio of explained variance over the unexplained variance. This can be written mathematically in two equivalent forms:

$$F = \frac{\Sigma (y_c - \bar{y})^2/k}{\Sigma (y - y_c)^2/(n-k-1)} = \frac{\text{Mean Square due to regression}}{\text{Mean Square about regression}} = \frac{MSR}{s^2} \qquad (3.9)$$

where n = total number of observations, and

k = the number of independent variables,

or $$F = \frac{R^2/k}{(1 - R^2)/(n - k - 1)}$$

where R^2 = coefficient of determination.

In this study, a 0.05 level of significance was tested when the calculated F value is compared to the corresponding value from an F-table with k and (n - k - 1) degree of

freedom. In general, the higher a given F-value, the greater the probability that the relationship is significant.

Examination of Residuals

The residuals are defined as the n differences $e_i = y_i - y_c$, $i = 1, 2, \ldots, n$, where y_i is an observation and y_c is the corresponding fitted value obtained by use of the fitted regression equation. In performing the regressions analysis, the usual assumptions are that the errors, e_i, have a zero mean and a constant variance. A fitted model is regarded as correct if no evidence of violation of the above assumption is found. This criterion used in judging the performance of model is with the help of graphs plotted between predicted value of the dependent variable to the residuals. The main objective is to obtain a horizontal band about the zero line, with a narrow band width indicating small variance and thus obtaining a good fit. As the band width increases, the variance of error increases. Generally, the defects of the models can be revealed by such plots. For instance, a wedge-shaped plot indicates that the scatter of the residuals increases with fitted y. To overcome these problems, the transformation on the observations before making a regression is needed (15).

Stepwise Regression

There are many computational methods available for performing multiple regression calculation. The stepwise regression procedure developed by Efroymson (16) is one of the most widely used at this time. The most outstanding characteristics of stepwise regression analysis are that the final model contains only those variables that are significantly contributing to the reduction of residuals in the model. In other words, the stepwise regression procedure provides a means of choosing the independent variables which will provide the best prediction possible with fewest independent variables. The basic steps in the procedure are outlined below (17)(18):

1. The stepwise starts with the simple correlation calculation and enters into regression the X variable most highly correlated with y, say X_1.
2. Using the partial correlation coefficients,it selects, as the next variable to enter regression, that X variable whose partial correlation with y is highest, say X_e.
3. Compute F_e (F-test for the entering variable X_e; F-test

for the entering variable considers only that increase in Regression Mean Square which is attributable to X_e) and if $F_e > F_o$ (F_o is an F-value pertaining to a preselected level of significance) enter X_e, otherwise go back to Step 2. Next compute F_ℓ (F-value for the variable leaving, all variables already in the equation may potentially leave), if $F_\ell < F_o$ remove X_ℓ from the model and go back to Step 2. When there are no X_e and X_ℓ left go to Step 4.

4. Adopt the model as "best".

Stepwise regression is believed to be the best of the variable selection procedures (19). Thus, this computation method was adopted to develop the cost models in this study. It should be noted that all cost models were generated through computer analysis, utilizing the BMDO2R program and checked for statistical validity by testing the F-value at a 0.05 level of significance.

CHAPTER IV

METHODS FOR COST DATA ACQUISITION

Basically, the treatment cost models developed are based on a mass of cost data. Thus, the first step in developing a cost model is to estimate the treatment costs. Generally, there are two methods which can be used to estimate the costs. One may be termed as a deductive method by which the cost is constructed from data reported for existing plants. The other may be termed as an inductive method by which the costs is projected from basic estimates of different portions of the overall treatment technique. In other words, the former is based on reported cost data from the existing treatment plants, and the latter is a calculation of unit cost for each process within the system, adding the appropriate add-on costs to obtain the total cost.

Deductive Method

The major task for the deductive method of estimating treatment cost is to collect the cost data for existing plants. The method of procuring cost information is to scan the published literature and reports. Generally, the

government research reports (e.g., EPA's) have the most useful cost data. Occasionally, cost information may be obtained from equipment manufacturers.

The treatment cost data, collected from a wide variety of original sources reflect different time periods. In order to perform data analysis, it is essential to update all costs to a common base. Rather than completely revising cost estimates at specific time periods, cost indexes could be employed to accomplish cost estimate updating. Among the most frequently used indexes in the wastewater field are the indexes prepared by Engineering News Record (ENR) and U.S. Government. These indexes include: the ENR Construction Cost Index issued by ENR; the ENR Building Cost Index issued by ENR, the Sewage Treatment Plant Index issued by EPA; the ENR Labor Index issued by ENR; and Labor Cost Index issued by the U.S. Department of Labor. With the wide variety of indexes available, it is usually possible to find a suitable index. In addition, accounting for possible regional differences is also necessary for data analysis. A number of indexes exist that might be used to convert the cost data obtained from various parts of the country to a common base. One of the most popular indexes is ENR indexes to twenty cities. These twenty cities' indexes are used to obtain the U.S. average cost index. The U.S. could be partitioned into twenty regions on a county line

basis and each region could correspond to one of the twenty cities (19). Therefore, the regional prices are no problem to be converted into a common base with monthly indexes available for twenty cities (20).

Inductive Method

Basically, the inductive method of estimating costs is to estimate the cost of the major components of the treatment system. To the total of the component costs, the appropriate add-on costs such as engineering, contingencies, and administration are added to obtain the total capital cost. Operation and maintenance costs are also computed on a component basis and summed. The treatment cost models through inductive estimates of treatment cost could be outlined below in two steps.

STEP 1: Developing Cost Models for Unit Wastewater Treatment Processes

The unit wastewater treatment processes applicable to the industry are shown in Figure 1. As shown in Figure 1, many treatment sequences of waste treatment process units, including pretreatment, primary, secondary, tertiary treatment and sludge disposal methods can be applied to achieve various treatment requirements. Most of cost information concerning the cost for unit wastewater treatment may be found in the literature, in government research reports, and occasionally may be obtained from equipment manufacturers. Generally speaking, most of the cost data

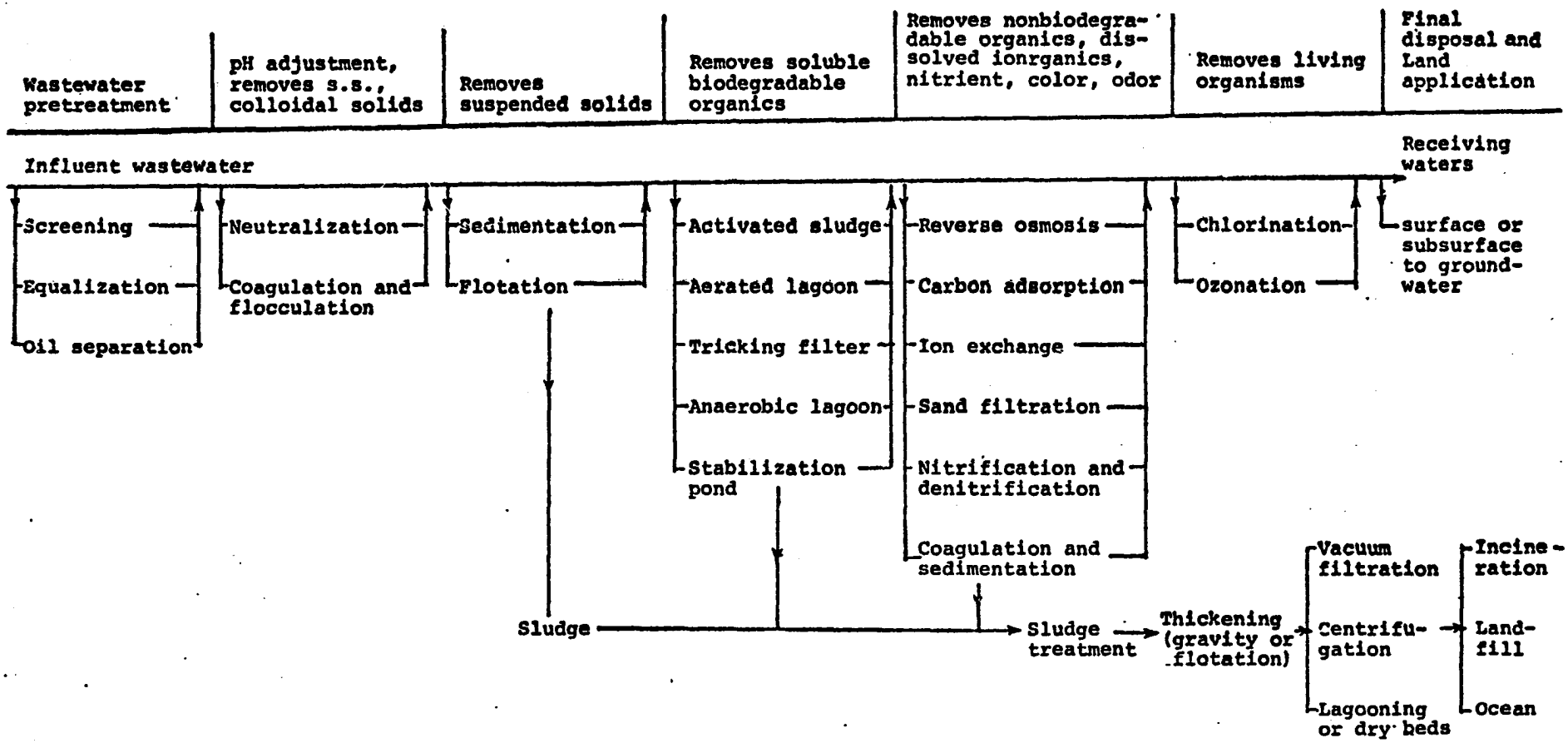


FIGURE 1 POSSIBLE CHOICES FOR INDUSTRIAL WASTEWATER TREATMENT AND THEIR SEQUENCE

is demonstrated by graphs. In this step, the mathematical models which have best accuracy and reliability for each unit of treatment process by utilizing these graphs plus a wide variety of original sources are developed. The basis and relationships for determining the unit process cost models for industrial waste treatment could be summarized as Table 1 (21).

The unit process cost data used for unit cost models development must be updated, if necessary. The cost indexes could also be employed to accomplish this cost updating. After updating the cost data, the unit process cost models for industrial waste treatment can be readily developed through regression analysis.

STEP 2: Synthesizing the Total Cost of the Treatment Plant

After selecting treatment sequence for the specific industrial wastewater, the sizes of components of the overall treatment plants are computed on the basis of appropriate design criteria. The treatment sequences were analyzed in terms of pretreatment, BPT[1], and BAT[2] in this study. The costs also analyze for various ranges and combinations of the input design parameters, including flow rate, influent and effluent, BOD, etc. The cost for

[1]BPT = best practical waste treatment technology.

[2]BAT = best available technology economically achievable.

TABLE 1

SUMMARY OF BASES FOR UNIT COST MODELS

Oil Separation	Cost vs. flow rate
Equalization	Cost vs. volume
Neutralization	Cost vs. flow rate, acidity
Primary Clarifier	Cost vs. surface area
Activated Sludge	
Aeration basins	Cost vs. volume
Aerators	Cost vs. power of aerators
Sludge return pump	Cost vs. flow rate
Final clarifier	Cost vs. surface area
Chemical Coagulation	Cost vs. flow rate
Lime Recalcination	Cost vs. furnace output of lime
Biological Nitrification	Cost vs. flow rate
Biological Denitrification	Cost vs. flow rate
Flotation	Cost vs. surface area
Chlorination	Cost vs. basin volume
Granular Media Filtration	Cost vs. filter area
Activated Carbon	Cost vs. flow rate
Reverse Osmosis	Cost vs. flow rate
Gravity Thickening	Cost vs. surface area
Vacuum Filtration	Cost vs. filter area
Aerated Lagoon	Cost vs. volume
Digester	Cost vs. volume
Sludge Incineration	Cost vs. solids feed rate

each component or unit process can be obtained from the unit process cost models developed in the first step. The total construction cost of a treatment plant is synthesized by a summation of the costs of the individual unit processes, plus the appropriate add-on costs such as engineering, contingencies, and administration. The add-on cost is usually expressed as a percentage of the total cost of construction. Culp (22) and Chow (23) analyzed the percentage of miscellaneous cost in the total construction cost of treatment. They concluded that the miscellaneous cost, including engineering, legal, administrative, and contingency costs, was about 35 percent of the basic installed construction cost. Operation and maintenance cost for the entire plant is also computed on a component basis from the unit process cost model for operation and maintenance, and summed.

Selection of Cost Estimating Method

In this study, the first attempt to procure the cost data was made through the deductive method. After a survey of the published literature and reports (24-87), it was found that there were many difficulties associated with compiling cost data for existing plants from various sources. A common problem is the lack of descriptive detail concerning the exact treatment technique and sequence for which the cost estimate was made. For example, a cost may be presented for the "activated sludge process"

without specifying whether the estimate includes sludge hauling and disposal, treatment technique modification, or influent and effluent characteristics. Another difficulty associated with treatment costs was that cost data reported varied widely, therefore, good correlation between cost and design parameters was hard to obtain. Inversely, better correlation was obtained through the inductive method of estimating treatment costs which reflected the waste parameters properly. It was then decided to use the inductive method to determine the cost of simulated design of plants to treat wastes with a range of plant capacity and waste characteristics.

In order to obtain treatment cost estimates by inductive method, it was necessary to make a detailed study of unit process cost models for industrial waste treatment. The following chapter will deal with these unit cost models that were developed. All costs used in this study were keyed to May 1979 price level. The "Engineering News Record" construction cost index and skilled labor index were generally used for updating. A factor of 35 percent of the basic installed construction cost was used for engineering, legal, administration, and contingency costs.

CHAPTER V

UNIT PROCESS COST MODELS FOR INDUSTRIAL WASTEWATER TREATMENT

There currently exists a large variety of unit treatment processes designed to remove pollutants from industrial wastewater. These unit processes can be combined to form process trains; i.e., treatment sequence, which can produce a specific degree of treated wastewater as the effluent. In this study, the unit cost models for most common unit treatment processes applicable for industrial wastewater were developed by utilizing and summarizing a wide variety of original sources. These unit process cost models developed are presented and described in this chapter.

Oil Separation

The typical method for removing oily substances from industrial wastes is by a gravity type separator. Costs for oil separators were obtained from the existing separators reported in the FWPCA publication (88). Based on these reported cost data, cost models developed were as follows.

$$CCOS = 132\ Q^{0.84} \tag{5.1}$$

$$OCOS = 5.91\ Q^{-0.56} \tag{5.2}$$

where

CCOS = Construction cost of oil separator ($1,000)

OCOS = Operation and maintenance costs of oil separator (¢/1,000 gal)

Q = Flow through treatment plant (MGD)

Equalization

The need for equalizing wastewater from many industrial plants as an intermediate step in a treatment system is well established. Biological processes and physical-chemical systems operate more effectively if the composition and volume of the wastewater feed is relatively constant.

The costs on equalization with mechanical mixing has been reported by Chow (89), Stanley Consultants (90), and Siegrist (91). By summarizing the above information, the cost models for equalization were developed as the following:

$$CCEQ = 187(V)^{0.64} \tag{5.3}$$

$$OCEQ = [1.05(MH)(LR) + 0.75(HR)(PC)]/3,650Q \tag{5.4}$$

where

CCEQ = Construction cost of Equalization Basin ($1,000)

V = Basin volume (MG)

OCEQ = Operation and maintenance costs of Equalization Basin (¢/1,000 gal)

MH = Man-hours per year = 402 (Mixers horse-power)$^{0.38}$

LR = Labor rate ($/hr)

HR = Hp-hr/yr

PC = Power cost ($/kwh)

Q = Flow through treatment plant (MGD)

In this study, labor rate was assumed to be $7.00/hr and power rate is assumed to be $0.04/Kwh. The power for mixing was assumed at an input rate of 15 HP/MG.

Neutralization

Industrial wastes often contain acidic or alkaline components which require neutralization before chemical or biological treatment. The biological process itself provides a neutralization and buffer capacity as a result of production of CO_2, which forms carbonates and bicarbonates in solution. The removal of BOD in the biological process is related to the production of CO_2, which may provide for partial neutralization of alkaline wastes. Laboratory and field results have indicated that a completely mixed

activated sludge system, operating properly, can neutralize 0.5 lb of hydroxide alkalinity (as $CaCO_3$) per lb of BOD_5 removed (92). Generally, alkaline wastes do not present as serious a problem as acidic wastes. Acid wastes on the other hand are quite common and their neutralization present many difficulties. So far, it appears that the lime neutralization is the most cost effective method on a large scale. The cost models for lime neutralization were obtained from the studies of the inorganic chemical industry (24)(26).

$$CCNE = 4.24\ Q^{0.83}\ A^{0.79} \tag{5.5}$$

$$CONE = 0.52\ Q^{-0.082}\ A^{0.65} \tag{5.6}$$

where

CCNE = Construction cost of lime neutralization ($1,000)

CONE = Operation and maintenance costs of lime neutralization (¢/1000 gal)

Q = Flow through treatment plant (MGD)

A = Acidity (mg/ℓ as $CaCO_3$)

With considering some probable unreactive part of the lime that will be disposed with the sludge, the sludge production will be approximately 1.7 times of the acidity on a basis of weight (24).

Primary Clarification

Primary clarification is used in industrial wastewater treatment to separate suspended solids from wastewaters. Removal by sedimentation is based on the difference in specific gravity between solids particles and the bulk of the liquid, which results in settling of suspended solids.

Since the primary clarification technique has been utilized widely for a long time, there currently exists a large number of cost estimates describing this technique (25) (26) (27) (89) (91) (93) (94) (95). The cost for primary clarifiers were associated with the surface area rather than volume of the clarifier. The cost functions were expressed as:

$$CCPC = 1.61\ (SA)^{0.56} \qquad (5.7)$$

$$COPC = 1.21\ (SA^{0.214}/Q) \qquad (5.8)$$

where

CCPC = Construction cost of primary clarifier ($1,000)

COPC = Operation and maintenance costs of primary clarifier (¢/1,000 gal)

SA = Surface area of primary clarifier (sq. ft.)

Q = Flow through treatment plant (MGD)

In this study, the surface area of primary clarifier was computed on the basis of appropriate design overflow rate in gpd/sq.ft.

Activated Sludge

The activated sludge process can be defined as a system in which the flocculated, biological growth are continuously circulated and contacted with organic wastewater in the presence of oxygen. The process consists of an aeration tank, a sedimentation tank called a secondary clarifier, and a recycle system for the settled culture (sludge).

This process has been used for wastewater treatment for approximately half a century (96). There was much cost information available (25)(26)(27)(89)(90)(91)(93)(94)(95)(97). After an extensive survey these available information, the cost functions which best expresses the costs for activated sludge treatment, excluding sludge treatment, were represented by the following set of models:

a) Construction Cost

1. Aeration Basin

$$CCAB = 410(V)^{0.71} \qquad (5.9)$$

where

CCAB = construction cost of aeration basin ($1,000)

V = volume of aeration (MG)

2. Aerators

$$CCAE = 2.51(KW)^{0.81} \quad (5.10)$$

where

CCAE = construction cost of aerators ($1,000)

KW = power rating of the aerators used (KW)

3. Sludge return pumps

$$CCSR = 9.72 + 3.01Q \quad (5.11)$$

where

CCSR = construction cost of sludge return pumps ($1,000)

Q = flow through the plant (MGD)

4. Final clarifier

$$CCFC = 141(SA)^{0.61} \quad (5.12)$$

where

CCFC = construction of final clarifier ($1,000)

SA = surface area of final clarifier (1,000 sq. ft.)

b. Operation and Maintenance Cost

1. Activated sludge (including sludge return pumps, and final clarifier; excluding power cost for aerators)

$$COAS = \left(\frac{V}{Q}\right)\left(5.84 + \frac{8.49}{V^{0.5}}\right) \qquad (5.13)$$

where

COAS = operation and maintenance costs of activated sludge process (¢/1,000 gal)

V = volume of aeration basin (MG)

Q = flow through treatment plant (MGD)

2. Power cost for aerators

$$COAE = (PC \times KW \times 24)/(1{,}000\ Q) \qquad (5.14)$$

where

COAE = power cost for aerators (¢/1,000 gal)

PC = power cost (¢/KWh)

KW = power rating of the aerators used (KW)

Q = flow through treatment plant (MGD)

In this study, the completely mixed activated sludge process was adopted for treating the industrial wastewater. The completely mixed basins offer the advantage of dispersing and mixing the wastewater throughout the basin contents, thus serving to damper fluctuations in influent strength and enhance process stability. The basic

process models applied to the design of completely mixed system were summarized below (98):

1. BOD removal kinetics:

$$\frac{S_o - S_e}{X_v t} = kS_e \qquad (5.15)$$

where

S_o = Influent BOD_5 (mg/ℓ)

S_e = Effluent BOD_5 (mg/ℓ)

X_v = MLVSS (mg/ℓ)

t = Retention time (hr)

k = BOD removal rate coefficient (ℓ/mg-hr)

2. Sludge yield

$$\Delta X_v = aS_r - bX_a \qquad (5.16)$$

where

ΔX_v = sludge yield (lb·VSS/day)

a = yield coefficient

b = cell auto-oxidation rate coefficient (day^{-1})

S_r = BOD removed (lb/day)

X_a = MLVSS (lb)

3. Oxygen requirement

$$O_2 = a'S_r + b'X_a \qquad (5.17)$$

where

O_2 = oxygen requirement (lb·O_2/day)

a' = oxygen utilization coefficient for cell synthesis

b' = oxygen utilization rate for endogenous respiration (day^{-1})

S_r = BOD removed (lb/day)

X_a = MLVSS (lb)

The appropriate amount of certain nutrient is required for both synthesis and respiration phases of aerobic biological degradation of wastes. Required nutrients include nitrogen, phosphorus, calcium, magnesium, and vitamins (96). Most of these nutrients, which are required only in trace quantities, are usually present in wastewaters. However, many industrial wastewaters are deficient in nitrogen and phosphorus. If deficiency exists, the addition of nutrients to wastewater is necessary. The accepted nutrient demand for proper microorganism growth is BOD:N:P ratio of at least 100:5:1 (99). In this study, if the incoming industrial wastewater did not include this much nitrogen or phosphorus, it was added to the wastewater. A cost of 12¢/lb. of N and a cost of 18¢/lb. of P were assumed.

Chemical Coagulation

The term chemical coagulation as used herein is a treatment process made up of three distinct operations: (1) rapid mixing, (2) slow mixing (flocculation), and (3) sedimentation.

The costs for chemical coagulation has been studied by Black and Veatch (100), Environmental Quality System (101), as modified by Koon (102). Based on the cost reported by Koon (102), the cost relationships for chemical coagulation can be expressed as (91):

$$CCCO = 229\ Q^{0.74} \tag{5.18}$$

$$COCO = 11.6\ Q^{-0.468} \tag{5.19}$$

where

CCCO = construction cost of chemical coagulation (including chemical feed facilities, rapid mixing, flocculation, and sedimentation) ($1,000)

COCO = operation and maintenance costs of chemical coagulation (excluding chemical cost) (¢/1,000 gal)

Q = flow through treatment plant (MGD)

Actually, the principal cost of chemical treatment is the cost of the added chemicals. In this study, the costs of chemical addition were assumed as follows[1]:

1. Ferric chloride

chemical cost (¢/1,000 gal) =

(0.042)x(chemical dosage in mg/ℓ) (5.20)

[1] In this study, prices of chemicals were from Chemical Marketing Reporter, May 21, 1979, published by Schnell Publishing Company, Inc., New York.

2. Alum

chemical cost (¢/1,000 gal) =

(0.033)x(chemical dosage in mg/ℓ) (5.21)

3. Quick lime

chemical cost (¢/1,000 gal) =

(0.013)x(chemical dosage in mg/ℓ) (5.22)

Lime Recalcination

Calcination for recovery of lime involves burning calcium carbonate precipitate at temperatures of 600-2000°F to generate calcium oxide and carbon dioxide (103):

$$CaCO_3 \rightarrow CaO \text{ (lime)} + CO_2 \uparrow$$

The basic installed cost of lime recalcination facilities including thickener, centrifuge, and furnace or kiln, was obtained from Smith and McMichael (104), and Adams (105). Summarizing this cost data, the following relationship was found:

$$CCRE = 287\ F^{0.50} \quad (5.23)$$

where

CCRE = construction cost of lime recalcination ($1,000)

F = furnace output of lime (TPD)

The operating costs relationship for recalcination was found to be (26):

$$CORE = 48\ F^{0.80} \quad (5.24)$$

where

CORE = operation and maintenance costs of recalcination ($/day)

F = furnace output of lime (TPD)

The fuel cost in the above model was based on $9x10^6$ BTU/Ton of output at $\$1.00/10^6$ BTU.

Flotation

Air flotation is considered one of the most effective methods for the removal of grease and solids from the industrial wastewater. Basically, the air flotation process relies on the entrainment of minute air bubbles which upon attachment to a discrete particle reduces the effective specific gravity of the aggrepate particle to less than that of water and thus causes its separation and rise to the liquid surface as foam or float.

The costs of flotation has been studied by Hazen and Sawyer (106). Included in the cost were all tanks and internals, air-pressurizing equipment, recycle-pumping equipment, operating valves and piping, all fully installed. By utilizing this cost data, the cost models were developed as follows:

$$CCFL = 482\ A^{0.95} \tag{5.29}$$

$$COFL = 14.7\ A^{0.92} \tag{5.30}$$

where

CCFL = construction cost of flotation ($1,000)

COFL = operation and maintenance costs of flotation ($1,000/yr)

A = surface area (1,000 sq. ft.)

Air flotation is a process generally used in petroleum refinery installations as a secondary oil/solids removal process to enhance oil and suspended solids removal (28). It is commonly preceded by a gravity oil separator to remove grass quantities of oil and suspended matter. Generally, chemical addition with rapid mix and flocculation chambers are employed as a part of the flotation unit, breaking the oil emulsion and enhancing the phase separation (107). Chemicals normally used include aluminum, iron, and calcium salts. Costs for air flotation with chemical coagulation in petroleum refinery has been investigated and reported in the FWPCA publication (88). The following relationships were found:

$$CCPF = 208\ Q^{0.74} \tag{5.31}$$

$$COPF = 21.5\ Q^{-0.27} \tag{5.32}$$

where

CCPF = construction cost of flotation with chemical coagulation in petroleum refinery ($1,000)

COPF = operation and maintenance costs of flotation with chemical coagulation in petroleum refinery (¢/1,000 gal)

Q = flow through treatment plant (MGD)

Chlorination

The addition of chlorine or some other form of chlorine, which is called chlorination, is the process most commonly used for wastewater disinfection.

The cost of chlorination, which is a function of contact time and dosage, can be estimated by the following models (26)(108):

$$CCCB = 2.66\ V^{0.60} \tag{5.33}$$

$$CCCF = 13.17\ D^{0.37} \tag{5.34}$$

$$COCH = 0.98\ D^{0.60} \tag{5.35}$$

where

CCCB = construction cost of chlorine contact basins ($1,000)

CCCF = construction cost of chlorine feed system ($1,000)

COCH = operation and maintenance costs of chlorination (excluding chlorine cost) ($1,000/yr)

V = basin volume (1,000 gal)

D = chlorine usage (ton Cl_2/yr)

In this study, chlorine cost computed at $140/Ton.

Granular Media Filtration

Filtration is a common unit operation for removal of suspended solids from wastewater effluents of biological and chemical treatment processes (109). The mixed media filtration, which more optimally utilize the filter bed depth, is thought to be most applicable.

The costs for mixed media filtration were taken from data appearing in the literature (104)(106)(110)(111)(112). The following relationships were obtained:

$$CCFI = 7.98\ A^{0.61} \tag{5.36}$$

$$COFI = 5.97\ Q^{-0.24} \tag{5.37}$$

where

CCFI = construction cost of filtration ($1,000)

COFI = operation and maintenance costs of filtration (¢/1,000 gal)

A = filter area (sq. ft.)

Q = flow through treatment plant (MGD)

Carbon Adsorption

Removal of soluble organics from wastewater can be achieved by adsorption on activated carbon. This process can be applied either as tertiary conditioning following biological treatment, or as the second phase in physical-chemical treatment systems (103). Conventional biological treatment processes may remove nearly all of those organics

measured by the BOD (Biochemical Oxygen Demand) test, but are not as effective in removing the "so called" refractory organics measured by COD (Chemical Oxygen Demand) test. However, carbon adsoption is capable of removing refractory organics from wastewater to a considerable degree (112). Additionally, the efficiency of adsorption is not lost during conditions which would be inhibitory or toxic to biological systems.

Activated carbon can be classified in two groups: powdered and granular. Powdered carbon, commonly used in water treatment, has not received widespread application in wastewater process, due to the difficulty of regeneration. In wastewater application, a fixed-bed column with granular carbon is often used (103).

As for the nature and performance of the carbon adsorption, Ford (113) noted:

> "It is well known that the performance of both biological treatment and fixed bed activated carbon are affected by the influent pollutant concentration. The kinetics which describe biochemical oxidation of organic constituents in either a fluidized system or a fixed biological surface infer higher organic removal velocities with increasing influent concentrations.

The same is true with fixed-bed carbon adsorption systems, as a higher concentration gradient, or driving force, is responsible for a more effective removal of the adsorbate".

Ford (113) has also found the relationships, between costs and flow rate at different influent COD concentrations for carbon adsorption. Based on the cost data reported by Ford (113), the following models were developed:

$$CCAC = 617\ Q^{0.60}(COD)^{0.28} \qquad (5.38)$$

$$COAC = 1.41\ Q^{-0.33}(COD)^{0.77} \qquad (5.39)$$

where

CCAC = construction cost of carbon adsorption ($1,000)

COAC = operation and maintenance costs of carbon adsorption (¢/1,000 gal)

Q = flow rate through treatment plant (MGD)

COD = influent COD concentration (mg/ℓ)

Reverse Osmosis

Reverse Osmosis (RO) is commonly used to remove dissolved solids from wastewater. The basic component of a RO unit are the semipermeable membrane. The driving force which separates dissolved solids from the wastewater

feed is the reverse osmosis pressure — the net difference between the applied pressure and the average osmotic pressure of the feed and the concentrate (107). No suspended solids can be tolerated in the membrane feedwater or the membrane will rapidly clog and production will cease. Pretreatment of a secondary effluent with filtration is usually necessary.

Various sources of cost information were investigated (24)(91)(108)(114); the cost relationships could be expressed as follows:

$$CCRO = 1221\ Q^{0.75} \tag{5.40}$$

$$CORO = 53.4\ Q^{-0.21} \tag{5.41}$$

where

CCRO = construction cost of reverse osmosis ($1,000)

CORO = operation and maintenance costs (¢/1,000 gal)

Q = flow through treatment plant (MGD)

The operating cost in the above models did not include brine disposal. The concentrated brine can be disposed by mechanical evaporation, solar evaporation, deep well disposal or other methods, depending on the situation (26). The cost of brine disposal were too unpredictable to be included in the model.

Gravity Thickening

Gravity thickening is the simplest and least expensive process for consolidating waste sludges. Gravity thickening is accomplished in a tank that is very similar in appearance to the circular clarifiers used in primary and secondary sedimentation; the solids are allowed to settle to the bottom where a heavy-duty mechanism scrapes them to a hopper from which they are withdrawn for further processing.

The cost models of gravity thickener were developed from the data reported by Edwards (26), and Koon (102) which gave the cost as a function of thickener area.

$$CCGT = 1.86\ A^{0.48} \tag{5.42}$$

$$COGT = 0.14\ A^{0.49} \tag{5.43}$$

where

CCGT = construction cost of gravity thickener ($1,000)

COGT = operation and maintenance costs of gravity thickener ($1,000/yr)

A = thickener floor area (ft^2)

In this study, the thickener floor area was computed on the basis of appropriate design mass loading in lb solids/day/sq. ft..

Vacuum Filtration

Vacuum filtration is probably the most popular method of mechanical dewatering in use, and subsequently the method is considered in this study. Vacuum filtration is accomplished in a vacuum filter which is a cylindrical rotating drum covered with a porous media. Water is removed under applied vacuum through the porous media which retains solids but allows liquid to pass through.

Based on the cost data reported by Edwards (26), Smith (93), Koon (102), Di Gregorio (115), and Quirk (116), the following cost models were developed.

$$CCVF = 17.6\ A^{0.45} \tag{5.44}$$

$$COVF = 1.7\ A^{0.36} \tag{5.45}$$

where

CCVF = construction cost of vacuum filter ($1,000)

COVF = operation and maintenance costs of vacuum filter ($1,000/yr)

A = filter area (ft^2)

In this study, the filter area was determined on the basis of appropriate loading rate in lb solids/hr/sq. ft..

Sludge Hauling and Landfill Charge

The final sludge disposal cost of $9.00/Ton was assumed.

CHAPTER VI

INDUSTRIAL WASTEWATER TREATMENT COST ESTIMATING PROGRAMS

The unit process cost models and the design relationships for sizing the individual processes has been developed and described in the previous chapter. After selecting the treatment sequence for a specific industrial wastewater, the size of each process (component) can be computed on the basis of appropriate design criteria and process design models. The construction cost of each process (component) is determined by the unit process cost model which relates the unit process cost to the major size variable associated with the process. The individual process construction costs are totaled, and costs for engineering, legal, administration, and contingency are added to arrive at a total capital cost for the entire plant. The computing procedure for estimating the operation and maintenance costs (O&M costs) for the entire plant is similar to that for estimating the capital cost. The O&M costs for unit processes are determined from the

unit process cost models for O&M costs, and summed to give an overall O&M costs for the entire treatment sequence.

The above computing procedure for estimating the capital and O&M costs for the entire plant is very tedious. To tackle this problem effectively and efficiently, the use of either "large" computers (electronic computers) or "small" computers (programmable calculators) is almost essential. For this study, the programmable calculator was adopted for the following reasons:

1. The compactness and affordability of programmable calculators enable an individual ownership.
2. Generally, the programmable calculators are portable which allows an engineer to solve the problems even in the field.
3. The programs for programmable calculators can be recorded in a small piece of magnetic tape which acts like a "built-in" program. Once the program listing is completed and stored in the tape, this program can be readily used by an engineer with his or her own programmable calculator.

4. In reference to research on college campuses, the increasing contention for computer results in mounting inaccessibility to the computer and inconvenience.

In the civil engineering and environmental science field, Croley (117) has successfully applied the programmable calculator to solve the tedious hydrologic and hydraulic computation. Reid and Arnold (118) did pioneering work toward selecting the appropriate technology in water/wastewater treatment for developing countries on programmable calculators.

Currently, programmable calculators with a range of machines of various capability are produced by the manufacturers. The programs presented in this study are for the Model TI-59 Programmable Calculator manufactured by Tesax Instruments. Most of the programmable calculators have the same logic systems, thus, these programs developed for this study can be easily adapted to other calculators.

Programs for Estimating Industrial Wastewater Treatment Costs

Two programmable calculator programs were completed by this study for estimating industrial wastewater treatment costs. The first program is for estimating the capital cost and a list of this program is included in Appendix A. The other program is for estimating O&M costs and a listing of this program is included in Appendix B. These two programs were made up of subsets of unit process cost models and process design models developed and

described in Chapter V. The treatment processes that can be costed by these two programs are summarized in Table 2. Approximately fifty cost and process design models were included in the programs. Each executive or calling program contains a major program with seventeen subroutines, each of which computes either construction or O&M costs of a single unit treatment process for industrial wastewaters listed in Table 2. The programs then sum up the individual process costs to give the total capital cost in 1,000 dollars as well as O&M cost in cents per 1,000 gallons of influent.

In these programs, the treatment costs are computed on a process by process basis. The user selects the treatment sequence that he wishes to include in the computation from Table 2. Depending on the particular processes which are selected, the user must supply appropriate input, either 0 or 1 for each process, into the program. Only the processes that were selected by the user will be computed and summed up by the program.

There are two more specific programs developed for estimating the treatment costs of electroplating wastewater by skid-mounted package systems. These two specific programs which simulate the cost of installing and operating these systems will be described and discussed in Chapter VII.

All of the above cost estimating programs were used to generate costs for various treatment process

TABLE 2

UNIT TREATMENT PROCESSES THAT CAN BE COSTED BY THE WASTEWATER PLANT COST ESTIMATING PROGRAMS

Oil Separation
Equalization
Neutralization
Primary Clarifier
Activated Sludge
Chemical Coagulation
Lime Recalcination
Flotation
Chlorination
Granular Media Filtration
Carbon Adsorption
Reverse Osmosis
Gravity Thickening
Vacuum Filtration

combinations. After selecting the treatment sequence for a specific wastewater, the costs were obtained for a range of possible values of the waste characteristics through the use of programs. These costs were then presented in the form of a mathematical model through the use of stepwise regression analysis. The analyses in this study were performed with the assistance of a computer statistical package, BMDO2R.

CHAPTER VII

WASTEWATER PRETREATMENT AND COMPLETE TREATMENT COST MODELS FOR SELECTED INDUSTRIES

In this study, wastewater pretreatment and complete treatment — BPT and BAT — cost models were developed for each of the following selected industries:

Petroleum Refining

Pulp and Paper

Electroplating

Organic Chemical Manufacturing

Inorganic Chemical Manufacturing

BPT refers to the "best practical waste treatment technology" and BAT refers to the "best available technology economically achievable". Based on PL92-500 (1) and PL95-217(2), industrial wastewater treatment plants are required to provide BPT by July 1, 1977 and to provide BAT by July 1, 1984[1].

[1]The PL95-217, Federal Water Pollution Control Act Amendments of 1977, has extended the date for BAT from July 1, 1983 to July 1, 1984.

The BPT is generally defined as the equivalent of secondary treatment presently being practiced in the particular industrial category. BAT is generally defined as treatment technology that has been demonstrated on an advanced laboratory or pilot plant scale to be technically and economically feasible for a specific industrial category(107).

The treatment sequences for pretreatment, BPT and BAT selected for this study are corresponding to the most common control technologies applicable for each industrial category. It is emphasized that the listed treatment sequences are not mandatory and not necessary to be the least cost. Control and treatment of industrial wastewater is usually a case-by-case problem.

In the remainder of this chapter, the industrial wastewater treatment cost models developed by this study are presented. Note that the cost models for BAT technology refer to the costs of incremental BAT technology.

Petroleum Refining

The petroleum industry produces consumer goods such as gasoline, jet fuels, and lubricating products. These materials are derived from crude oil by means of distillation, catalytic conversion, solvent extraction, and chemical conversion operations. The wastewater generated by refining are diverse and complex, representing a full range of organic and inorganic materials (119).

Wastewater treatment technology relies heavily upon the use of biological treatment methods preceded by appropriate pretreatment to insure the proper conditioning.

1. Pretreatment

The pretreatment sequence for petroleum refining wastewater is oil separation followed by dissolved air flotation (including chemical coagulation) for secondary oil/solids removal. The following pretreatment cost models were developed:

$$CCPP = 456\ Q^{0.78} \quad (7.1)$$

$$(*)\ (r^2 = 0.995)$$

$$COPP = 24.9\ Q^{-0.25} \quad (7.2)$$

$$(*)\ (r^2 = 0.991)$$

where

CCPP = capital cost of pretreatment for petroleum refining wastewater ($1,000)

COPP = O&M costs of pretreatment for petroleum refining wastewater (¢/1,000 gal)

Q = wastewater flow rate (MGD)

---

*Satisfies F-test criteria.

2. BPT Technology

The heart of the BPT technology consists of activated sludge and post filtration processes. The BPT treatment sequence is shown in Figure 2. The major waste characteristics and design criteria inputs supplied for the cost estimating program are shown in Table 3 (26)(28)(42)(107)(120)(121).

The cost models of BPT technology for petroleum refining wastes were developed as follows:

$$\ell n\ C = 6.085 + 0.694\ \ell n\ Q + 0.218\ \ell n\ I - 0.035\ \ell n\ K - 0.042\ \ell n\ E \quad (7.3)$$

(*) ($R^2 = 0.996$)

$$\ell n\ M = 1.376 - 0.186\ \ell n\ Q + 0.333\ \ell n\ I - 0.050\ \ell n\ K - 0.062\ \ell n\ E \quad (7.4)$$

(*) ($R^2 = 0.946$)

where

C = capital cost of BPT technology for petroleum refining waste ($1,000)

M = O&M costs of BPT technology for petroleum refining waste (¢/1,000 gal)

Q = wastewater flow rate (MGD)

I = influence BOD_5 (mg/ℓ)

E = effluent BOD_5 (mg/ℓ)

K = BOD removal rate coefficient (ℓ/mg-hr)

*Satisfies sequential F-test criteria.

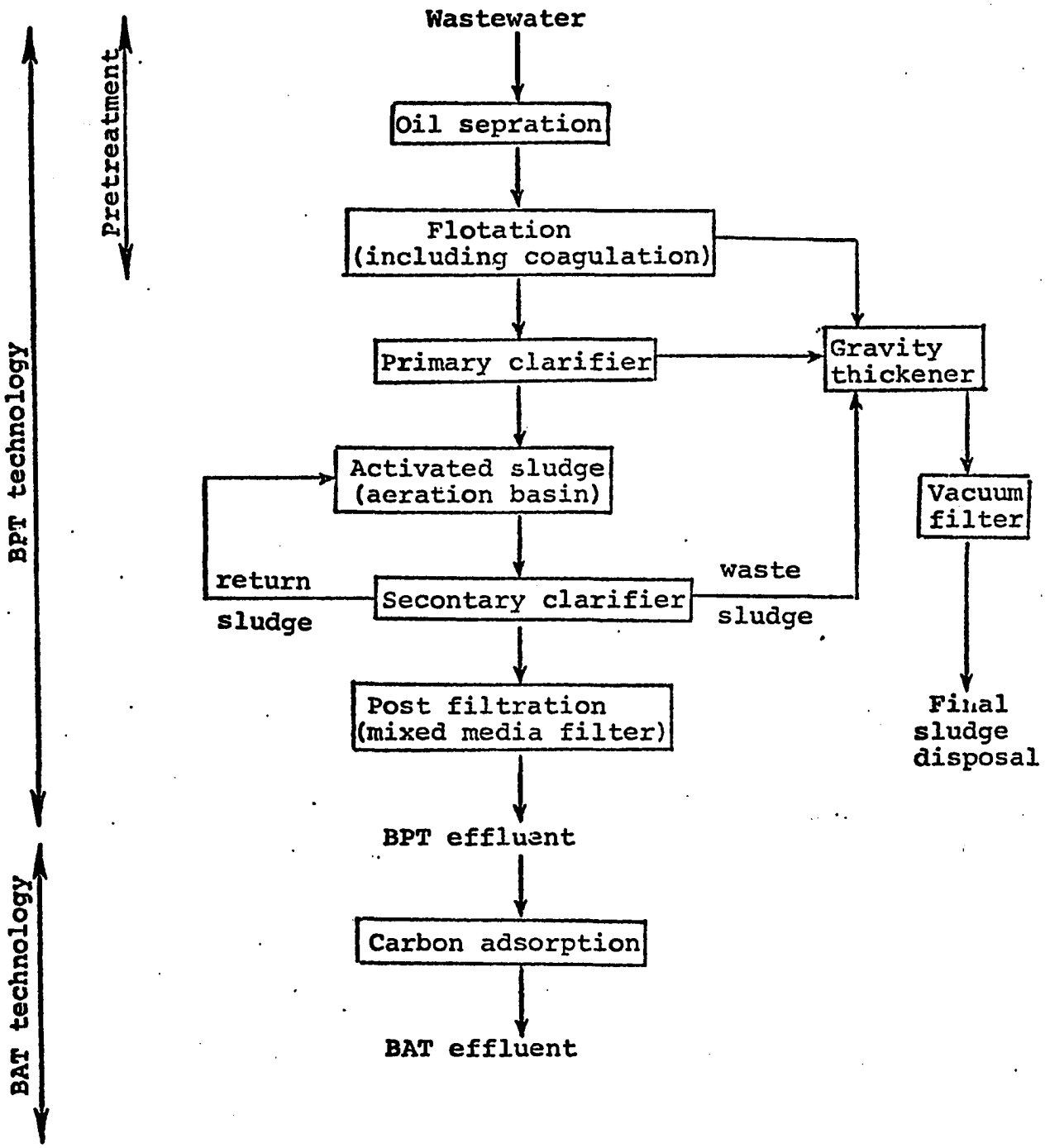


FIGURE 2 WASTEWATER TREATMENT TECHNOLOGY FOR PETROLEUM REFINING INDUSTRY

TABLE 3

WASTE CHARACTERISTICS AND DESIGN CRITERIA

ASSUMPTIONS FOR PETROLEUM REFINING

Waste flow rate	= 0.1 ~ 100 MGD
BOD_5 (Influent)	= 100 ~ 3,000 mg/ℓ
BOD_5 (Effluent)	= 20 ~ 80 mg/ℓ
K	= 0.0025 ~ 0.00005ℓ/mg-hr
a	= 0.70 day^{-1} (Ave)
b	= 0.14 (Ave)
a'	= 0.56 day^{-1} (Ave)
b'	= 0.20 (Ave)
Surface loading (Primary clarifier)	= 500 gpd/sq. ft.
Surface loading (Secondary clarifier)	= 500 gpd/sq. ft.
Mass loading (Gravity thickener)	= 10 lbs solids/sq. ft./day
Filter Loading (Vacuum filter) (15% cake solids)	= 4 lbs solids/sq. ft./hr
Filtration rate (Post mixed media filtration)	= 3 gpm/sq. ft.

3. BAT Technology

Carbon adsorption was selected as BAT technology for petroleum refining wastes. Cost relationships were found as follows:

$$CCPA = 833\ Q^{0.60}\ D^{0.08} \quad (7.5)$$

$$(*)\ (R^2 = 0.924)$$

$$COPA = 1.41\ Q^{-0.33}\ D^{0.77} \quad (7.6)$$

$$(*)\ (R^2 = 0.936)$$

where

CCPA = capital cost of carbon adsorption ($1,000)

COPA = O&M costs of carbon adsorption (¢/1,000 gal)

Q = wastewater flow rate (MGD)

D = COD of BPT effluent (mg/ℓ)

In the above models, COD of BPT effluent is ranged from 30 to 400 mg/ℓ.

Pulp and Paper

Pulp and paper mills may include several types of operations relative to the raw material used and its preparation. Operations in pump mills may include wood preparation, pulping, screening, washing, and bleaching, while operations in paper mills may include stock preparation,

*Satisfies sequential F-test criteria.

paper-machine processing, converting and finishing (121). The sources of wastewater are typically from the pulping, bleaching, and paper-machine operations. The wastewaters contains BOD, COD, suspended solids, dissolved solids, color, heat, etc. BOD reduction is commonly accomplished by biological processes, including aerated lagoon and activated sludge process. Color removal is generally accomplished by lime treatment with clarification.

1. Pretreatment

Equalization was employed as the pretreatment method. Retention time was assumed to be one day, and power of 15 HP/MG. The cost functions can be expressed as:

$$CCPP = 253\ Q^{0.64} \quad (7.7)$$

(*) ($r^2 = 0.893$)

$$COPP = 2.51\ Q^{-0.18} \quad (7.8)$$

(*) ($r^2 = 0.705$)

where

CCPP = capital cost of pretreatment for pulp and paper wastes ($1,000)

COPP = O&M costs of pretreatment for pulp and paper wastes (¢/1,000 gal)

Q = wastewater flow rate (MGD)

*Satisfies F-test criteria.

2. BPT Technology

Equalization followed by an activated sludge process was selected as the BPT technology for pulp and paper wastes. The flow diagram of treatment processes is shown in Figure 3. The major inputs supplied for cost estimating programs are shown in Table 4 (27)(53)(54)(55)(120)(121):

$$\ln C = 5.308 + 0.666 \ln Q + 0.295 \ln I - 0.047 \ln K - 0.060 \ln E \quad (7.9)$$

(*) ($R^2 = 0.994$)

$$\ln M = -0.414 - 0.177 \ln Q + 0.521 \ln I - 0.079 \ln K - 0.102 \ln E \quad (7.10)$$

(*) ($R^2 = 0.961$)

where

C = capital cost of BPT technology for pulp and paper waste ($1,000)

M = O&M costs of BPT technology for pulp and paper waste (¢/1,000 gal)

Q = wastewater flow rate (MGD)

I = influent BOD_5 (mg/ℓ)

E = effluent BOD_5 (mg/ℓ)

K = BOD removal rate coefficient (ℓ/mg-hr)

*Satisfies sequential F-test criteria.

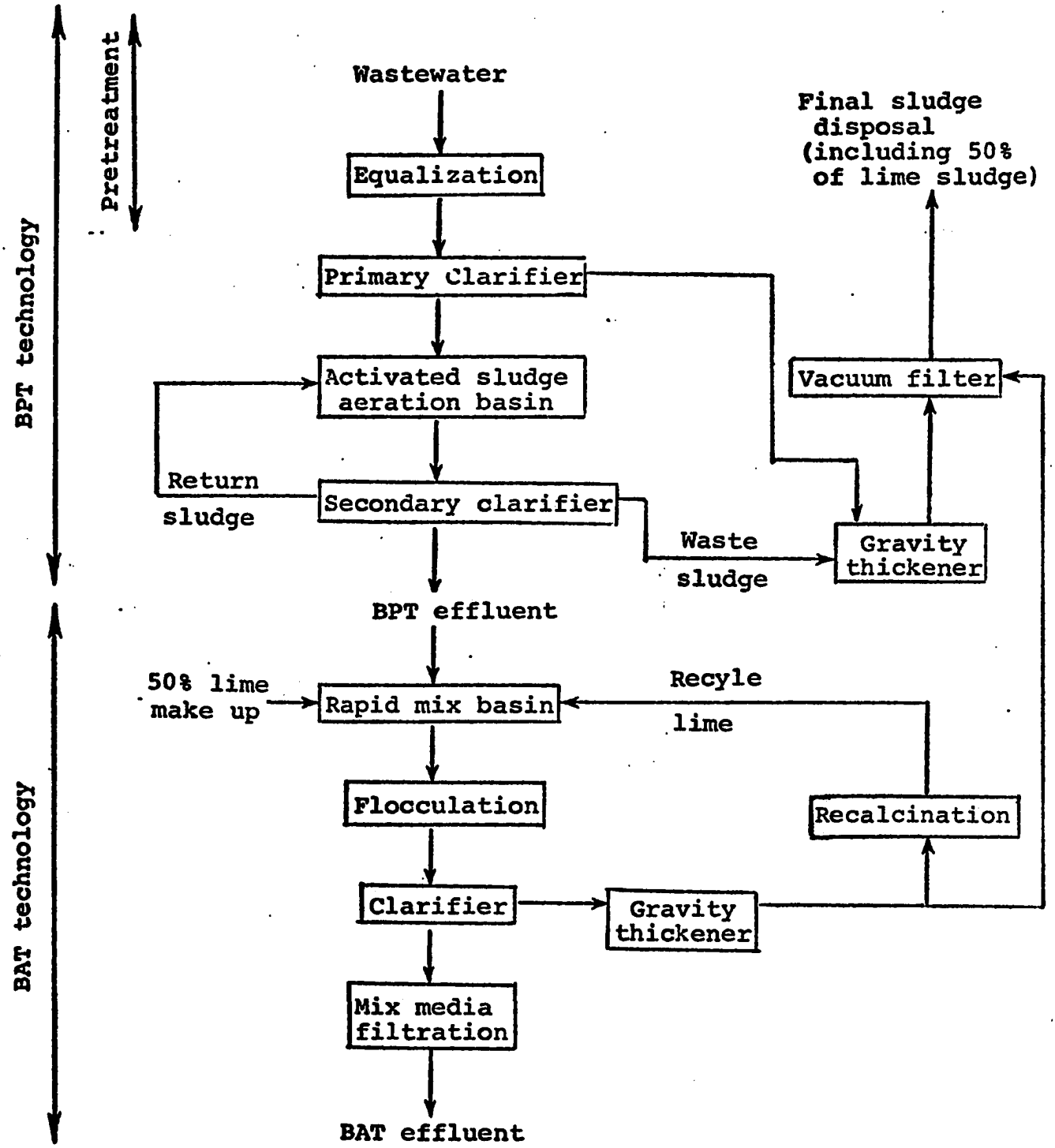


FIGURE 3 WASTEWATER TREATMENT TECHNOLOGY FOR PULP AND PAPER INDUSTRY

TABLE 4

WASTE CHARACTERISTICS AND DESIGN CRITERIA

ASSUMPTIONS FOR PULP AND PAPER

Waste flow rate	= 0.1 ~ 100 MGD
BOD (Influent)	= 100 ~ 3,000 mg/ℓ
BOD (Effluent)	= 20 ~ 80 mg/ℓ
K	= 0.002 ~ 0.00005 ℓ/mg-hr
a	= 0.50 (Ave)
b	= 0.08 day^{-1} (Ave)
a'	= 0.48 (Ave)
b'	= 0.11 day^{-1} (Ave)
Surface loading (Primary clarifier)	= 500 gpd/sq. ft.
Surface loading (Secondary clarifier)	= 500 gpd/sq. ft.
Lime dosage[1]	= 450 mg/ℓ
Filtration rate (Mixed media filtration	= 3 gpm/sq. ft.
Mass loading (Gravity thickener)	= 10 lb solids/sq. ft./day
Filter Loading (Vacuum filter) (15% cake solids)	= 4 lb solids/sq. ft./hr

[1] 50% of lime sludge was for sludge disposal, and 50% of lime was for recalcination. Make up lime was computed by using the assumption that 450 mg/ℓ of lime (CaO) was required and that 0.9 tons/day/mgd was recovered through recalcination.

3. BAT Technology

Lime coagulation followed by granular media filtration (mixed media filtration) was selected as BAT technology for pulp and paper wastes. The treatment sequence is shown in Figure 3. It was assumed that 50% of lime sludge was for sludge disposal, and 50% of lime sludge was for recalcination. Make up lime was computed by using the assumption that 450 mg/ℓ of lime (CaO) was required and that 0.9 tons/day/mgd was recovered through recalcination. The cost models developed are as the following:

$$CCPB = 1344\ Q^{0.63} \qquad (7.11)$$

$$(*)(r^2 = 0.998)$$

$$COPB = 36.46\ Q^{-0.22} \qquad (7.12)$$

$$(*)(r^2 = 0.989)$$

where

CCPB = capital cost of BAT technology for pulp and paper wastes ($1,000)

COPB = O&M costs of BAT technology for pulp and paper wastes (¢/1,000 gal)

Q = wastewater flow rate (MGD)

Electroplating[1]

Electroplating wastes results from the plating of metal parts into final products. The process involves

*Satisfies F-test criteria.

[1]Besides the cost models for electroplating, the cost models presented in this chapter are based on the unit cost models described in Chapter V, and the TI-59 programs described in Chapter VI.

stripping, removal of undesirable oxides, cleaning, and plating of the parts (121). Pollutants include acids, alkaline cleaners, cyanides, and heavy metals such as chromium, zinc, nickel, copper, cadmium.

Treatment of electroplating wastes by neutralization followed by gravity settling for separation of suspended solids — with additional treatment steps for hexavalent chromium and cyanide — has become so widely used in the electroplating industry that it is usually referred to as "conventional" treatment. In this study, this conventional treatment was selected as pretreatment and BPT technology for electroplating wastes. Because the pretreatment standards required for electroplating wastes do not account for the further incidental treatment to be performed by municipal treatment systems, the application of BPT technology to pretreat the electroplating wastes is necessary (72).

1. Pretreatment and BPT Technologies

The treatment sequences of pretreatment and BPT technologies are shown in Figure 4. Figure 4 is a schematic of a conventional treatment facility for electroplating wastes containing chromium and cyanides in addition to other heavy metals, acids, and alkalines. The unit processes shown in Figure 4 (122) are used extensively in the electroplating industry and has become somewhat standard.

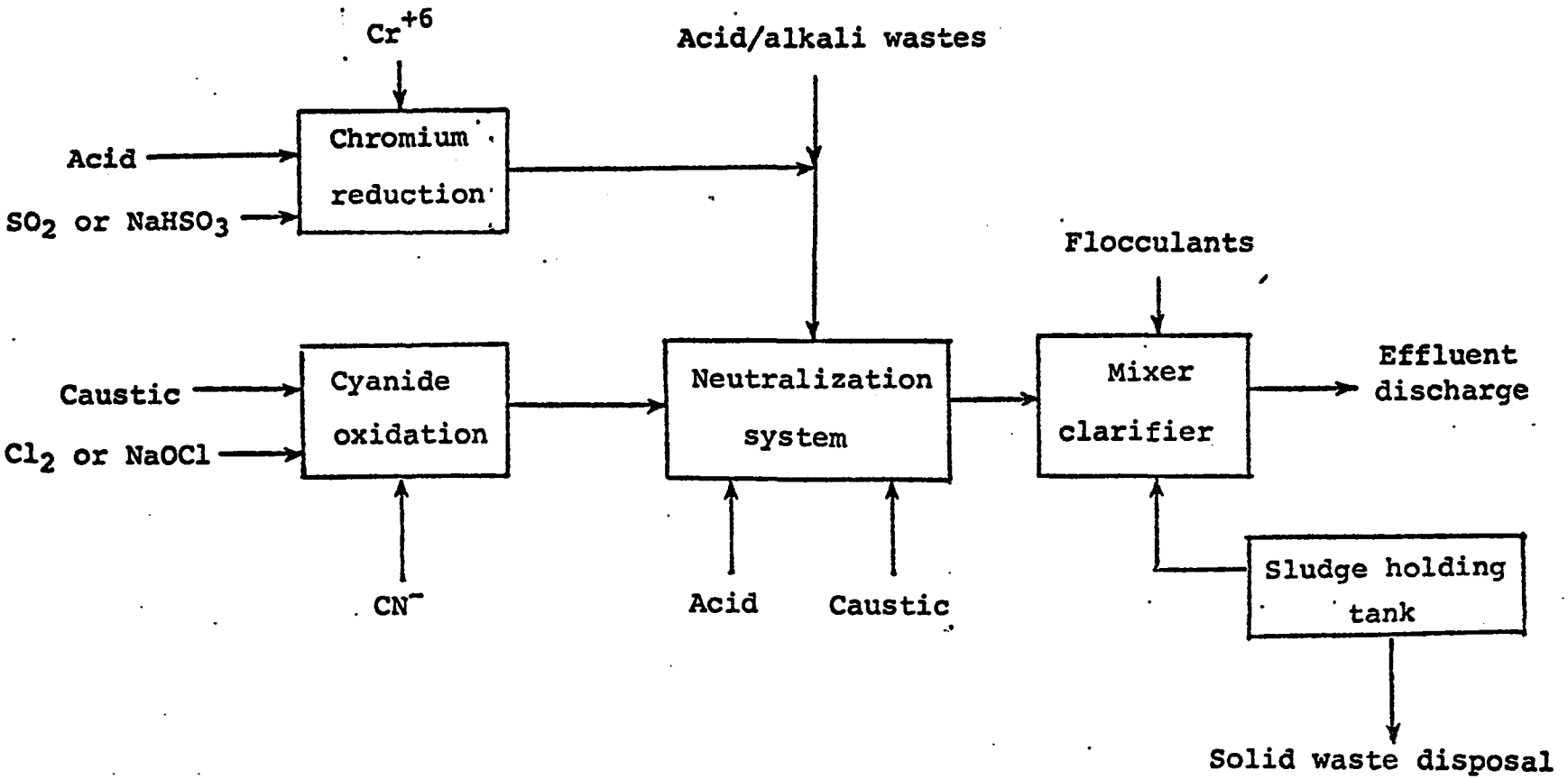


FIGURE 4 CONVENTIONAL ELECTROPLATING WASTEWATER TREATMENT (122)

Standardization and the high cost of site preparation and construction have led to the development of skid-mounted package systems, complete with all hardware and auxiliaries. Thus, it was decided to use the skid-mounted package systems in this study.

The skid-mounted package systems for electroplating waste treatment consist of four components: chromium reduction units, cyanide oxidation units, neutralization/ precipitation units, and a clarification mechanism.

Chromium Reduction Units: Hexavalent chromium first must be reduced to trivalent chromium. Reduction usually is done by reaction with gaseous sulfur dioxide (SO_2) or a solution of sodium bisulfite ($NaHSO_3$). Sulfur dioxide was selected for this study with the net reaction being expressed as:

$$3\ SO_2 + 2H_2Cr_2O_4 + 3\ H_2O \rightarrow Cr_2\ (SO_4)_3 + 5\ H_2O$$

Based on the cost data provided by equipment vendor (122), the installed cost model developed for skid-mounted chromium reduction units is as the following:

$$C = 20 + 0.1\ Q \qquad (7.13)$$

$$(*)(r^2 = 0.988)$$

*Satisfied F-test criteria.

where

C = installed cost of skid-mounted chromium reduction units ($1,000)

Q = flow rate of hexavalent chromium bearing waste stream (gpm)

Cyanide Oxidation Units: It is necessary to oxidize the highly toxic cyanide, first to less toxic cyanate, then to harmless bicarbonates and nitrogen. The oxidation reagent is commonly chlorine, which can be introduced into the system by adding chlorine gas (Cl_2) or sodium hypochlorite (NaOCl). In this study, chlorine gas was selected, and the typical reactions are as follows:

First Stage:

$$NaCN + 2NaOH + Cl_2 \rightarrow NaCNO + 2NaCl + H_2O$$

Second Stage:

$$2NaCNO + 5NaOH + 3Cl_2 \rightarrow 6NaCl + CO_2 + N_2 + NaHCO_3 + 2H_2O$$

Based on the cost data provided by equipment vender (122), the installed cost model developed for skid-mounted cyanide oxidation units is as the following:

$$C = 35 + 0.23Q \quad (7.14)$$

$$(*)\ (r^2 = 0.966)$$

*Satisfies F-test criteria.

where

C = installed cost of skid-mounted cyanide oxidation units ($1,000)

Q = flow rate of cyanide bearing waste stream (gpm)

Neutralization/Precipitation System: The mixed acid/alkali waste streams from the various metal cleaning and plating operations are combined in the neutralizer with the chromium reduction and cyanide oxidation steps. Because the heavy metals are soluble at low pH conditions in the wastewater, the pH is adjusted to a range of 7.5 to 9.5. Within this range, the minimum solubility of a mixture of metals is reached and the metals precipitate as hydroxides. The alkali such as lime, $Ca(OH)_2$ or caustic soda, NaOH, can be used for neutralization. In this study, NaOH was selected.

Based on the cost data obtained from equipment manufacturer (122), the cost model developed for skid-mounted neutralization/precipitation system is given below:

$$C = 11.1\ Q^{0.20} \qquad (7.15)$$

$$(*)(r^2 = 0.996)$$

where

C = installed cost for skid-mounted neutralization/precipitation system ($1,000)

Q = waste flow rate (gpm)

*Satisfies F-test criteria.

Flocculation/Clarification System: Metal hydroxides and other insoluble pollutants are removed by gravity settling. To enhance the settling charactertics of the suspended solids, flocculents, such as alum, ferrous sulfate, polyelectrolyte can be added to the mixing-flocculation chamber.

Based on the cost data (122) obtained from manufacturers, the following cost model was developed:

$$C = 7.83 + 0.16\ Q \qquad (7.16)$$

$$(*)(r^2 = 0.988)$$

where

C = installed cost of skid-mounted flocculation/clarification system ($1,000)

Q = wastewater flow rate (gpm)

The solids from clarifiers are typically discharged to the sludge holding tank. The cost of the sludge holding tank is approximately 10% of total installed cost (122).

Capital Cost Model: All of the above unit cost models for electroplating waste treatment were compiled on TI-59 programmable calculator and program list is included in Appendix C. Regression analysis were carried out using the capital cost data generated from the programs for a range of values of input variables. It was found that the capital cost of pretreatment and BPT with conventional treatment technology can be well represented by the following models

*Satisfies sequential F-test criteria.

$$\ell n\ C = 3.609 + 0.031\ \ell n\ Q_1 + 0.025\ \ell n\ Q_2 + 0.260\ \ell n\ Q_3 \quad (7.17)$$

$$(*)(R^2 = 0.991)$$

where

C = capital cost for conventional electroplating wastewater treatment ($1,000)

Q_1 = flow rate of hexavalent chromium bearing waste stream (gpm)

Q_2 = flow rate of cyanide bearing waste stream (gpm)

Q_3 = total waste flow rate (gpm)

The above capital model is suitable for:

$Q_1 \leq 80$ gpm

$Q_2 \leq 40$ gpm

$Q_3 \leq 120$ gpm

O&M Cost Model: Although the capital costs for conventional wastewater treatment systems depend principally on wastewater flow rates, the O&M costs will primarily depend on the chemical and final sludge disposal costs. Industrial Environmental Research Laboratory (122) has estimated chemical consumption and cost (See Figure 5), and final sludge disposal cost (See Figure 6) for electroplating wastes. The sludge (4% solids) was assumed to be

*Satisfies sequential F-test criteria.

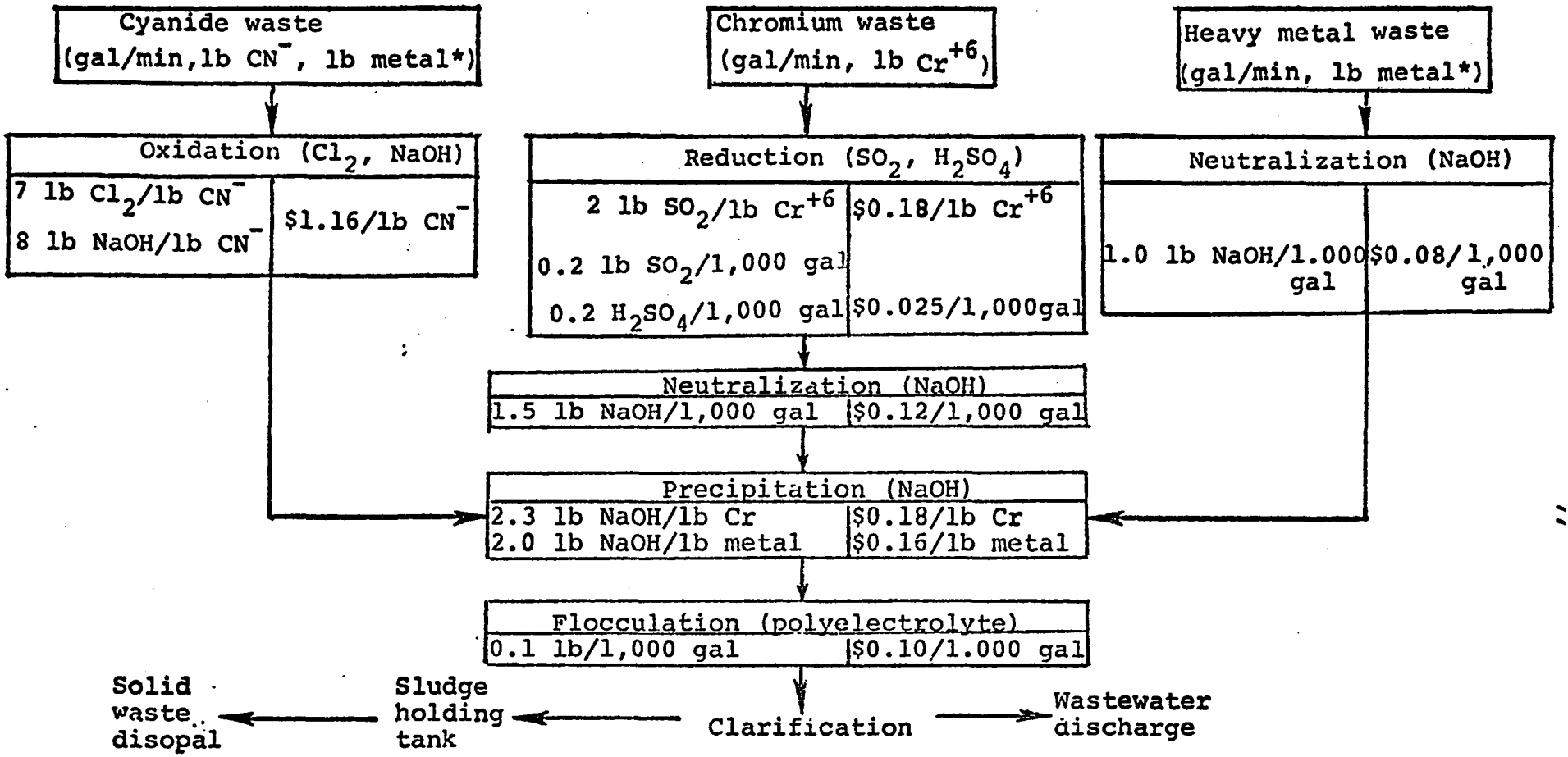
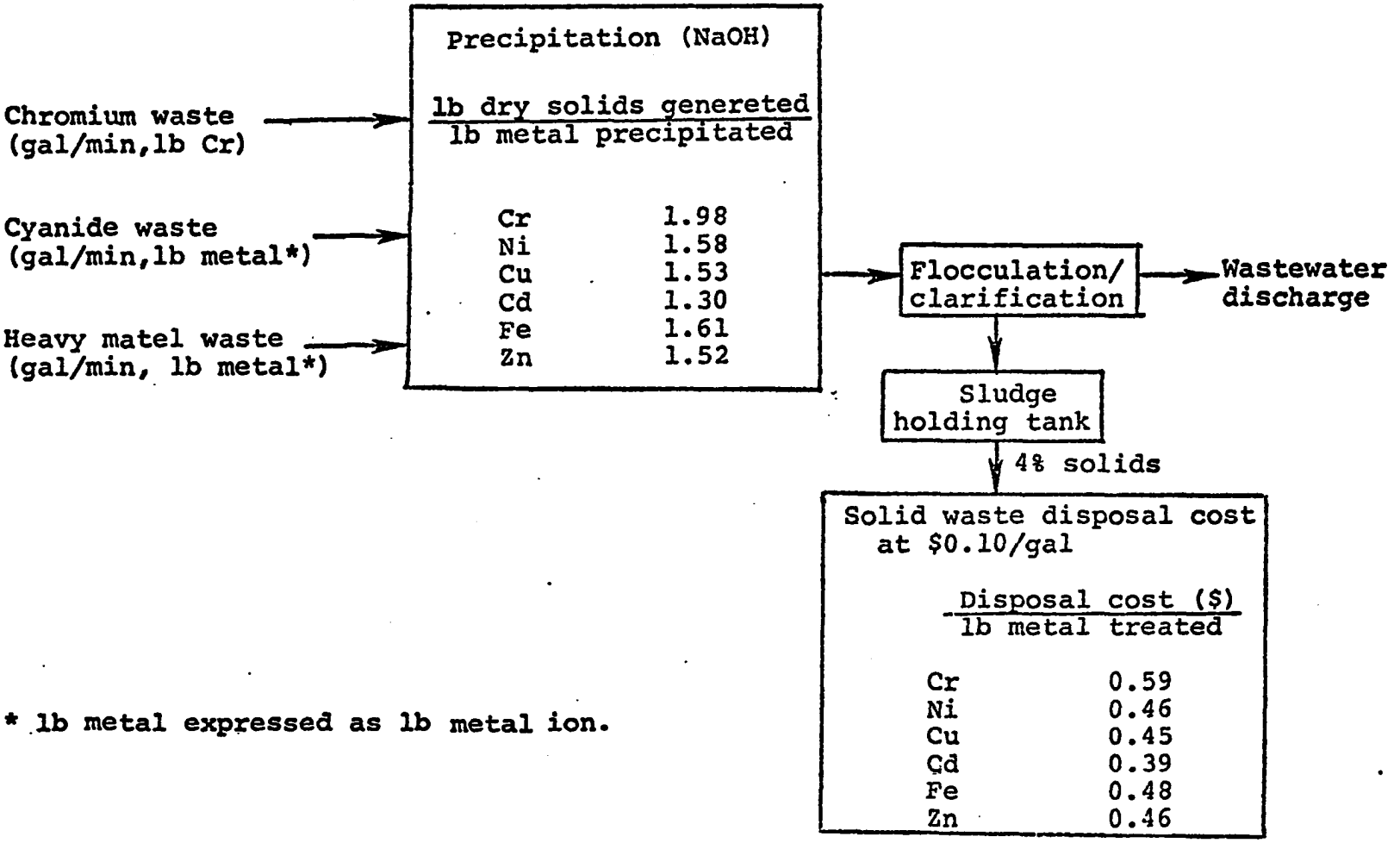


FIGURE 5 CONSUMPTION AND COST FACTORS FOR WASTEWATER TREATMENT CHEMICALS (122)



* lb metal expressed as lb metal ion.

FIGURE 6 SOLIDS PRODUCTION, AND SLUDGE DISPOSAL COST FOR CONVENTIONAL ELECTROPLATING WASTEWATER TREATMENT (122)

hauled to a licensed chemical landfill at a disposal cost of $0.10/gal. Operation and maintenance labor costs is approximately 18% of capital cost (122). Figure 5 and 6 were compiled on TI-59 programmable calculator to generate O&M cost data. The program list is included in Appendix D. From regression analysis, the following O&M cost model was developed:

$$C = 594.392 - 2.259\ Q_1 - 2.472\ Q_2 - 2.031\ Q_3 + 1.154\ M_1 + 5.396\ M_2 + 8.723\ M_3 + 4.621\ M_4 + 4.606\ M_5 + 4.522\ M_6 + 3.868\ M_7 + 3.693\ M_8 \quad (7.18)$$

$$(*)\ (R^2 = 0.927)$$

where

C = O&M costs for conventional electroplating wastewater treatment (¢/1,000 gal)

Q_1 = flow rate of hexavalent chromium waste stream (gpm)

Q_2 = flow rate of cyanide bearing waste stream (gpm)

Q_3 = rate of flow to be neutralized (gpm)

M_1 = Cr^{+6} reduced (lb/hr)

M_2 = total Cr precipitated (lb/hr)

M_3 = CN^- oxidized (lb/hr)

*Satisfies sequential F-test criteria.

M_4 = Zn^{+2} precipitated (lb/hr)

M_5 = Fe^{+2} precipitated (lb/hr)

M_6 = Ni^{+2} precipitated (lb/hr)

M_7 = Cu^{+2} precipitated (lb/hr)

M_8 = Cd^{+2} precipitated (lb/hr)

The above model is suitable for:

$Q_1 \leq 80$ gpm

$Q_2 \leq 40$ gpm

$Q_3 \leq 120$ gpm

$M_1 \leq 400$ mg/ℓ

$M_2 \leq 600$ mg/ℓ

$M_3 \leq 250$ mg/ℓ

$M_4 \leq 400$ mg/ℓ

$M_5 \leq 2{,}000$ mg/ℓ

$M_6 \leq 3{,}000$ mg/ℓ

$M_7 \leq 400$ mg/ℓ

$M_8 \leq 50$ mg/ℓ

2. BAT Technology

Evaporators are recommended by Industrial Environmental Research Laboratory (123) as the BAT Technology for electroplating wastes. Based on the cost estimated by this Laboratory, the following capital cost models for single-effect evaporators were developed:

$$C_1 = 10.78\ Q_1^{0.31} \quad (7.19)$$
$$(*)\ (r^2 = 0.923)$$

$$C_2 = 3.74\ Q_2^{0.56} \quad (7.20)$$
$$(*)\ (r^2 = 0.908)$$

$$C_3 = 5.35\ Q_3^{0.51} \quad (7.21)$$
$$(*)\ (r^2 = 0.992)$$

where

C_1 = installed cost of single-effect evaporator for cyanide bearing waste stream to evaporator ($1,000)

C_2 = installed cost of single-effect evaporator for chromium bearing waste stream to evaporator ($1,000)

C_3 = installed cost of single-effect evaporator for nickel bearing waste stream to evaporator ($1,000)

Q_1 = flow rate of cyanide bearing waste stream to evaporator (gal/hr)

Q_2 = flow rate of nickel bearing waste stream to evaporator (gal/hr)

Q_3 = flow rate of chromium bearing waste stream to evaporator (gal/hr)

Although the individual pollutant has its own capital cost model, the effect on the O&M costs is very limited.

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*Satisfies F-test criteria.

A general O&M cost for single-effect evaporator can be estimated by the following model (26)(122):

$$C = 5.22\ Q^{-0.35} \qquad (7.22)$$

$$(*)\ (r^2 = 0.987)$$

where

C = O&M costs of single-effect evaporator ($/hr)

Q = wastewater flow to evaporator (gal/hr)

The above BAT cost models are suitable for a flow rate to evaporator less than or equal to 300 gal/hr. Note that the evaporation process can recover plating chemicals. Thus, the economic advantages could be realized by installing the evaporator units.

Organic Chemical Manufacturing

Organic chemicals are the raw materials for a multitude of products, the public uses daily, including plastics, synthetic fibers, dyes, solvents, food additives, lubricants, detergents, and cosmetics. Wastewaters from this industrial group are organic in nature. Because the organic chemicals are derived from a variety of raw materials, and involve different physical and chemical conversion operations, the BOD removal rates (K) are also different. For example, K values for the plastic and synthetic material industry may differ as follows (26):

---

*Satisfies F-test criteria.

Rayon	K = 0.00016	ℓ/mg-hr
Cellophane	K = 0.00014	ℓ/mg-hr
Polyester	K = 0.0012	ℓ/mg-hr
Nylon	K = 0.0004	ℓ/mg-hr

It was found that K values for organic industrial wastewaters are ranged from 0.00003 to 0.0028ℓ/mg-hr (120). Because the pollutants in organic chemical wastewater are primarily organic matters, biological treatment method should be applicable.

1. Pretreatment

The pretreatment technology selected for the organic chemical industry is oil separation, followed by equalization, and neutralization.

Acidic and alkaline discharges are characteristic of most organic chemical plants. Neutralization is accomplished by the addition of alkali to acids or by the addition of acid to alkalies as required to achieve the required pH adjustment. In practical situations, the process variations during manufacturing operations may cause gross pH fluctuations and occasional slugs of acidic or alkaline wastes. Thus, using an equalization facility to dampen the pH fluctuations is necessary.

For this study, the wastewater from an organic chemical plant was assumed to be acidic. Although partial neutralization might have been accomplished after equalizing,

further neutralization is still necessary. Lime neutralization is selected for this further neutralization.

Based on the above assumption, the pretreatment cost models for organic chemical industry were developed as follows:

$$\ell n\ C = 3.236 + 0.801\ \ell n\ Q + 0.623\ \ell n\ A \qquad (7.23)$$

$$(*)\ (R^2 = 0.994)$$

$$\ell n\ M = 0.065 - 0.101\ \ell n\ Q + 0.567\ \ell n\ A \qquad (7.24)$$

$$(*)\ (R^2 = 0.998)$$

where

C = capital cost of pretreatment for organic chemical industry ($1,000)

M = O&M costs of pretreatment for organic chemical industry (¢/1,000 gal)

Q = wastewater flow rate (MGD)

A = acidity to be neutralized (mg/ℓ as $CaCO_3$)

When neutralization of acidity is not required, the pretreatment cost can be obtained by letting A(acidity) = o in Eqs. 7.23 and 7.24.

2. BPT Technology

The BPT technology used for the organic chemical industry is an activated sludge process preceded by oil separation, equalization, and neutralization as pretreat-

*Satisfies sequential F-test criteria.

ment. The flow diagram is shown in Figure 7, and the major waste characteristics and design criteria inputs for estimating programs are listed in Table 5. The cost relationship can be well represented by the following models:

$$\ln C = 4.265 + 0.765 \ln Q + 0.132 \ln I - 0.022 \ln K - 0.025 \ln E + 0.414 \ln A \quad (7.25)$$

(*) ($R^2 = 0.994$)

$$\ln M = 0.357 - 0.106 \ln Q + 0.163 \ln I - 0.026 \ln K - 0.030 \ln E + 0.411 \ln A \quad (7.26)$$

(*) ($R^2 = 0.943$)

where

C = capital cost of BPT technology for organic chemical industry ($1,000)

M = O&M costs of BPT technology for organic chemical industry (¢/1,000 gal)

I = influent BOD_5 (mg/ℓ)

E = effluent BOD_5 (mg/ℓ)

K = BOD removal rate coefficient (ℓ/mg-hr)

A = acidity to be neutralized (mg/ℓ as $CaCO_3$)

*Satisfies sequential F-test criteria.

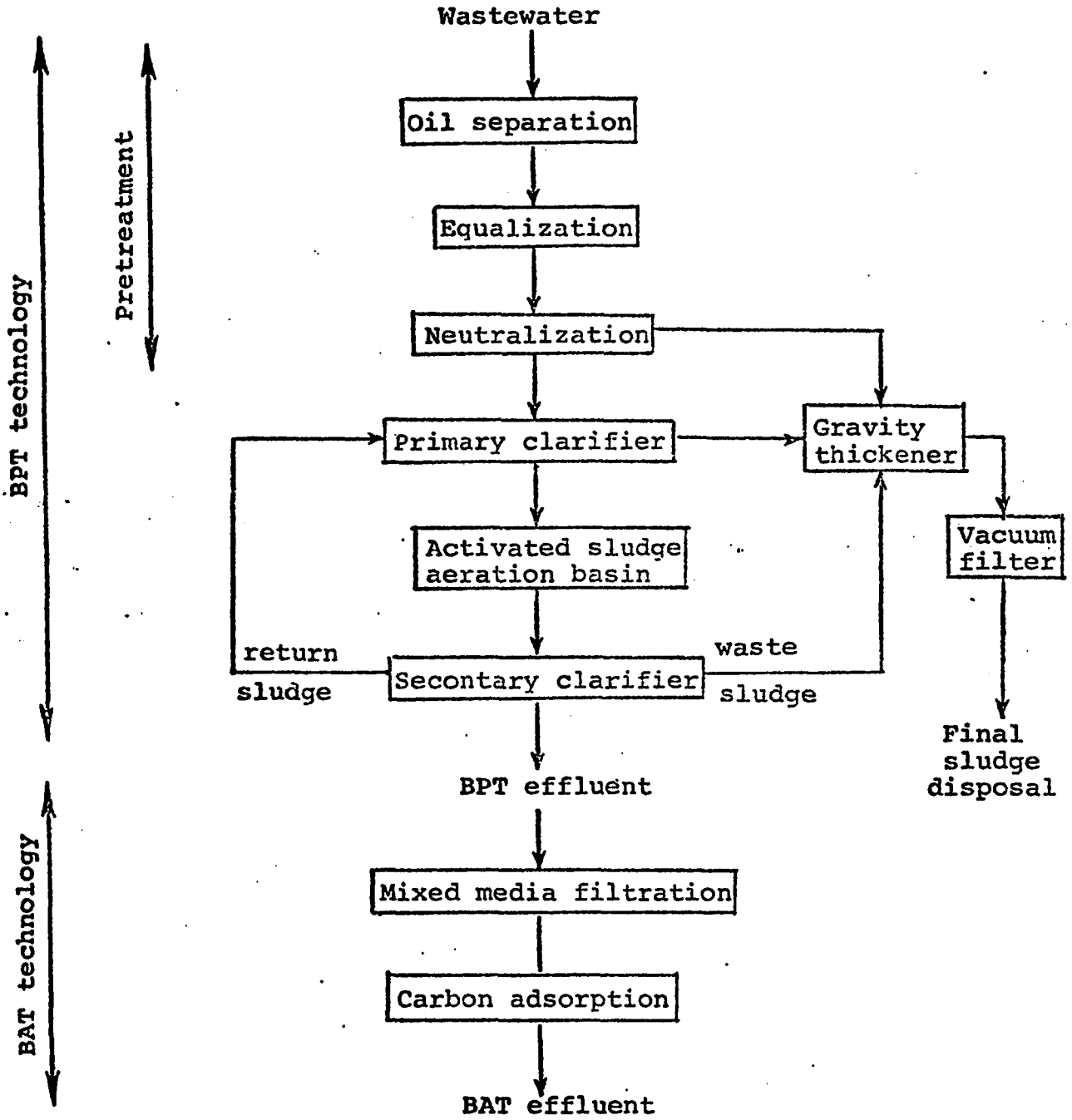


FIGURE 7 WASTEWATER TREATMENT TECHNOLOGY FOR ORGANIC CHEMICAL MANUGACTURING

TABLE 5

WASTE CHARACTERISTICS AND DESIGN CRITERIA ASSUMPTIONS

FOR ORGANIC CHEMICAL MANUFACTURING

Waste flow rate	= 0.1 ~ 60 MGD
BOD (Influent)	= 100 ~ 3,000 mg/ℓ
BOD (Effluent)	= 20 ~ 80 mg/ℓ
K	= 0.00003 ~ 0.0028 ℓ/mg-hr
a	= 0.62 day^{-1} (Ave)
b	= 0.10 (Ave)
a'	= 0.45 day^{-1} (Ave)
b'	= 0.14 (Ave)
Retention Time (Equalization	= 1 day
Surface loading (Primary clarifier)	= 650 gpd/sq. ft.
Surface loading (Secondary clarifier)	= 650 gpd/sq. ft.
Filtration rate (Mixed media filtration)	= 3 gpm/sq. ft.
Mass loading (Gravity thickener)	= 8 lbs solids/sq. ft./day
Filter loading (Vacuum filter) (15% cake solids)	= 4 lbs solids/sq. ft./day

When neutralization of acidity is not required, the BPT cost models can also be obtained by letting A (Acidity) = o in Eqs. 7.25 and 7.26.

3. BAT Technology

Mixed media filtration followed by carbon adsorption was chosen as BAT technology for the organic chemical industry. The cost models developed are the following:

$$\ell n\ C = 6.904 + 0.601\ \ell n\ Q + 0.259\ \ell n\ D \qquad (7.27)$$
$$(*)\ (R^2 = 0.996)$$

$$\ell n\ M = 1.088 - 0.295\ \ell n\ Q + 0.478\ \ell n\ D \qquad (7.28)$$
$$(*)\ (R^2 = 0.954)$$

where

C = capital cost of BAT technology for organic chemical industry ($1,000)

M = O&M costs of BAT technology for organic chemical industry (¢/1,000 gal)

Q = wastewater flow rate (MGD)

D = COD (mg/ℓ)

Inorganic Chemical Manufacturing

The most important manufacuring groups of the inorganic chemical industry consist of the alkalines and

*Satisfies sequential F-test criteria.

chlorine, industrial gases, inorganic pigments, industrial inorganic chemicals, paints and allied products, and fertilizers (24). The composition of wastes from the inorganic chemical industry can be classified as:

Acidity or alkalinity
Suspended solids
Dissolved solids
High temperature

Various combinations of the above types of pollutants may occur in an inorganic chemical wastewater. The typical ranges of the values for pollutants which found from the industry were as follows (24):

Waste flow rate	0.5 ~ 50 MGD
Acidity	200 ~ 20,000 mg/ℓ as $CaCO_3$
Suspended solids	0 ~ 500 mg/ℓ
Dissolved solids	1,000 ~ 150,000 mg/ℓ
Temperature	up to 180°F

The above ranges were considered for cost estimation by this study. Note that biological treatment is not applicable because these pollutants are primarily inorganic dissolved or suspended solids.

1. Pretreatment

A lime neutralization plant shown in Figure 8 is selected as pretreatment for inorganic industrial wastes.

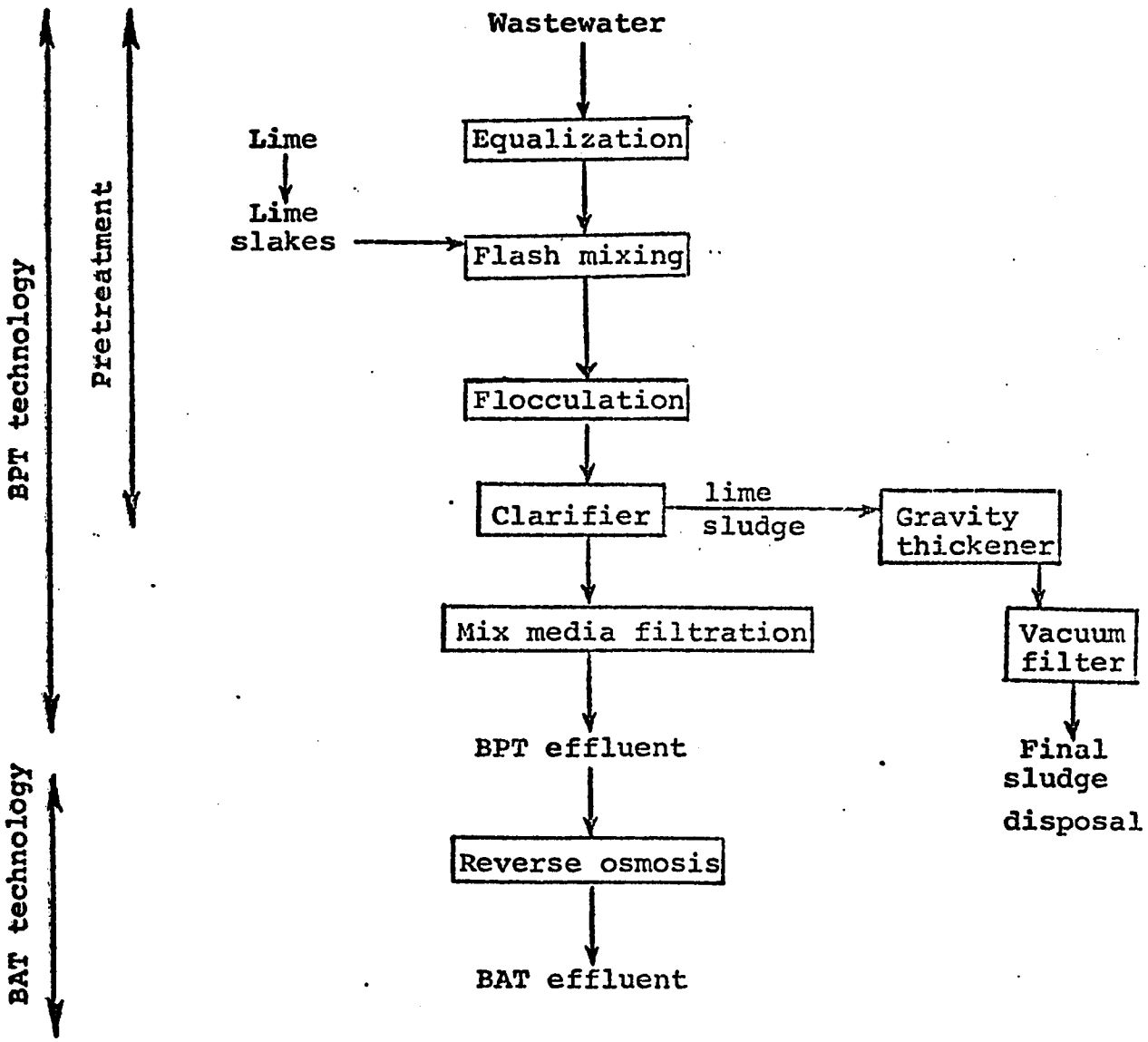


FIGURE 8 WASTEWATER TREATMENT TECHNOLOGY FOR INORGANIC CHEMICAL INDUSTRY

As shown in Figure 8, an equalization basin is also included for pretreatment of wastes because of pH and temperature considerations. The developed cost models are as follows:

$$\ln C = 2.558 + 0.795 \ln Q + 0.704 \ln A \quad (7.29)$$
$$(*)\ (R^2 = 0.998)$$

$$\ln M = -0.279 - 0.097 \ln Q + 0.606 \ln A \quad (7.30)$$
$$(*)\ (R^2 = 0.993)$$

where

C = capital cost of pretreatment for inorganic chemical industry ($1,000)

M = O&M cost of pretreatment for inorganic chemical industry (¢/1,000 gal)

Q = wastewater flow rate (MGD)

A = acidity to be neutralized (mg/ℓ as $CaCO_3$)

2. BPT Technology

Equalization followed by lime neutralization, and mixed media filtration is chosen as BPT technology for inorganic chemical industry. The treatment sequence is shown in Figure 8. Through the use of cost estimating programs and regression analysis, the following models were developed:

$$\ln C = 3.341 + 0.772 \ln Q + 0.618 \ln A \quad (7.31)$$
$$(*)\ (R^2 = 0.934)$$

*Satisfies sequential F-test criteria.

$$\ell n\ M = 0.430 - 0.115\ \ell n\ Q + 0.529\ \ell n\ A \qquad (7.32)$$

$$(*)\ (R^2 = 0.967)$$

where

C = capital cost of BPT technology for inorganic chemical industry ($1,000)

M = O&M costs of BPT technology for inorganic chemical industry (¢/1,000 gal)

Q = wastewater flow rate (MGD)

A = acidity to be neutralized (mg/ℓ as $CaCO_3$)

3. BAT Technology

Reverse osmosis (RO) is selected as BAT technology for the inorganic chemical industry. The cost models developed for RO are as follows:

$$C = 1648\ Q^{0.75} \qquad (7.33)$$

$$(*)\ (r^2 = 0.894)$$

$$M = 53.4\ Q^{-0.21} \qquad (7.34)$$

$$(*)\ (r^2 = 0.886)$$

where

C = capital cost of RO ($1,000)

M = O&M costs of RO (¢/1,000 gal)

Q = wastewater flow rate (MGD)

*Satisfies sequential F-test criteria.

Generally, the pH range for a RO process can vary between 4.0 to 7.5 (109). Thus, neutralization of acidity may be not necessary, and the neutralization plant could be bypassed. But, the filtration will still be required as a pretreatment to decrease fouling potential.

The above cost models for the RO process did not include brine disposal. Because the concentrated brine can be disposed by mechanical evaporation, solar evaporation, deep well disposal or other methods, depending on the situation, the cost of brine disposal were too unpredictable to be included in the model.

CHAPTER VIII

ECONOMICS OF INDUSTRIAL WASTEWATER TREATMENT

There exists considerable economic concern related to selection of the proper alternative for industrial waste handling. Three principal alternatives can be classified as:

1. Pretreatment and discharge, leaving secondary or advanced wastewater treatment as the municipal responsibility,
2. Joint collection and treatment from several sites (i.e., group treatment),
3. Treatment and discharge and/or reuse at the site.

Among these alternatives, municipal treatment has advantages of scale. On-site complete treatment has advantages of convenience and construction time. Group treatment has the advantage of scale and equalization. An industry must decide whether to discharge wastes to a

municipal system, to join a group industrial waste treatment from several sites, or to provide treatment of its own effluents at the site. Based on the cost models developed in the previous chapter, the above alternatives together with treatment-cost relationships for industrial waste treatment are discussed below.

Decision-Making Strategy for Municipal Versus On-Site Treatment of Industrial Wastewater

Industrial wastewater management has undergone great changes since the enactment of PL 92-500. With PL 92-500 in full effect, industry must decide whether to treat its own waste or to contact with a municipality to accept, treat, and dispose of its waste without pretreatment or if necessary with pretreatment. Note also that industrial waste discharged through municipal systems is required to pay for industry cost recovery (ICR) and service charges.

Thus, there exists a question of "which path to follow" by industry to assure a least costly alternative. To help manufacturing plants in such alternative selection, cost models for pretreatment and complete treatment (BPT and BAT) have been developed for selected industries. In this section, the procedure to choose the optimum alternative accompanied with a series of mathematical equations which can be used with these cost models will be developed.

With known wastewater characteristics at a manufacturing plant, the annual capital cost for complete (BPT or BAT) treatment of its industrial wastewater is:

$$C_c = 1{,}000\ (I)(\lambda) \qquad (8.1)$$

where

C_c = annual capital cost for complete (BPT or BAT) treatment ($/yr)

(I) = capital cost for complete (BPT or BAT) treatment computed from an appropriate BPT or BAT capital cost model described in Chapter VII ($1,000)

(λ) = capital recovery factor.

Equation for operational and maintenance costs is given by:

$$C_{o\&m} = (J)(H)/100 \qquad (8.2)$$

where

$C_{o\&m}$ = annual operation and maintenance cost for complete (BPT or BAT) treatment ($/yr)

(J) = unit O&M cost for complete (BPT or BAT) treatment computed from an appropriate BPT or BAT O&M cost model described in Chapter VII (¢/1,000 gal)

(H) = total waste flow per (1,000 gal/yr)

Now total annual cost for the industrial wastewater system with complete (BPT or BAT) treatment is given by adding Eqs. 8.1 and 8.2.

$$C_t = C_c + C_{o\&m} \tag{8.3}$$

where

C_t = total annual cost for complete (BPT or BAT) treatment ($/yr)

C_c, $C_{o\&m}$ = as previously defined.

Now looking at annual ICR payment for the municipal wastewater system (124):

$$C_{ICR} = \left(\frac{a_1}{b}\right) X_1 + \left(\frac{a_2}{b}\right) X_2 + \left(\frac{a_3}{b}\right) X_3 \tag{8.4}$$

where

C_{ICR} = total ICR payment per year in dollars.

a_1 = equal ICR unit cost (flow related) of construction for the useful life of the treatment works in $/1,000 gal/day

a_2 = equal ICR unit cost (BOD related) of construction for the useful life of the treatment works in $/lbs/day

a_3 = equal ICR unit cost (S.S. related) of construction for the useful life of the treatment works in $/lbs/day.

b = ICR period[1]

X_1 = design daily flow of industrial wastewater in 1,000 gal/day.

X_2 = design daily BOD loading of industrial wastewater in lbs/day.

X_3 = design daily S.S. loading of industrial wastewater in lbs/day.

The annual service charges to industry is given by the following sample operation and maintenance cost equation:

$$C'_{o\&m} = C_1Y_1 + C_2Y_2 + C_3Y_3 \qquad (8.5)$$

where

$C'_{o\&m}$ = annual operational and maintenance cost charge to industry by city municipal waste system in dollars.

C_1 = city charge to industry in \$/1,000 gallons.

C_2 = city charge to industry in \$/lb of BOD.

C_3 = city charge to industry in \$/lb of S.S.

Y_1 = design yearly flow of industrial wastewater in 1,000 gallons/yr.

---

[1] It has been established as 30 years or the useful life of the treatment works. The lesser time period to be utilized. Federal grant amounts subject to ICR are to be recovered from the industrial users over this ICR period (Ref. 124).

Y_2 = Design yearly BOD loading of industrial wastewater in lbs/yr.

Y_3 = design yearly daily S.S. loading of industrial wastewater in lbs/yr.

Adding Eqs. 8.4 and 8.5 gives total annual charge by the city municipal wastewater system.

$$C_{mc} = C_{ICR} + C'_{o\&m} \tag{8.6}$$

where

C_{mc} = total annual charge to the industry by the city municipal wastewater system ($/yr)

C_{ICR}, $C'_{o\&m}$ = as previously defined.

If the waste would be required to provide pretreatment. The annual capital cost for pretreatment of industrial wastewater can be given by:

$$C_{pi} = 1000(L)(\lambda) \tag{8.7}$$

where

C_{pi} = annual pretreatment cost ($/yr)

(L) = capital cost for pretreatment computed from an appropriate pretreatment capital cost model described in Chapter VII ($1,000/yr)

(λ) = as previously defined.

Equation for operation and maintenance cost is given by:

$$C_{po\&m} = (M)(H)/100 \qquad (8.8)$$

where

$C_{po\&m}$ = total annual operation and maintenance cost for pretreatment ($/yr)

(M) = unit O&M cost for pretreatment computed from an appropriate pretreatment O&M cost model described in Chapter VII (¢/1,000 gal)

(H) = as previously defined.

Adding Eqs. 8.7 and 8.8 gives total annual pretreatment cost for industry.

$$C_{pc} = C_p + C_{po\&m} \qquad (8.9)$$

where

C_{pc} = total annual pretreatment cost ($/yr)

C_p, $C_{po\&m}$ = as previously defined.

In case of industrial wastewater without pretreatment requirement, the total annual cost of industrial wastewater treatment system is approximately equal to the total annual charge by the city municipal wastewater system.

$$C_{(w/o)p} = C_{mc} \qquad (8.10)$$

where

$C_{(w/o)p}$ = total annual cost (without pretreatment requirement) ($/yr)

C_{mc} = as previously defined.

In case of industrial wastewater with pretreatment requirement, the total annual cost of industrial wastewater treatment system will be the sum of annual pretreatment cost and annual charge by the city municipal wastewater system.

$$C_{(w/)p} = C_{mc} + C_{pc} \tag{8.11}$$

where

$C_{(w/)p}$ = total annual cost (with pretreatment requirement) ($/yr)

C_{mc}, C_{pc} = as previously defined.

What we need is to minimize the total annual cost of industrial wastewater treatment system by either tying into municipal treatment system or treating its own waste at site. If C_t is greater than $C_{(w/o)p}$ or $C_{(w/)p}$, it will be cost effective for the industry to discharge its wastewater to a municipal wastewater system. However, if C_t is less than $C_{(w/o)p}$ or $C_{(w/)p}$, the industrial plant to construct its own wastewater treatment system will be cost effective.

The following includes a numerical example of the application of the equations described above to typical

economic decision. This example illustrates how pre-treatment, BPT and BAT cost models can guide the industries when confronted with municipal versus on-site (complete) treatment problem.

A pulp and paper company with a daily wastewater flow rate of 5.0 MGD needs to know whether it is economical to build a wastewater plant or to continue using city municipal wastewater system. It is assumed that the city sewage service charges to industry are: $0.40 per 1,000 gal, $0.04 per lb of BOD, and $0.06 per lb of S.S. Assuming that the ICR period has been established as 30 years for this municipal wastewater system. Equal ICR unit costs are $529.08/1,000 gal/day for flow related, $75.15/lb/day for BOD related, $25.62/lb/day for S.S. related.

The waste characteristics of this pulp and paper company are assumed as follows:

BOD	600 mg/ℓ
SS	600 mg/ℓ
K	0.00015 ℓ/mg-hr

Alternative A: On-site treatment (build a wastewater treatment at its site)

Treatment level required: BPT (equlization + activated sludge process)

Effluent quality required: 30 mg/ℓ of BOD

Capital cost of treatment plant (from Eq. 7.9) = $5,011,000

O&M costs of treatment plant (from Eq. 7.10) = 21.3 ¢/1,000 gal

CRF (10%, 15 years) = 0.1315

Total annual cost with BPT technology (from Eqs. 8.1, 8.2 and 8.3) = $1,032,000

Alternative B: Municipal treatment (Use municipal wastewater system)

Pretreatment required: Equalization

Capital cost of pretreatment (from Eq. 7.7) = $709,000

O&M costs of pretreatment (from Eq. 7.8) = 1.9 ¢/1,000 gal

CRT (10%, 15 years) = 0.1315

Total annual cost for pretreatment (from Eqs. 8.7, 8.8, and 8.9) = $128,000

Annual sewer service charge to the company (from Eq. 8.5) = $1,576,000

Annual ICR payment (from Eq. 8.4) = $172,000

The sum of annual pretreatment cost, annual sewer service charge, and annual ICR payment (From Eqs. 8.6 and 8.11) = $1,876,000

Thus, total annual cost of alternative A (on-site treatment) is $1,032,000, and total annual cost of alternative B (joining municipal wastewater system) is $1,876,000. It is evident that for the pulp and paper company, to build its own treatment plant will be more economical.

Based on the above analysis, with PL 92-500 in full effect, it could be more economic for the manufacturing plant to construct and operate its own wastewater system.

The other notable advantage to a on-site treatment is that industries might benefit from the time saving in constructing their own wastewater treatment facilities. The lack of adequate wastewater facilities will control new manufacturing plant start-ups and plant expansions. Delay may be encountered in manufacturing production because of the four to eight years it now takes to construct a municipal wastewater facility. Initially it was thought that a city's wastewater system could be constructed or improved in three to four years. This estimate has increased to eight years for cities applying for funds under PL 92-500.

Economic Analysis of Group Industrial Wastewater Treatment

A group treatment of industrial wastewaters from several sites offers economics of construction scale and consolidation of operating requirements. It is well known that "economy of scale" — the cost per unit of capacity decreases as the capacity increases.

Cost models developed in the previous chapter has shown that most industrial waste treatment costs can be conveniently expressed as:

Capital cost (C_c):

$$C_c = a_o + a_1 \ln X_1 + a_2 \ln X_2 + \ldots + a_m \ln X_m \quad (8.12)$$

O&M cost (C_o):

$$C_o = b_o + b_1 \ln X_1 + a_2 \ln X_2 + \ldots + a_n \ln X_n \quad (8.13)$$

These may also be written as:

$$C_c = a_o' X_1^{a_1} X_2^{a_2} \ldots X_m^{a_m} \quad (8.14)$$

$$C_o = b_o' X_1^{b_1} X_2^{b_2} \ldots X_n^{b_n} \quad (8.15)$$

where

C_o = capital cost of industrial waste treatment plant

C_o = annual O&M cost of individual waste treatment plant

$X_1, X_2, \ldots, X_m, X_1, X_2, \ldots X_n$ = waste variables (as flow rate, BOD, etc)

$a_1, a_2, \ldots, a_m, b_1, b_2, \ldots, b_n$ = scale factor (measure of the economy of scale corresponding to each of waste variables).

a_o, b_o = constants

a_o', b_o' = antilogarithm of a_o and b_o, respectively.

Values of the constants (a_o, b_o, a_1, a_2,..., a_k, b_1, b_2,..., b_k) for both capital and O&M cost models had been presented in the previous chapter.

The savings in total annual cost to be expected by the individual industry from joining a group treatment system can be approximated by manipulation of the cost models presented in the previous chapter, and equations 8.14 and 8.15 presented above. This manipulation is affected as described below:

1. The following subscripts are employed to designate source of flow:
   i = individual industrial wastewater
   j = total joint industrial wastewater

2. Individual industrial wastewater flows are expressed as fractions of total flow using the following nomenclature:

   f_i = fraction of total joint industrial wastewater flow represented by a single industry.

$$f_i = \frac{Q_i}{\Sigma Q_i} = \frac{Q_i}{Q_j} \qquad (8.16)$$

3. Total annual cost of a treatment plant expressed as follows:

$$(TAC) = (C_c)(CRF) + C_o \qquad (8.17)$$

$$(TAC) = (a_o')(CRF)\ X_1^{a_1} X_2^{a_2} \ldots X_m^{a_m} + (b_o')\ X_1^{b_1} X_2^{b_2} \ldots X_n^{a_n} \qquad (8.18)$$

where TAC is total annual cost, CRF is capital recovery factor, and other symbols are as previously defined.

4. Assuming that individual industries share the capital cost of group treatment plant on the basis of individual waste flow rate. The individual industries are also charged by waste flow rate for O&M cost of group treatment plant.

5. The expression of TAC (total annual cost) savings for individual plant from joining group treatment is stated in terms of a percentage of TAC for independent solution as follows:

% savings for individual plant in TAC

$$= 1 - \frac{f_i [a_o'(CRF) X_1^{a_1} X_2^{a_2} \ldots X_m^{a_m} + b_o' X_1^{b_1} X_2^{b_2} \ldots X_n^{b_n}]}{[a_o'(CRF) X_1^{a_1} X_2^{a_2} \ldots X_m^{a_m} + b_o' X_1^{b_1} X_2^{b_2} \ldots X_n^{b_n}]_i} \qquad (8.19)$$

6. Using this expression and a range of values for f_i, the savings in total annual cost for individual industry from joining a group treatment can be approximated.

For the purpose of illustration, an economic analysis of a group treatment for several organic chemical industrial wastes is included below.

As described in the previous chapter, the capital and O&M cost of organic chemical industrial wastes can be expressed as the following models (i.e., Eqs. 7.25 and 7.26):

BPT capital cost model —

$$C_C = 71{,}165\ Q^{0.765}\ I^{0.132}\ K^{-0.022}\ E^{-0.025}\ A^{0.414} \qquad (8.20)$$

BPT O&M cost model —

$$C_O = 5{,}215\ Q^{0.894}\ I^{0.163}\ K^{-0.026}\ E^{-0.030}\ A^{0.411} \qquad (8.21)$$

where

C_C = capital cost of BPT for organic chemical industry ($)

C_O = O&M cost of BPT for organic chemical industry ($/yr)

Q = waste flow rate (MGD)

I = influent BOD (mg/ℓ)

K = BOD removal rate coefficient (ℓ/mg-hr)

E = effluent BOD (mg/ℓ)

A = acidity to be neutralized (mg/ℓ as $CaCO_3$)

By substitution of the scale factors and constants of equations 8.20 and 8.21 in the equation 8.19, equation 8.19 is further simplified by using the same waste characteristics for both individual and joint industrial plants, i.e.

$$I_i = I_j$$

$$E_i = E_j$$

$$K_i = K_j$$

$$A_i = A_j$$

Using these expressions together with the capital cost amortized at an interest rate of 10 percent for 15 years (CRF = 0.1315), the savings in total annual cost for individual industry from joining a group treatment can be approximated by equation 8.19. Results of this numerical analysis are shown as Curve A in Figure 9.

As shown in Curve A , the percentage of savings for individual industry from joining a group treatment depends on the ratio of the individual waste flow to the total joint flow (f_i). The lower the ratio is, the higher the savings will be. Referring to Curve A, an average savings of 20 percent can be assumed for organic chemical industry.

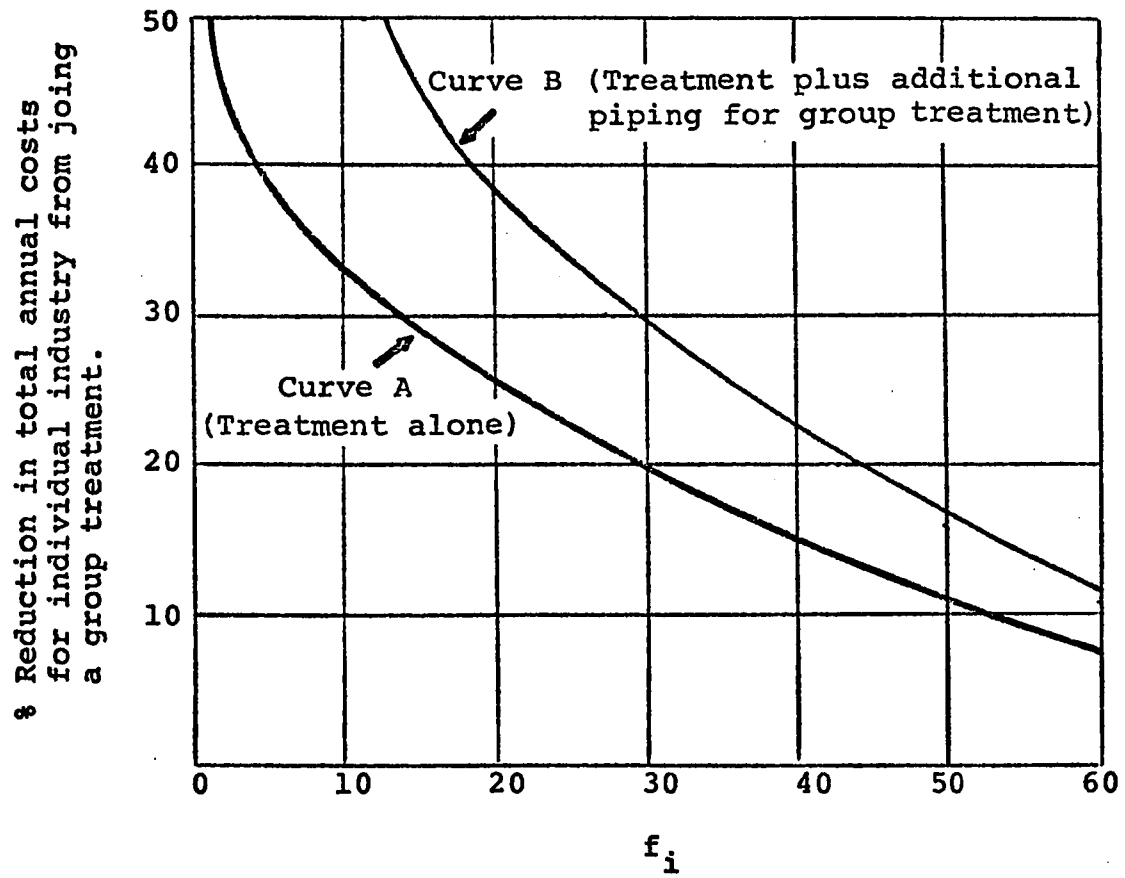


FIGURE 9. Economic Comparisons of Group Treatment.

When additional piping cost for group treatment is considered, the savings will be increased (See Curve B in Figure 9).

The other notable advantage to group treatment is that only one discharge permit for several industries, thus aiding both users and regulatory agencies.

Cost Sensitivity Analysis

Sensitivity analysis is designed to analyze a treatment cost for its relative dependence on the input parameters. The most significant of these parameters is the treatment level selected — pretreatment, BPT or BAT. Whenever government legistration imposes different water quality requirements, the total treatment cost picture can change. The petroleum refining waste is selected to perform the cost sensitivity analysis for purpose of illustration.

The capital cost and annual O&M cost for petroleum refining wastes for each of pretreatment[1], BPT[2], and BAT[3] were calculated using cost models developed and presented

---

[1]Pretreatment process = oil separation + flotation,

[2]BPT process = oil separation + flotation + activated sludge process + mixed media filtration

[3]BAT process = oil separation + flotation + activated sludge process + mixed media filtration + carbon adsorption

in the previous chapter (Eqs. 7.1, 7.2, 7.3, 7.4, 7.5 and 7.6). These costs are shown in Figures 10 and 11. Using a CRF = 0.1315 (10%, 15 years), the total annual costs calculated are shown in Figure 12. All the costs shown in the above figures are expressed as capital, annual O&M, and total annual costs per mgd of wasteflow. The cost sensitivity analysis is shown in Table 6.

From Figures 10, 11 and 12, it can be derived that attaining BAT level will entail a huge jump in costs over that for BPT level. The increase in total annual costs due to the addition of the incremental BAT level (carbon adsorption system) is about 87 percent of the cost of the BPT level alone but is a far smaller percentage increase if the costs are considered on a unitized basis, as shown in Table 6. Annual cost per increased percent of BOD removal per MGD is $1,600 for BPT level, and $67,000 for BAT level. Annual cost per increased percent of COD removal per MGD is $1,800 for BPT level, and $21,000 for BAT level. In this context, certain questions must be analyzed:

1. From a national point of view, it is necessary to insure that the water pollution goals sought, are defensible in terms of their net benefits. A sensitivity analysis of costs to BPA and BAT levels of treatment (Table 6)

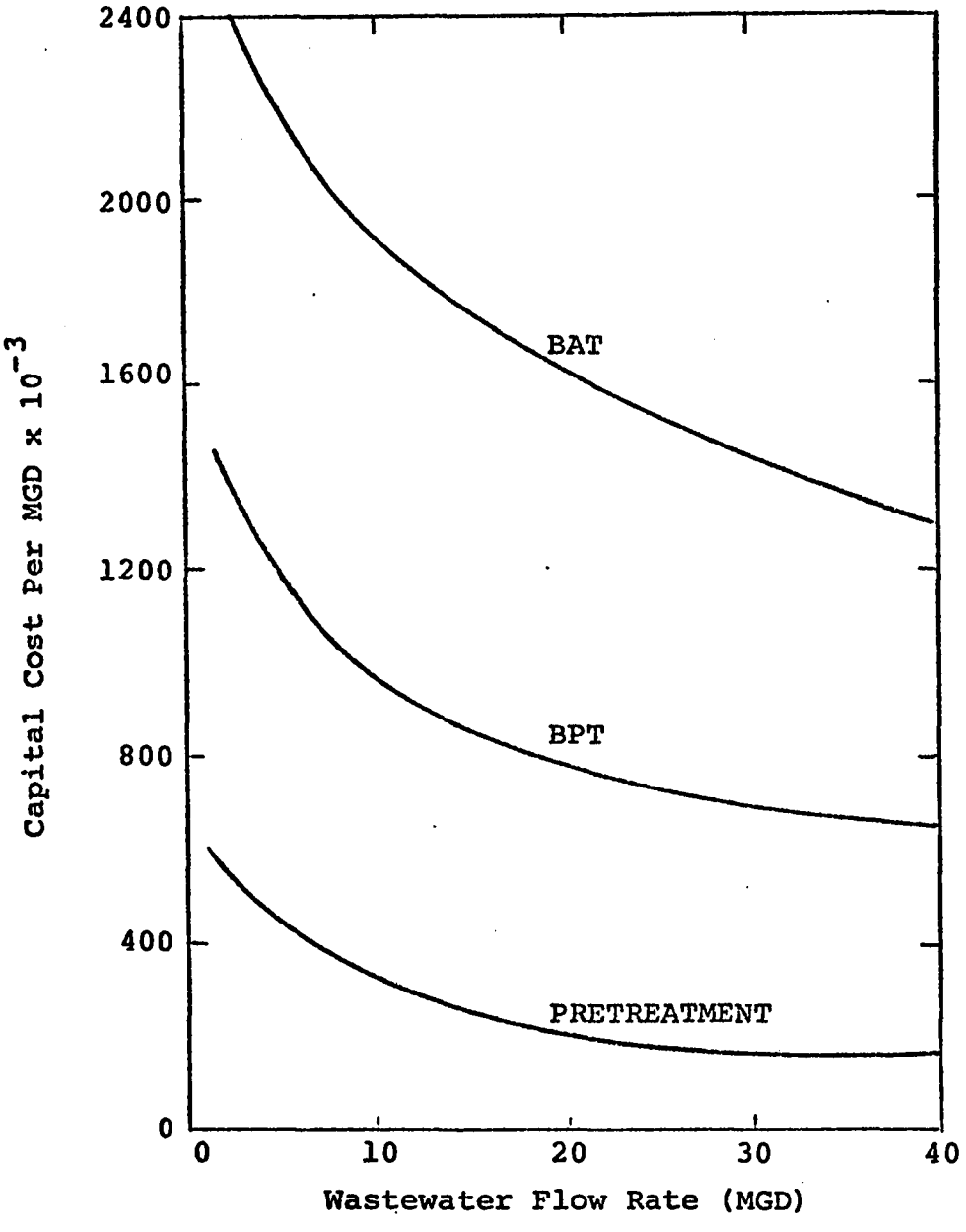


FIGURE 10. Capital Cost for Petroleum Refining Waste.

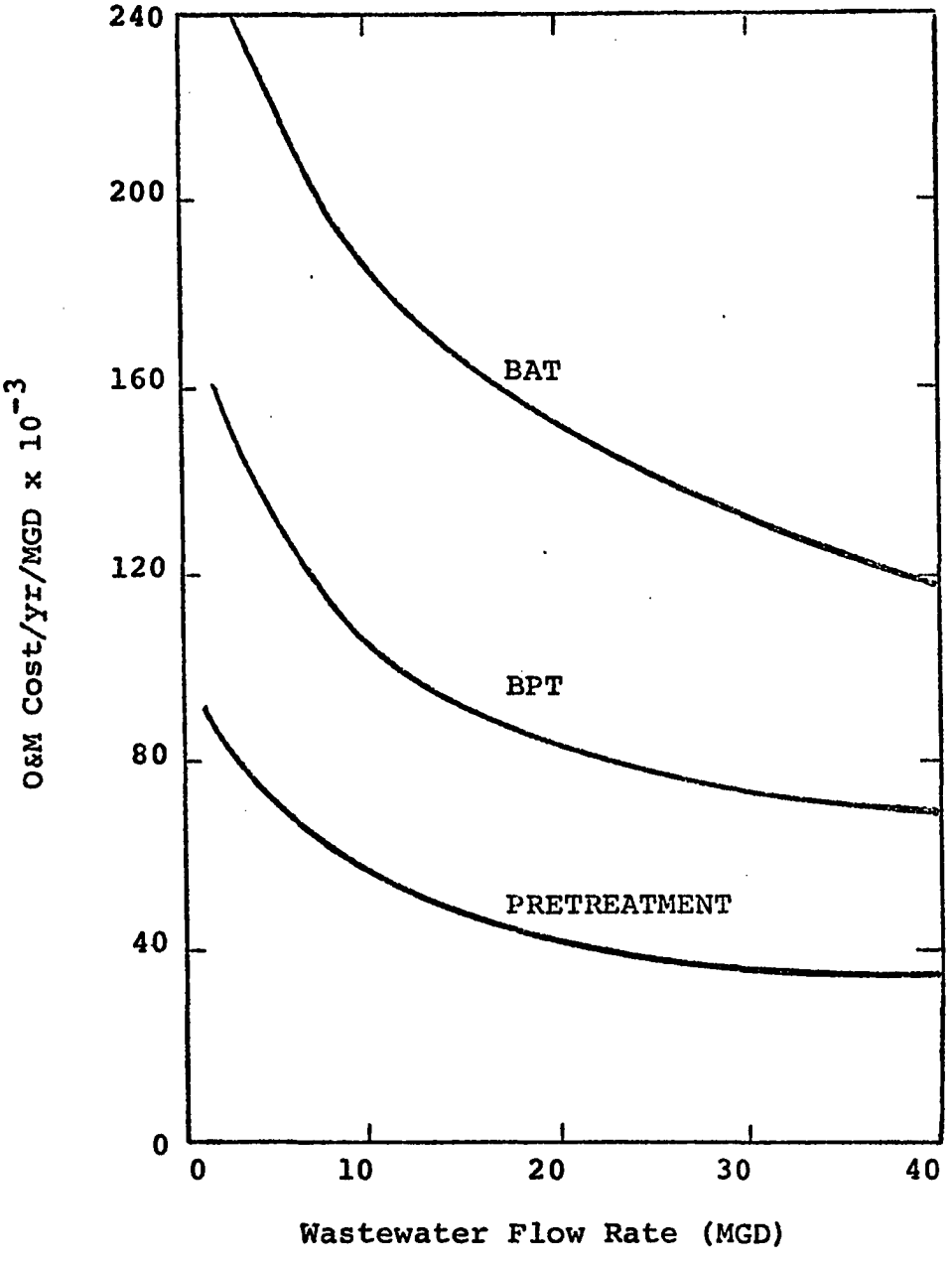


FIGURE 11. O&M Cost for Petroleum Refining Waste.

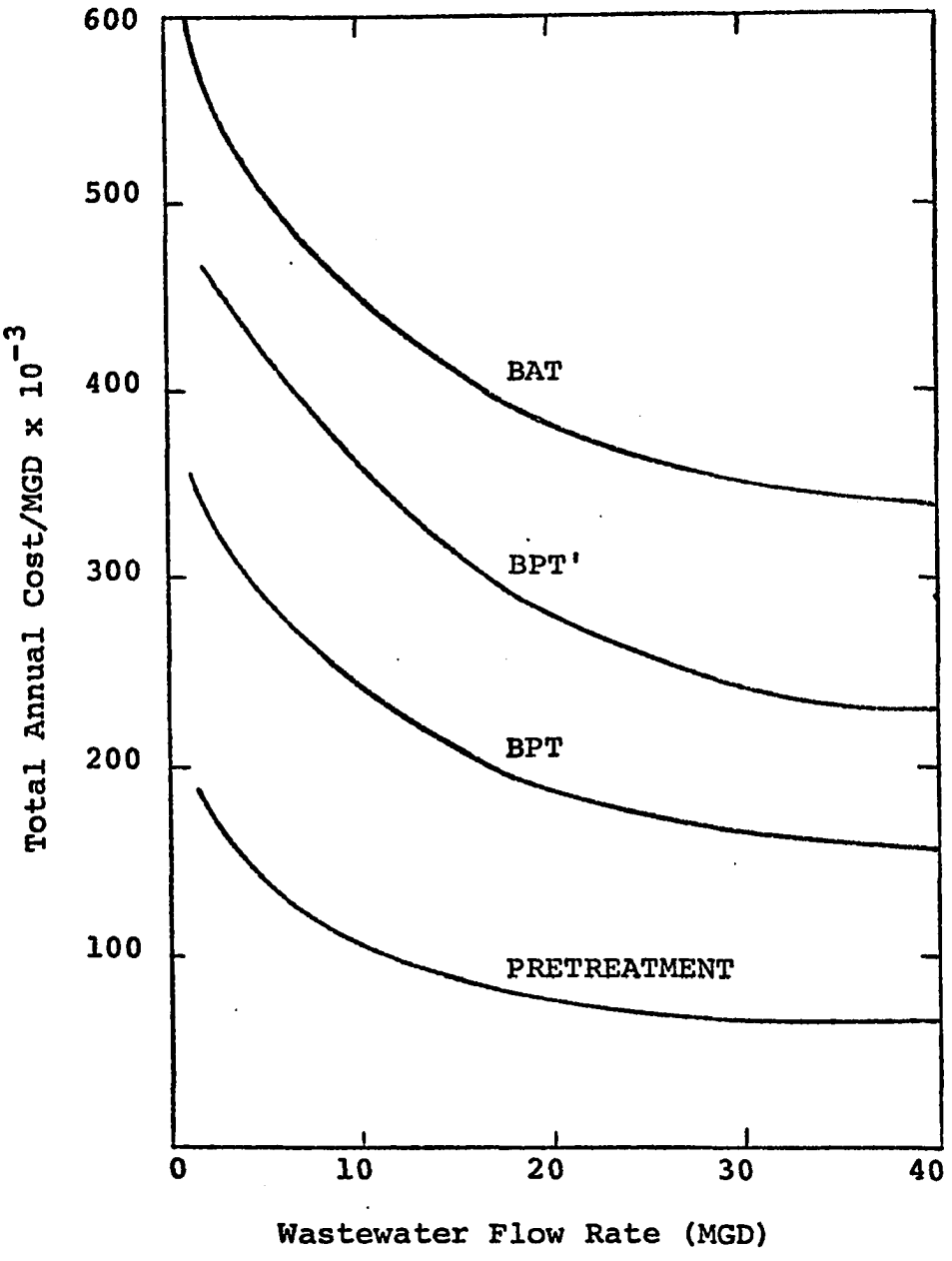


FIGURE 12. Total Annual Cost for Petroleum Refining Waste.

TABLE 6

COST SENSITIVITY ANALYSIS OF TREATMENT LEVELS

Treatment Level	Ave. Relative Total Annual Cost[1]	BOD[2]		COD[2]	
		% Removal	Cost Per Increased Percent of Removal Per MGD (Ave.)	% Removal	Cost Per Increased Percent of Removal Per MGD (Ave.)
BPT	100%	97.5	$1,600	91.0	$1,800
BAT	187%	99.5	$67,000	97.5	$21,000

Notes:

1. It stands for the relative percentage of BPT cost represented by BAT level.

2. Costs shown are total annual costs.

has shown that the costs accelerate rapidly as higher levels of treatment are sought. In general, the objectives in the BPT treatment level require an equivalent of secondary treatment. The gains from improvement in beneficial uses of waters from such BPT treatment levels are likely to exceed the costs. However, beyond this level the costs of pollution control may exceed the values of the beneficial uses. Because of the uncertainty of benefits at high levels of waste reduction, a cost/benefit assessment must be under taken to determine the national cost of higher level of pollution controls and necessity of these controls.

2. It is a uniform application of carbon adsorption technology to polishing secondary (biological) effluent. However, based on Table 6, it is evident that the cost of the activated carbon system (BAT level) per increased percent of pollutant removed is many times that of the biological treatment system (BPT level). This raises the next question:

whether or not the uniform application of carbon applications to polishing secondary (biological) effluent is a necessary and a cost-effective requirement for meeting the quality standard set for nation's waters.

3. Assuming that the treatment level for municipal waste system is BPT and city charges to industry for sewer fees, the equal ICR unit costs, and the ICR period are the same as that described on page 102. The sum of annual pretreatment cost, annual sewer service charge, and annual ICR payment for petroleum refining wastes was computed and plotted as Curve BPT' in Figure 12. As shown in Figure 12, it is evident to the industry that the annual cost for participating in municipal waste system (Curve BPT') is less than the annual cost for constructing independent treatment plant to provide BAT level (Curve BAT). Thus, The following question is raised: Could government require BAT level for industry and BPT level for the municipal system?

Optimum Combinations of Inplant Modification and End-of-Pipe Treatment Measures

The right approach for an industrial wastewater pollution abatement program is one which considers all opportunities for inplant modification to reduce pollutant discharges at their sources. This approach can often result in effluent discharge requirements being met at minimum cost by a combination of inplant modification and end-of-pipe treatment.

The preceding section illustrates how to find the optimum combination of internal and external measures by the application of the external treatment cost models developed and presented in previous chapters. The sulphate pulp mill is selected herein for illustrating total cost optimization technique.

For purpose of illustration, the inplant modifications considered in a sulphate pulp mill by this study include (27):

a. Closing Brown Stock Screening
b. Stripping of Condensates
c. Chemicals Spills Collection

The detailed description of these inplant modifications are discussed in EKONO report (27). Only the reduction of pollutant discharges due to these measures and costs of these measures reported by EKONO Consulting Engineers are presented as Tables 7 and 8, respectively.

TABLE 7

REDUCTION OF POLLUTANTS BY SULPHATE MILL

INPLANT MODIFICATION

Inplant Modification	Discharge Reduction	
	Wastewater (gal/ton)	BOD (lb/ton)
No inplant modification	26,400	80
a. Closing brown stock screening	6,000	12
b. Stripping of condensates	960	21
c. Chemical spills collections	960	6

TABLE 8

COST OF INPLANT MODIFICATION FOR POLLUTANT REDUCTION IN A SULPHATE MILL

Inplant Modification	Sulphate Pulp Production					
	350 tpd			800 tpd		
	Investment Cost ($1,000)	Operating Cost ($/Ton)	Total[1] Cost ($/Ton)	Investment Cost ($1,000)	Operating Cost ($/Ton)	Total[1] Cost ($/Ton)
a. Closing brown stock screening	170	-0.21	0	400	-0.21	0
b. Stripping of condensates	1,050	0.56	1.90	2,010	0.43	1.51
c. Chemical spills collections	730	--	0.94	1,220	--	0.65

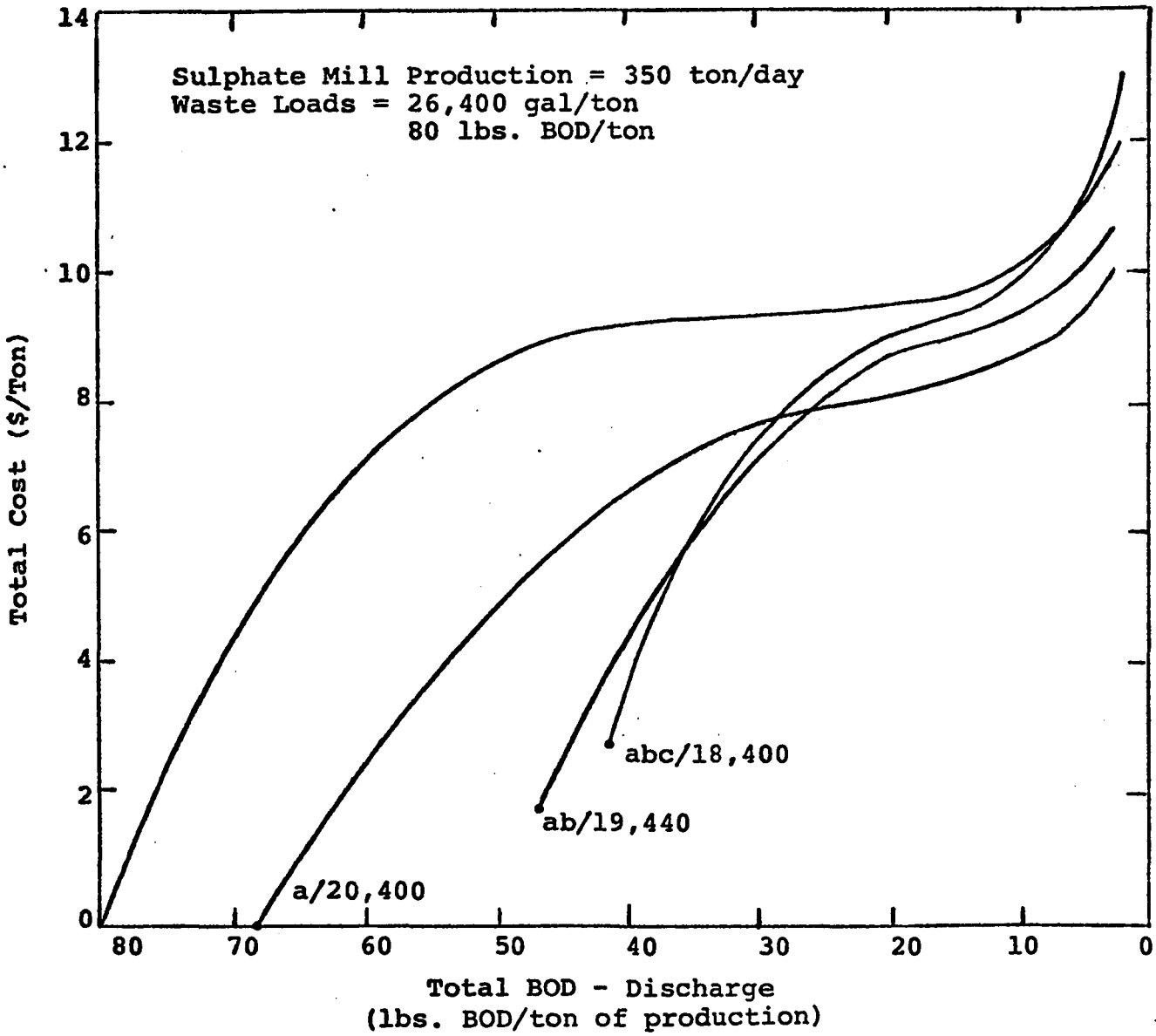
[1]Total cost = 15% capital cost + operating costs.

Assuming that the daily sulphate pulp production of a sulphate mill is 350 ton/day. The raw waste loads are 26,400 gal/ton of production and 80 lbs. BOD/ton of production. The above inplant modifications are adopted in the order of a, ab, and abc, respectively. Using these assumptions and a range of effluent BOD limitation in lbs. BOD per ton of production, the overall total treatment cost considering inplant modification cost (Tables 7 and 8) and corresponding cost for required end-of-pipe treatment (Eqs. 7.9 and 7.10) can be computed. Results of this numerical analysis are shown on Figure 13.

Figure 13 shows that the further decrease in overall treatment cost is resulted from a combination of internal and external measures.

Assuming that the BPT effluent limitation for the sulphate mill is 10.0 lbs. BOD/ton of production. From Figure 13, this limitation could best be met with internal modification "a" only followed by external treatment to the specific effluent limit of 10.0 lbs BOD/ton of production. As shown in Figure 13, an average savings of 17 percent in total treatment cost can be expected by applying an inplant modification of closing brown stock screening when compared to the external treatment without any internal measures.

Based on the above analysis, it is evident that a combination of internal and external measures can often result in effluent limitation requirements being met at minimum cost.



Legends: Internal measures a/20,400 Effluent (gal/ton)

a = Closing brown stock screening
b = Stripping of condensates
c = Chemical spills collections

FIGURE 13. Effects of Combination of Internal and External Measures on Treatment Cost.

CHAPTER IX

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to develop treatment cost models for pretreatment, BPT and BAT technology, and their relations to economic of industrial waste treatment.

An engineering cost estimate through the use of unit process cost models and process design models was selected as the method for determining cost. This was the most feasible and accurate approach to the problem since an attempt was made to correlate total costs of treatment in existing plants with waste variables which resulted in incomplete information not permitting accurate correlations. All of the unit process cost models and process design models were compiled on the programmable calculator. Based on the cost data generated from the cost estimating programs for a number of input combinations and for various process combinations, the predictive cost models were developed using stepwise regression technique for the following selected industries:

Petroleum refining

Pulp and paper

Electroplating

Organic chemical manufacturing

Inorganic chemical manufacturing

Through an evaluation of these cost models developed, the major findings of this study are as follows:

1. Considering the effects of the new acts (P.L. 92-500 and 95-217) on industry, two separate situations have been considered in this study. The first and more complex situation is where industry discharges waste to a public owned treatment system after any pretreatment and paying ICR and service charge to the municipal system. The other situation involves industry providing treatment of its own effluents (on-site treatment). A decision-making procedure which was accompanied with a series of mathematical equations together with cost models has been developed to guide the industries when confronted with municipal versus on-site treatment problems. It was found that, with new act in full effect, it could be

more economic for the manufacturing plant to construct and operate its own wastewater system. The other notable advantage to an on-site treatment is that industries might benefit from the time saving in constructing their own wastewater facilities. The lack of adequate wastewater facilities will control new manufacturing plant start-ups and plant expansions. Delay may be encountered in manufacturing production because of the four to eight years it now takes to construct a municipal wastewater facility. Initially it was thought that a city's wastewater system could be constructed or improved in three to four years. This estimate has increased to eight years for cities applying for funds under PL 92-500.

2. A group treatment of industrial wastewaters from several sites offers economic of construction scale and consolidation of operating requirement. It was found that an average savings of 20 percent in total annual treatment cost can be expected for an individual organic chemical industry from joining a group industrial waste treatment system. When additional piping cost

for group treatment is considered, the savings will be increased. The other notable advantage to a group treatment is only one discharge permit for entire group treatment plant, thus aiding both users and regulatory agencies.

3. From a cost sensitivity analysis on factors affecting the treatment cost, it was found that treatment costs are directly related to effluent limitations and regulatory enforcement. Whenever government legistration imposes different effluent standards, the total cost picture can change. From a national point of view, it is necessary to insure that the water pollution goals sought, are defensible in terms of their net benefits. A sensitivity analysis of costs to BPA and BAT level of treatment has shown that costs increase rapidly as higher levels of treatment are sought. In general, the objectives in the BPT treatment level require an equivalent of secondary treatment. The gains from improvement in beneficial uses of waters from such BPT treatment levels are likely to exceed the costs. However, beyond this level, the costs of

pollution control may exceed the values of the beneficial uses. Because of the uncertainty of benefits at high levels of waste reduction, a cost/benefit assessment must be under taken to determine the national cost of high level of pollution controls and the necessity of these controls. Furthermore, it is evident to the industry that the annual cost for participating in a BPT municipal waste system is less than that for constructing an independent treatment plant to provide a BAT level. Thus, the following question is also raised: Could the government require BAT for the industry and BPT for the municipal system?

4. The application of carbon adsorption technology to polishing secondary (biological) effluent is becoming more popular. However, based on this study, it is found that cost of the activated carbon system (BAT level) per increased percent of pollutant removed is many times that of the biological treatment system (BPT level). For example, in petroleum refining industry, annual cost per increased percent of BOD removal per MGD is $1,600

for BPT level, and $67,000 for BAT level. Annual cost per increased percent of COD removal per MGD is $1,800 for BPT level, and $21,000 for BAT level. Then raises this question: whether or not the uniform application of carbon application to polishing secondary (biological) effluent is a necessity and a cost-effective requirement for meeting the quality standard set for nation's waters.

5. The right approach for an industrial wastewater pollution abatement program is one which considers all opportunities for inplant modification to reduce pollutant discharges at their sources. This approach can often result in effluent discharge requirements being met at minimum cost by a combination of inplant modification and end-of-pipe treatment. A methodology to find the solution for a combination of internal and external measures has been developed and described in Chapter VIII. For purpose of illustration, the inplant modification for a sulphate pulp mill was analyzed by this study. It was found

that an average savings of 17 percent in total treatment cost can be expected by applying the inplant measures of closing brown stock screening when compared to the external treatment without any internal measures.

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APPENDIX A

CAPITAL COST ESTIMATING PROGRAM FOR INDUSTRIAL WASTEWATER TREATMENT

Magnetic Card Title: TI-59 Program for estimating the capital cost of industrial wastewater treatment.

Memory Partition: 719:29

Press

3 2nd OP 17

Input Data:

Enter —— (Wastewater flow rate in MGD)

Press STO 01

Enter —— (Retention time of equalization in days)

Press STO 02

Enter —— (Acidity to be neutralized in mg/ℓ as $CaCO_3$)

Press STO 03

Enter —— (Surface loading of primary clarifier in gpd/sq.ft.)

Press STO 04

Enter —— (Influent BOD in mg/ℓ)

Press STO 05

Enter —— (Effluent BOD in mg/ℓ)

Press STO 06

Enter —— (MLVSS in mg/ℓ)

Press STO 07

Enter —— (BOD removal rate coeffieint in ℓ/mg-hr)

Press STO 08

Enter —— (Oxygen utilization coefficient for cell synthesis)

Press STO 09

Enter —— (Oxygen utilization rate for endogenous respiration in day^{-1})

Press STO 10

Enter —— (Aerator transfer capacity in pounds of oxygen per Hp-hr)

Press STO 11

Enter —— (Surface loading of secondary clarifier in gpd/sq.ft.)

Press STO 12

Enter —— (Influent S.S. in mg/ℓ)

Press STO 13

Enter —— (Sludge yield coefficient)

Press STO 14

Enter —— (Sludge auto-oxidation rate coefficient in day^{-1})

Press STO 15

Enter —— (Mass loading of gravity thickener in lbs of solids/sq.ft./day)

Press STO 16

Enter —— (Filter loading of vacuum filtration in lbs of solids/sq.ft./hr)

Press STO 17

Enter —— (Ratio of lime recovered through recalcination in tons of lime/day/MGD of waste flow rate)

Press STO 18

Enter —— (Filtration rate of mixed media filter in gpm/sq.ft.)

Press STO 19

Enter —— (COD to carbon adsorption units in mg/ℓ)

Press STO 20

Enter —— (Dosage of ferric chloride in mg/ℓ)

Press STO 21

Enter —— (Dosage of alum in mg/ℓ)

Press STO 22

Enter —— (Dosage of lime in mg/ℓ)

Press STO 23

Run Program:

Press RST

Press R/S

Press —— (1 if oil separation is used, or 0 if not)

Press R/S

Press —— (1 if equalization is used, or 0 if not)

Press R/S

Press —— (1 if neutralization is used, or 0 if not)

Press R/S

Press —— (1 if primary clarifier is used, or 0 if not)

Press R/S

Press —— (1 if activated sludge process is used, or 0 if not)

Press R/S

Press —— (1 if chemical coagulation is used, or 0 if not)

Press R/S

Press —— (1 if flotation is used, or 0 if not)

Press R/S

Press —— (1 if ferric chloride is used, or 0 if not)

Press R/S

Press —— (1 if alum is used, or 0 if not)

Press R/S

Press —— (1 if lime is used, or 0 if not)

Press R/S

Press —— (1 if recalcination is used, or 0 if not)

Press R/S

Press —— (1 if mixed media filtration is used, or 0 if not)

Press R/S

Press —— (1 if carbon adsorption is used, or 0 is not)

Press R/S

Press —— (1 if reverse osmosis is used, or 0 if not)

Press R/S

Press —— (1 if gravity thickener is used, or 0 if not)

Press R/S

Press —— (1 if vacuum filtration is used, or 0 if not)

Press R/S

Press ——— (1 if chlorination is used, or 0 if not)

Press R/S

Press R/S (Display: Capital cost in $1,000)

```
000  25 CLR
001  42 STO
002  00  00
003  91 R/S
004  61 GTO
005  95  =
006  76 LBL
007  11  A
008  01  1
009  07  7
010  08  8
011  93  .
012  02  2
013  65  ×
014  43 RCL
015  01  01
016  45 Y^x
017  93  .
018  08  8
019  04  4
020  95  =
021  92 RTN
022  76 LBL
023  94 +/-
024  44 SUM
025  00  00
026  92 RTN
027  76 LBL
028  12  B
029  02  2
030  05  5
031  02  2
032  93  .
033  05  5
034  65  ×
035  53  (
036  43 RCL
037  01  01
038  65  ×
039  43 RCL
040  02  02
041  54  )
042  45 Y^x
043  93  .
044  06  6
045  04  4
046  95  =
047  92 RTN
048  76 LBL
049  13  C
050  43 RCL
051  01  01
052  65  ×
053  43 RCL
054  03  03
055  65  ×
056  01  1
057  04  4
058  95  =
059  42 STO
060  26  26
061  05  5
062  93  .
063  07  7
064  02  2
065  65  ×
066  43 RCL
067  01  01
068  45 Y^x
069  93  .
070  08  8
071  03  3
072  65  ×
073  43 RCL
074  03  03
075  45 Y^x
076  93  .
077  07  7
078  09  9
079  95  =
080  92 RTN
081  76 LBL
082  14  D
083  43 RCL
084  13  13
085  65  ×
086  43 RCL
087  01  01
088  65  ×
089  05  5
090  93  .
091  04  4
092  95  =
093  42 STO
094  24  24
095  02  2
096  93  .
097  01  1
098  07  7
099  65  ×
100  53  (
```

```
101  43 RCL
102  01  01
103  65  ×
104  01  1
105  00  0
106  00  0
107  00  0
108  00  0
109  00  0
110  00  0
111  55  ÷
112  43 RCL
113  04  04
114  54  )
115  45 Y×
116  93  .
117  05  5
118  06  6
119  95  =
120  92 RTN
121  76 LBL
122  15  E
123  43 RCL
124  01  01
125  65  ×
126  53  (
127  43 RCL
128  05  05
129  75  -
130  43 RCL
131  06  06
132  54  )
133  55  ÷
134  43 RCL
135  07  07
136  55  ÷
137  43 RCL
138  08  08
139  55  ÷
140  43 RCL
141  06  06
142  55  ÷
143  02  2
144  04  4
145  95  =
146  42 STO
147  27  27
148  01  1
149  00  0
150  65  ×
```

```
151  43 RCL
152  14  14
153  65  ×
154  43 RCL
155  01  01
156  65  ×
157  53  (
158  43 RCL
159  05  05
160  75  -
161  43 RCL
162  06  06
163  54  )
164  75  -
165  01  1
166  00  0
167  65  ×
168  43 RCL
169  15  15
170  65  ×
171  43 RCL
172  07  07
173  65  ×
174  43 RCL
175  27  27
176  85  +
177  02  2
178  93  .
179  02  2
180  65  ×
181  43 RCL
182  13  13
183  65  ×
184  43 RCL
185  01  01
186  95  =
187  42 STO
188  25  25
189  05  5
190  05  5
191  03  3
192  93  .
193  05  5
194  65  ×
195  43 RCL
196  27  27
197  45 Y×
198  93  .
199  07  7
200  01  1
```

```
201  85  +
202  03  3
203  93  .
204  03  3
205  08  8
206  09  9
207  65  ×
208  53  (
209  53  (
210  43 RCL
211  09  09
212  65  ×
213  08  8
214  93  .
215  03  3
216  04  4
217  65  ×
218  43 RCL
219  01  01
220  65  ×
221  53  (
222  43 RCL
223  05  05
224  75  -
225  43 RCL
226  06  06
227  54  )
228  85  +
229  43 RCL
230  10  10
231  65  ×
232  08  8
233  93  .
234  03  3
235  04  4
236  65  ×
237  43 RCL
238  07  07
239  65  ×
240  43 RCL
241  27  27
242  54  )
243  55  ÷
244  02  2
245  04  4
246  55  ÷
247  43 RCL
248  11  11
249  65  ×
250  93  .
```

```
251  07  7
252  04  4
253  05  5
254  07  7
255  54  )
256  45 Y×
257  93  .
258  08  8
259  01  1
260  85  +
261  01  1
262  03  3
263  93  .
264  01  1
265  02  2
266  02  2
267  85  +
268  04  4
269  93  .
270  00  0
271  06  6
272  04  4
273  65  ×
274  43 RCL
275  01  01
276  85  +
277  01  1
278  09  9
279  00  0
280  93  .
281  06  6
282  65  ×
283  53  (
284  43 RCL
285  01  01
286  65  ×
287  01  1
288  00  0
289  00  0
290  00  0
291  55  ÷
292  43 RCL
293  12  12
294  54  )
295  45 Y×
296  93  .
297  06  6
298  01  1
299  95  =
300  92 RTN
```

```
301  76 LBL
302  19 D'
303  02  2
304  93  .
305  05  5
306  01  1
307  65  ×
308  53  (
309  43 RCL
310  29  29
311  55  ÷
312  43 RCL
313  16  16
314  54  )
315  45 Y^x
316  93  .
317  04  4
318  08  8
319  95  =
320  92 RTN
321  76 LBL
322  10 E'
323  02  2
324  03  3
325  93  .
326  06  6
327  09  9
328  65  ×
329  53  (
330  43 RCL
331  29  29
332  55  ÷
333  16 A'
334  55  ÷
335  43 RCL
336  17  17
337  54  )
338  45 Y^x
339  93  .
340  04  4
341  05  5
342  95  =
343  92 RTN
344  76 LBL
345  20 CLR
346  04  4
347  07  7
348  01  1
349  65  ×
350  43 RCL
351  01  01
352  45 Y^x
353  93  .
354  07  7
355  04  4
356  95  =
357  92 RTN
358  76 LBL
359  27 INV
360  05  5
361  09  9
362  00  0
363  65  ×
364  53  (
365  43 RCL
366  18  18
367  65  ×
368  43 RCL
369  01  01
370  54  )
371  45 Y^x
372  93  .
373  05  5
374  95  =
375  92 RTN
376  76 LBL
377  28 LOG
378  01  1
379  00  0
380  93  .
381  07  7
382  07  7
383  65  ×
384  53  (
385  43 RCL
386  01  01
387  65  ×
388  06  6
389  09  9
390  04  4
391  93  .
392  04  4
393  55  ÷
394  43 RCL
395  19  19
396  54  )
397  45 Y^x
398  93  .
399  06  6
400  01  1
```

```
401  95  =
402  92 RTN
403  76 LBL
404  29 CP
405  08  8
406  03  3
407  03  3
408  65  ×
409  43 RCL
410  01  01
411  45 Y^x
412  93  .
413  06  6
414  65  ×
415  43 RCL
416  20  20
417  45 Y^x
418  93  .
419  02  2
420  08  8
421  95  =
422  92 RTN
423  76 LBL
424  30 TAN
425  02  2
426  08  8
427  01  1
428  65  ×
429  43 RCL
430  01  01
431  45 Y^x
432  93  .
433  07  7
434  04  4
435  95  =
436  92 RTN
437  76 LBL
438  36 PGM
439  01  1
440  06  6
441  04  4
442  08  8
443  65  ×
444  43 RCL
445  01  01
446  45 Y^x
447  93  .
448  07  7
449  05  5
450  95  =
451  92 RTN
452  76 LBL
453  37 P/R
454  02  2
455  02  2
456  93  .
457  02  2
458  65  ×
459  43 RCL
460  01  01
461  45 Y^x
462  93  .
463  06  6
464  85  +
465  03  3
466  04  4
467  93  .
468  07  7
469  65  ×
470  43 RCL
471  01  01
472  45 Y^x
473  93  .
474  03  3
475  07  7
476  95  =
477  92 RTN
478  76 LBL
479  16 A'
480  05  5
481  93  .
482  01  1
483  65  ×
484  43 RCL
485  01  01
486  65  ×
487  43 RCL
488  21  21
489  95  =
490  42 STO
491  27  27
492  92 RTN
493  76 LBL
494  17 B'
495  02  2
496  93  .
497  09  9
498  65  ×
499  43 RCL
500  01  01
```

```
501  65  ×
502  43 RCL
503  22  32
504  95  =
505  42 STO
506  28  28
507  92 RTN
508  76 LBL
509  18 C'
510  01  1
511  02  2
512  93  .
513  07  7
514  65  ×
515  43 RCL
516  01  01
517  65  ×
518  43 RCL
519  23  23
520  95  =
521  42 STO
522  29  29
523  43 RCL
524  24  24
525  85  +
526  43 RCL
527  25  25
528  85  +
529  43 RCL
530  26  26
531  85  +
532  43 RCL
533  27  27
534  85  +
535  43 RCL
536  28  28
537  85  +
538  43 RCL
539  29  29
540  95  =
541  42 STO
542  29  29
543  92 RTN
544  76 LBL
545  95  =
546  32 X↕T
547  25 CLR
548  67  EQ
549  22 INV
550  11  A
551  71 SBR
552  94 +/-
553  76 LBL
554  22 INV
555  91 R/S
556  32 X↕T
557  25 CLR
558  67  EQ
559  23 LNX
560  12  B
561  71 SBR
562  94 +/-
563  76 LBL
564  23 LNX
565  91 R/S
566  32 X↕T
567  25 CLR
568  67  EQ
569  24 CE
570  13  C
571  71 SBR
572  94 +/-
573  76 LBL
574  24 CE
575  91 R/S
576  32 X↕T
577  25 CLR
578  67  EQ
579  25 CLR
580  14  D
581  71 SBR
582  94 +/-
583  76 LBL
584  25 CLR
585  91 R/S
586  32 X↕T
587  25 CLR
588  67  EQ
589  32 X↕T
590  15  E
591  71 SBR
592  94 +/-
593  76 LBL
594  32 X↕T
595  91 R/S
596  32 X↕T
597  25 CLR
598  67  EQ
599  44 SUM
600  71 SBR
```

```
601  20 CLR
602  71 SBR
603  94 +/-
604  76 LBL
605  44 SUM
606  91 R/S
607  32 X:T
608  25 CLR
609  67  EQ
610  54  )
611  71 SBR
612  30 TAN
613  71 SBR
614  94 +/-
615  76 LBL
616  54  )
617  91 R/S
618  32 X:T
619  25 CLR
620  67  EQ
621  33 X²
622  16 A'
623  76 LBL
624  33 X²
625  91 R/S
626  32 X:T
627  25 CLR
628  67  EQ
629  34 ΓX
630  17 B'
631  76 LBL
632  34 ΓX
633  91 R/S
634  32 X:T
635  25 CLR
636  67  EQ
637  35 1/X
638  18 C'
639  76 LBL
640  35 1/X
641  91 R/S
642  32 X:T
643  25 CLR
644  67  EQ
645  45 Y^X
646  71 SBR
647  27 INV
648  71 SBR
649  94 +/-
650  76 LBL
651  45 Y^X
652  91 R/S
653  32 X:T
654  25 CLR
655  67  EQ
656  52 EE
657  71 SBR
658  28 LOG
659  71 SBR
660  94 +/-
661  76 LBL
662  52 EE
663  91 R/S
664  32 X:T
665  25 CLR
666  67  EQ
667  53  (
668  71 SBR
669  29 CP
670  71 SBR
671  94 +/-
672  76 LBL
673  53  (
674  91 R/S
675  32 X:T
676  25 CLR
677  67  EQ
678  55  ÷
679  71 SBR
680  36 PGM
681  71 SBR
682  94 +/-
683  76 LBL
684  55  ÷
685  91 R/S
686  32 X:T
687  25 CLR
688  67  EQ
689  42 STO
690  19 D'
691  71 SBR
692  94 +/-
693  76 LBL
694  42 STO
695  91 R/S
696  32 X:T
697  25 CLR
698  67  EQ
699  43 RCL
700  10 E'
```

```
701   71 SBR
702   94 +/-
703   76 LBL
704   43 RCL
705   91 R/S
706   32 X:T
707   25 CLR
708   67  EQ
709   61 GTO
710   71 SBR
711   37 P/R
712   71 SBR
713   94 +/-
714   76 LBL
715   61 GTO
716   91 R/S
717   43 RCL
718   00  00
719   91 R/S
```

APPENDIX B

OPERATION AND MAINTENANCE COSTS ESTIMATING PROGRAM FOR INDUSTRIAL WASTEWATER TREATMENT

Magnetic Card Title: Ti-59 Program for estimating the operation and maintenance costs of industrial wastewater treatment.

Memory Partition: 719:29

Press

3 2nd OP 17

Input Data:

Enter —— (Wastewater flow rate in MGD)

Press STO 01

Enter —— (Retention time of equalization in days)

Press STO 02

Enter —— (Acidity to be neutralized in mg/ℓ as $CaCO_3$)

Press STO 03

Enter —— (Surface loading of primary clarifier in gpd/sq.ft.)

Press STO 04

Enter —— (Influent BOD in mg/ℓ)

Press STO 05

Enter —— (Effluent BOD in mg/ℓ)

Press STO 06

Enter —— (MLVSS in mg/ℓ)

Press STO 07

Enter —— (BOD removal rate coefficient in ℓ/mg-hr)

Press STO 08

Enter —— (Oxygen utilization coefficient for cell synthesis)

Press STO 09

Enter —— (Oxygen utilization rate for endogenous respiration in day^{-1})

Press STO 10

Enter —— (Aerator transfer capacity in pounds of oxygen per HP-hr)

Press STO 11

Enter —— (Influent S.S. in mg/ℓ)

Press STO 12

Enter —— (Sludge yield coefficient)

Press STO 13

Enter —— (Sludge auto-oxidation rate coefficient in day^{-1})

Press STO 14

Enter —— (Mass loading of gravity thickener in lbs solids/sq.ft./day)

Press STO 15

Enter —— (Operating hours of vacuum filter per day)

Press STO 16

Enter —— (Filter loading of vacuum filtration in lbs solids/sq.ft./hr)

Press STO 17

Enter —— (Ratio of lime recovered through recalcination in tons of lime/day/MGD of waste flow rate)

Press STO 18

Enter —— (Sludge hauling and landfill cost in $/Ton)

Press STO 19

Enter —— (COD to carbon adsorption unit in mg/ℓ)

Press STO 20

Enter —— (Labor cost in $/hr)

Press STO 21

Enter —— (Power cost in $/Kwh)

Press STO 22

Enter —— (Nitrogen in wastewater in mg/ℓ)

Press STO 23

Enter —— (Phosphorus in wastewater in mg/ℓ)

Press STO 24

Enter —— (Dosage of ferric chloride in mg/ℓ)

Press STO 25

Enter —— (Dosage of alum in mg/ℓ)

Press STO 26

Enter —— (Dosage of lime in mg/ℓ)

Press STO 27

Enter —— (Sludge solids in lbs/day which is stored in STO 29 of Program A with the same input data)

Press STO 29

Run Program:

Press RST

Press R/S

Press —— (1 if oil separation is used, or 0 if not)

Press R/S

Press —— (1 if equalization is used, or 0 if not)

Press R/S

Press —— (1 if neutralization is used, or 0 if not)

Press R/S

Press —— (1 if primary clarifier is used, or 0 if not)

Press R/S

Press —— (1 if activated sludge process is used, or 0 if not)

Press R/S

Press —— (1 if chemical coagulation is used, or 0 if not)

Press R/S

Press —— (1 if flotation is used, or 0 if not)

Press R/S

Press —— (1 if ferric chloride is used, or 0 if not)

Press R/S

Press —— (1 if alum is used, or 0 if not)

Press R/S

Press —— (1 if lime is used, or 0 if not)

Press R/S

Press —— (1 if recalcination is used, or 0 if not)

Press R/S

Press —— (1 if mixed media filtration is used, or 0 if not)

Press R/S

Press —— (1 if carbon adsorption is used, or 0 if not)

Press R/S

Press —— (1 if reverse osmosis is used, or 0 if not)

Press R/S

Press —— (1 if gravity thickener is used, or
0 is not)

Press R/S

Press —— (1 if vacuum filtration is used, or
0 if not)

Press R/S

Press —— (1 if chlorination is used, or 0 if not)

Press R/S

Press —— (1 if sludge hauling and landfill is
used, or 0 if not)

Press R/S

Press R/S (Display: O&M costs in ¢/1,000 gal)

```
000  25 CLR
001  42 STO
002  00  00
003  91 R/S
004  61 GTO
005  95  =
006  76 LBL
007  11  A
008  05  5
009  93  .
010  09  9
011  01  1
012  65  ×
013  43 RCL
014  01  01
015  45 Y^x
016  93  .
017  05  5
018  06  6
019  94 +/-
020  95  =
021  92 RTN
022  76 LBL
023  94 +/-
024  44 SUM
025  00  00
026  92 RTN
027  76 LBL
028  12  B
029  53  (
030  04  4
031  02  2
032  02  2
033  65  ×
034  53  (
035  43 RCL
036  01  01
037  65  ×
038  43 RCL
039  02  02
040  65  ×
041  01  1
042  05  5
043  54  )
044  45 Y^x
045  93  .
046  03  3
047  08  8
048  65  ×
049  43 RCL
050  21  21
051  85  +
052  43 RCL
053  01  01
054  65  ×
055  43 RCL
056  02  02
057  65  ×
058  09  9
059  08  8
060  05  5
061  05  5
062  00  0
063  65  ×
064  43 RCL
065  22  22
066  54  )
067  55  ÷
068  03  3
069  06  6
070  05  5
071  00  0
072  55  ÷
073  43 RCL
074  01  01
075  95  =
076  92 RTN
077  76 LBL
078  13  C
079  93  .
080  05  5
081  02  2
082  65  ×
083  43 RCL
084  03  03
085  45 Y^x
086  93  .
087  06  6
088  05  5
089  65  ×
090  43 RCL
091  01  01
092  45 Y^x
093  93  .
094  00  0
095  08  8
096  02  2
097  94 +/-
098  95  =
099  92 RTN
100  76 LBL
```

```
101  14  D
102  02  2
103  03  3
104  93  .
105  03  3
106  05  5
107  55  ÷
108  43  RCL
109  01  01
110  45  Y^x
111  93  .
112  07  7
113  08  8
114  06  6
115  55  ÷
116  43  RCL
117  04  04
118  45  Y^x
119  93  .
120  02  2
121  01  1
122  04  4
123  95  =
124  92  RTN
125  76  LBL
126  15  E
127  43  RCL
128  01  01
129  65  ×
130  53  (
131  43  RCL
132  05  05
133  75  -
134  43  RCL
135  06  06
136  54  )
137  55  ÷
138  43  RCL
139  07  07
140  55  ÷
141  43  RCL
142  08  08
143  55  ÷
144  43  RCL
145  06  06
146  55  ÷
147  02  2
148  04  4
149  95  =
150  42  STO
151  12  12
152  43  RCL
153  12  12
154  55  ÷
155  43  RCL
156  01  01
157  65  ×
158  53  (
159  05  5
160  93  .
161  08  8
162  04  4
163  85  +
164  08  8
165  93  .
166  04  4
167  09  9
168  55  ÷
169  43  RCL
170  12  12
171  45  Y^x
172  93  .
173  05  5
174  54  )
175  85  +
176  43  RCL
177  22  22
178  65  ×
179  02  2
180  93  .
181  04  4
182  65  ×
183  53  (
184  53  (
185  43  RCL
186  09  09
187  65  ×
188  08  8
189  93  .
190  03  3
191  04  4
192  65  ×
193  43  RCL
194  01  01
195  65  ×
196  53  (
197  43  RCL
198  05  05
199  75  -
200  43  RCL
```

```
201  06  06
202  54  )
203  85  +
204  43 RCL
205  10  10
206  65  ×
207  08  8
208  93  .
209  03  3
210  04  4
211  65  ×
212  43 RCL
213  07  07
214  65  ×
215  43 RCL
216  12  12
217  54  )
218  55  ÷
219  02  2
220  04  4
221  55  ÷
222  43 RCL
223  11  11
224  65  ×
225  93  .
226  07  7
227  04  4
228  05  5
229  07  7
230  54  )
231  55  ÷
232  43 RCL
233  01  01
234  95  =
235  92 RTN
236  76 LBL
237  17 B'
238  43 RCL
239  13  13
240  65  ×
241  93  .
242  01  1
243  95  =
244  92 RTN
245  76 LBL
246  18 C'
247  43 RCL
248  14  14
249  65  ×
250  93  .
251  01  1
252  05  5
253  95  =
254  92 RTN
255  76 LBL
256  19 D'
257  01  1
258  06  6
259  93  .
260  09  9
261  02  2
262  65  ×
263  43 RCL
264  01  01
265  45 Y^x
266  93  .
267  04  4
268  07  7
269  94 +/-
270  95  =
271  92 RTN
272  76 LBL
273  10 E'
274  02  2
275  01  1
276  93  .
277  05  5
278  65  ×
279  43 RCL
280  01  01
281  45 Y^x
282  93  .
283  02  2
284  07  7
285  94 +/-
286  95  =
287  92 RTN
288  76 LBL
289  20 CLR
290  93  .
291  00  0
292  04  4
293  02  2
294  65  ×
295  43 RCL
296  25  25
297  95  =
298  92 RTN
299  76 LBL
300  27 INV
```

```
301  93  .
302  00  0
303  03  3
304  03  3
305  65  ×
306  43 RCL
307  26  26
308  95  =
309  92 RTN
310  76 LBL
311  28 LOG
312  93  .
313  00  0
314  01  1
315  03  3
316  65  ×
317  43 RCL
318  27  27
319  95  =
320  92 RTN
321  76 LBL
322  29 CP
323  04  4
324  93  .
325  08  8
326  65  ×
327  43 RCL
328  18  18
329  45 Y^x
330  93  .
331  08  8
332  65  ×
333  43 RCL
334  01  01
335  45 Y^x
336  93  .
337  02  2
338  94 +/-
339  95  =
340  92 RTN
341  76 LBL
342  30 TAN
343  08  8
344  93  .
345  06  6
346  09  9
347  65  ×
348  43 RCL
349  01  01
350  45 Y^x
```

```
351  93  .
352  02  2
353  04  4
354  94 +/-
355  95  =
356  92 RTN
357  76 LBL
358  36 PGM
359  01  1
360  93  .
361  04  4
362  01  1
363  65  ×
364  43 RCL
365  01  01
366  45 Y^x
367  93  .
368  03  3
369  03  3
370  94 +/-
371  65  ×
372  43 RCL
373  20  20
374  45 Y^x
375  93  .
376  07  7
377  07  7
378  95  =
379  92 RTN
380  76 LBL
381  37 P/R
382  05  5
383  03  3
384  93  .
385  04  4
386  65  ×
387  43 RCL
388  01  01
389  45 Y^x
390  93  .
391  02  2
392  01  1
393  94 +/-
394  95  =
395  92 RTN
396  76 LBL
397  39 COS
398  93  .
399  00  0
400  03  3
```

```
401  08   8
402  65   ×
403  53   (
404  43 RCL
405  29   29
406  55   ÷
407  43 RCL
408  15   15
409  54   )
410  45 Y×
411  93   .
412  04   4
413  09   9
414  55   ÷
415  43 RCL
416  01   01
417  95   =
418  92 RTN
419  76 LBL
420  47 CMS
421  93   .
422  04   4
423  06   6
424  06   6
425  65   ×
426  53   (
427  43 RCL
428  29   29
429  55   ÷
430  43 RCL
431  16   16
432  55   ÷
433  43 RCL
434  17   17
435  54   )
436  45 Y×
437  93   .
438  03   3
439  06   6
440  55   ÷
441  43 RCL
442  01   01
443  95   =
444  92 RTN
445  76 LBL
446  38 SIN
447  93   .
448  08   8
449  65   ×
450  43 RCL
451  01   01
452  45 Y×
453  93   .
454  04   4
455  94 +/-
456  95   =
457  92 RTN
458  76 LBL
459  48 EXC
460  93   .
461  00   0
462  00   0
463  00   0
464  00   0
465  05   5
466  65   ×
467  43 RCL
468  19   19
469  65   ×
470  43 RCL
471  29   29
472  55   ÷
473  43 RCL
474  01   01
475  95   =
476  92 RTN
477  76 LBL
478  95   =
479  32 X:T
480  25 CLR
481  67   EQ
482  22 INV
483  11   A
484  71 SBR
485  94 +/-
486  76 LBL
487  22 INV
488  91 R/S
489  32 X:T
490  25 CLR
491  67   EQ
492  23 LNX
493  12   B
494  71 SBR
495  94 +/-
496  76 LBL
497  23 LNX
498  91 R/S
499  32 X:T
500  25 CLR
```

```
501  67  EQ
502  24  CE
503  13  C
504  71  SBR
505  94  +/-
506  76  LBL
507  24  CE
508  91  R/S
509  32  X↕T
510  25  CLR
511  67  EQ
512  25  CLR
513  14  D
514  71  SBR
515  94  +/-
516  76  LBL
517  25  CLR
518  91  R/S
519  32  X↕T
520  25  CLR
521  67  EQ
522  35  1/X
523  15  E
524  71  SBR
525  94  +/-
526  43  RCL
527  05  05
528  55  ÷
529  01  1
530  00  0
531  00  0
532  65  ×
533  05  5
534  75  -
535  43  RCL
536  23  23
537  95  =
538  42  STO
539  13  13
540  43  RCL
541  13  13
542  32  X↕T
543  25  CLR
544  77  GE
545  34  ΓX
546  17  B'
547  71  SBR
548  94  +/-
549  76  LBL
550  34  ΓX
551  43  RCL
552  05  05
553  55  ÷
554  01  1
555  00  0
556  00  0
557  75  -
558  43  RCL
559  24  24
560  95  =
561  42  STO
562  14  14
563  43  RCL
564  14  14
565  32  X↕T
566  25  CLR
567  77  GE
568  35  1/X
569  18  C'
570  71  SBR
571  94  +/-
572  76  LBL
573  35  1/X
574  91  R/S
575  32  X↕T
576  25  CLR
577  67  EQ
578  42  STO
579  19  D'
580  71  SBR
581  94  +/-
582  76  LBL
583  42  STO
584  91  R/S
585  32  X↕T
586  25  CLR
587  67  EQ
588  43  RCL
589  10  E'
590  71  SBR
591  94  +/-
592  76  LBL
593  43  RCL
594  91  R/S
595  32  X↕T
596  25  CLR
597  67  EQ
598  44  SUM
599  71  SBR
600  20  CLR
```

```
601  71 SBR
602  94 +/-
603  76 LBL
604  44 SUM
605  91 R/S
606  32 X:T
607  25 CLR
608  67  EQ
609  45 Y^x
610  71 SBR
611  27 INV
612  71 SBR
613  94 +/-
614  76 LBL
615  45 Y^x
616  91 R/S
617  32 X:T
618  25 CLR
619  67  EQ
620  52 EE
621  71 SBR
622  28 LOG
623  71 SBR
624  94 +/-
625  76 LBL
626  52 EE
627  91 R/S
628  32 X:T
629  25 CLR
630  67  EQ
631  53  (
632  71 SBR
633  29 CP
634  71 SBR
635  94 +/-
636  76 LBL
637  53  (
638  91 R/S
639  32 X:T
640  25 CLR
641  67  EQ
642  54  )
643  71 SBR
644  30 TAN
645  71 SBR
646  94 +/-
647  76 LBL
648  54  )
649  91 R/S
650  32 X:T
651  25 CLR
652  67  EQ
653  55  ÷
654  71 SBR
655  36 PGM
656  71 SBR
657  94 +/-
658  76 LBL
659  55  ÷
660  91 R/S
661  32 X:T
662  25 CLR
663  67  EQ
664  61 GTO
665  71 SBR
666  37 P/R
667  71 SBR
668  94 +/-
669  76 LBL
670  61 GTO
671  91 R/S
672  32 X:T
673  25 CLR
674  67  EQ
675  71 SBR
676  71 SBR
677  39 COS
678  71 SBR
679  94 +/-
680  76 LBL
681  71 SBR
682  91 R/S
683  32 X:T
684  25 CLR
685  67  EQ
686  75  -
687  71 SBR
688  47 CMS
689  71 SBR
690  94 +/-
691  76 LBL
692  75  -
693  91 R/S
694  32 X:T
695  25 CLR
696  67  EQ
697  65  ×
698  71 SBR
699  38 SIN
700  71 SBR
```

```
701   94 +/-
702   76 LBL
703   65  ×
704   91 R/S
705   32 X:T
706   25 CLR
707   67  EQ
708   81 RST
709   71 SBR
710   48 EXC
711   71 SBR
712   94 +/-
713   76 LBL
714   81 RST
715   91 R/S
716   43 RCL
717   00  00
718   91 R/S
```

APPENDIX C

CAPITAL COST ESTIMATING PROGRAM FOR ELECTROPLATING WASTE TREATMENT

Magnetic Card Title: TI-59 Program for estimating the capital cost of electroplating waste treatment.

Memory Partition: 559:49

Press

5 2nd OP 17

Input Data:

Enter —— (Flow rate of chromium bearing waste stream in gpm)

Press STO 01

Enter —— (Flow rate of cyanide bearing waste stream in gpm)

Press STO 03

Enter —— (Flow rate of acid/alkali waste in gpm)

Press STO 18

Run Program:

Press RST

Press R/S (Display: Capital cost in $1,000)

```
000  25 CLR
001  42 STO
002  00  00
003  61 GTO
004  95  =
005  76 LBL
006  11  A
007  01  1
008  93  .
009  01  1
010  65  ×
011  53  (
012  02  2
013  00  0
014  85  +
015  93  .
016  01  1
017  65  ×
018  43 RCL
019  01  01
020  54  )
021  95  =
022  42 STO
023  21  21
024  92 RTN
025  76 LBL
026  94 +/-
027  44 SUM
028  00  00
029  92 RTN
030  76 LBL
031  12  B
032  01  1
033  93  .
034  01  1
035  65  ×
036  53  (
037  03  3
038  05  5
039  85  +
040  93  .
041  02  2
042  03  3
043  65  ×
044  43 RCL
045  04  04
046  54  )
047  95  =
048  42 STO
049  22  22
050  92 RTN
051  76 LBL
052  13  C
053  01  1
054  93  .
055  01  1
056  65  ×
057  01  1
058  01  1
059  93  .
060  01  1
061  65  ×
062  53  (
063  43 RCL
064  01  01
065  85  +
066  43 RCL
067  04  04
068  85  +
069  43 RCL
070  18  18
071  54  )
072  45 Y×
073  93  .
074  02  2
075  95  =
076  42 STO
077  23  23
078  92 RTN
079  76 LBL
080  14  D
081  01  1
082  93  .
083  01  1
084  65  ×
085  01  1
086  93  .
087  01  1
088  65  ×
089  53  (
090  07  7
091  93  .
092  08  8
093  03  3
094  85  +
095  93  .
096  01  1
097  06  6
098  65  ×
099  53  (
100  43 RCL
```

```
101  01  01
102  85  +
103  43 RCL
104  04  04
105  85  +
106  43 RCL
107  18  18
108  54  )
109  54  )
110  95  =
111  42 STO
112  24  24
113  92 RTN
114  76 LBL
115  15  E
116  43 RCL
117  00  00
118  65  ×
119  93  .
120  01  1
121  65  ×
122  01  1
123  93  .
124  01  1
125  95  =
126  42 STO
127  25  25
128  92 RTN
129  76 LBL
130  95  =
131  11  A
132  71 SBR
133  94 +/-
134  12  B
135  71 SBR
136  94 +/-
137  13  C
138  71 SBR
139  94 +/-
140  14  D
141  71 SBR
142  94 +/-
143  15  E
144  71 SBR
145  94 +/-
146  43 RCL
147  00  00
148  91 R/S
```

APPENDIX D

OPERATION AND MAINTENANCE COSTS ESTIMATING PROGRAM FOR ELECTROPLATING WASTE TREATMENT

Magnetic Card Title: TI-59 Program for estimating the operation and maintenance costs of electroplating waste treatment.

Memory Partition: 559:49

Press

5 2nd OP 17

Input Data:

Enter —— (Flow rate of chromium bearing waste stream in gpm)

Press STO 01

Enter —— (Concentration of hexavalent chromium in mg/ℓ)

Press STO 02

Enter —— (Concentration of trivalent chromium in mg/ℓ)

Press STO 03

Enter —— (Flow rate of cyanide bearing waste stream in gpm)

Press STO 04

Enter —— (Concentration of cyanide bearing waste stream in mg/ℓ)

Press STO 05

Enter —— (Flow rate of zinc bearing waste stream in gpm)

Press STO 06

Enter —— (Concentration of Zn^{+2} in mg/ℓ)

Press STO 07

Enter —— (Flow rate of iron bearing waste stream in gpm)

Press STO 08

Enter —— (Concentration of Fe^{+2} in mg/ℓ)

Press STO 09

Enter —— (Flow rate of nickel bearing waste stream in gpm)

Press STO 10

Enter —— (Concentration of Ni^{+2} in mg/ℓ)

Press STO 11

Enter —— (Flow rate of copper bearing waste stream in gpm)

Press STO 12

Enter —— (Concentration of Cu^{+2} in mg/ℓ)

Press STO 13

Enter —— (Flow rate of cadmium bearing waste stream in gpm)

Press STO 14

Enter —— (Concentration of Cd^{+2} in mg/ℓ)

Press STO 15

Enter —— (Flow rate of acid/alkali waste in gpm)

Press STO 18

Run Program:

Press RST

Press R/S (Display: O&M costs in ¢/1,000 gal)

```
000  25 CLR
001  42 STO
002  00  00
003  61 GTO
004  95  =
005  76 LBL
006  11  A
007  43 RCL
008  01  01
009  65  ×
010  06  6
011  00  0
012  65  ×
013  43 RCL
014  02  02
015  55  ÷
016  01  1
017  01  1
018  09  9
019  09  9
020  00  0
021  04  4
022  95  =
023  42 STO
024  31  31
025  43 RCL
026  01  01
027  65  ×
028  06  6
029  00  0
030  65  ×
031  43 RCL
032  03  03
033  55  ÷
034  01  1
035  01  1
036  09  9
037  09  9
038  00  0
039  04  4
040  95  =
041  42 STO
042  32  32
043  43 RCL
044  31  31
045  65  ×
046  93  .
047  01  1
048  08  8
049  85  +
050  43 RCL
051  01  01
052  65  ×
053  06  6
054  00  0
055  55  ÷
056  04  4
057  00  0
058  00  0
059  00  0
060  00  0
061  95  =
062  42 STO
063  21  21
064  92 RTN
065  76 LBL
066  94 +/-
067  44 SUM
068  00  00
069  92 RTN
070  76 LBL
071  12  B
072  43 RCL
073  04  04
074  65  ×
075  06  6
076  00  0
077  65  ×
078  43 RCL
079  05  05
080  55  ÷
081  01  1
082  01  1
083  09  9
084  09  9
085  00  0
086  04  4
087  95  =
088  42 STO
089  30  30
090  43 RCL
091  30  30
092  65  ×
093  01  1
094  93  .
095  01  1
096  06  6
097  95  =
098  42 STO
099  22  22
100  92 RTN
```

```
101  76 LBL
102  13  C
103  43 RCL
104  01  01
105  65  ×
106  06  6
107  00  0
108  55  ÷
109  08  8
110  03  3
111  03  3
112  03  3
113  85  +
114  43 RCL
115  18  18
116  65  ×
117  06  6
118  00  0
119  55  ÷
120  01  1
121  02  2
122  05  5
123  00  0
124  00  0
125  95  =
126  42 STO
127  23  23
128  92 RTN
129  76 LBL
130  14  D
131  43 RCL
132  31  31
133  85  +
134  43 RCL
135  32  32
136  95  =
137  42 STO
138  33  33
139  43 RCL
140  06  06
141  65  ×
142  06  6
143  00  0
144  65  ×
145  43 RCL
146  07  07
147  55  ÷
148  01  1
149  01  1
150  09  9
151  09  9
152  00  0
153  04  4
154  95  =
155  42 STO
156  34  34
157  43 RCL
158  08  08
159  65  ×
160  06  6
161  00  0
162  65  ×
163  43 RCL
164  09  09
165  55  ÷
166  01  1
167  01  1
168  09  9
169  09  9
170  00  0
171  04  4
172  95  =
173  42 STO
174  35  35
175  43 RCL
176  10  10
177  65  ×
178  06  6
179  00  0
180  65  ×
181  43 RCL
182  11  11
183  55  ÷
184  01  1
185  01  1
186  09  9
187  09  9
188  00  0
189  04  4
190  95  =
191  42 STO
192  36  36
193  43 RCL
194  12  12
195  65  ×
196  06  6
197  00  0
198  65  ×
199  43 RCL
200  13  13
```

```
201  55  ÷
202  01  1
203  01  1
204  09  9
205  09  9
206  00  0
207  04  4
208  95  =
209  42  STO
210  37  37
211  43  RCL
212  14  14
213  65  ×
214  06  6
215  00  0
216  65  ×
217  43  RCL
218  15  15
219  55  ÷
220  01  1
221  01  1
222  09  9
223  09  9
224  00  0
225  04  4
226  95  =
227  42  STO
228  38  38
229  43  RCL
230  33  33
231  65  ×
232  93  .
233  01  1
234  08  8
235  85  +
236  93  .
237  01  1
238  06  6
239  65  ×
240  53  (
241  43  RCL
242  34  34
243  85  +
244  43  RCL
245  35  35
246  85  +
247  43  RCL
248  36  36
249  85  +
250  43  RCL
251  37  37
252  85  +
253  43  RCL
254  38  38
255  54  )
256  95  =
257  42  STO
258  24  24
259  92  RTN
260  76  LBL
261  15  E
262  43  RCL
263  33  33
264  65  ×
265  01  1
266  93  .
267  09  9
268  08  8
269  85  +
270  43  RCL
271  34  34
272  65  ×
273  01  1
274  93  .
275  05  5
276  02  2
277  85  +
278  43  RCL
279  35  35
280  65  ×
281  01  1
282  93  .
283  06  6
284  01  1
285  85  +
286  43  RCL
287  36  36
288  65  ×
289  01  1
290  93  .
291  05  5
292  08  8
293  85  +
294  43  RCL
295  37  37
296  65  ×
297  01  1
298  93  .
299  05  5
300  03  3
```

```
301  85  +
302  43  RCL
303  38   38
304  65  ×
305  01   1
306  93  .
307  03   3
308  00   0
309  95  =
310  42  STO
311  29   29
312  43  RCL
313  33   33
314  65  ×
315  93  .
316  05   5
317  09   9
318  85  +
319  43  RCL
320  34   34
321  65  ×
322  93  .
323  04   4
324  06   6
325  85  +
326  43  RCL
327  35   35
328  65  ×
329  93  .
330  04   4
331  08   8
332  85  +
333  43  RCL
334  36   36
335  65  ×
336  93  .
337  04   4
338  06   6
339  85  +
340  43  RCL
341  37   37
342  65  ×
343  93  .
344  04   4
345  05   5
346  85  +
347  43  RCL
348  38   38
349  65  ×
350  93  .
```

```
351  03   3
352  09   9
353  95  =
354  42  STO
355  25   25
356  92  RTN
357  76  LBL
358  16  A'
359  53  (
360  43  RCL
361  01   01
362  85  +
363  43  RCL
364  04   04
365  85  +
366  43  RCL
367  18   18
368  54  )
369  65  ×
370  06   6
371  00   0
372  55  ÷
373  01   1
374  00   0
375  00   0
376  00   0
377  65  ×
378  93  .
379  01   1
380  95  =
381  42  STO
382  26   26
383  92  RTN
384  76  LBL
385  17  B'
386  04   4
387  09   9
388  93  .
389  04   4
390  65  ×
391  43  RCL
392  01   01
393  45  Y^x
394  93  .
395  01   1
396  04   4
397  65  ×
398  43  RCL
399  04   04
400  45  Y^x
```

```
401  93  .
402  00  0
403  06  6
404  65  ×
405  43  RCL
406  18  18
407  45  Y^x
408  93  .
409  01  1
410  01  1
411  95  =
412  42  STO
413  19  19
414  43  RCL
415  19  19
416  65  ×
417  01  1
418  00  0
419  00  0
420  00  0
421  65  ×
422  93  .
423  01  1
424  08  8
425  55  ÷
426  04  4
427  08  8
428  00  0
429  00  0
430  95  =
431  42  STO
432  27  27
433  92  RTN
434  76  LBL
435  95  =
436  11  A
437  71  SBR
438  94  +/-
439  12  B
440  71  SBR
441  94  +/-
442  13  C
443  71  SBR
444  94  +/-
445  14  D
446  71  SBR
447  94  +/-
448  15  E
449  71  SBR
450  94  +/-
451  16  A'
452  71  SBR
453  94  +/-
454  17  B'
455  71  SBR
456  94  +/-
457  43  RCL
458  00  00
459  65  ×
460  01  1
461  00  0
462  00  0
463  55  ÷
464  06  6
465  00  0
466  55  ÷
467  53  (
468  43  RCL
469  01  01
470  85  +
471  43  RCL
472  04  04
473  85  +
474  43  RCL
475  18  18
476  54  )
477  65  ×
478  01  1
479  00  0
480  00  0
481  00  0
482  95  =
483  42  STO
484  20  20
485  43  RCL
486  20  20
487  91  R/S
```