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MANUAL FOR ESTIMATING COST OF VOC REMOVAL FROM GROUNDWATER CONTAMINATED WITH JET FUEL

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The objective of this guidance manual is to provide a tool to U.S. Air Force engineers and decision makers for use in evaluation and selection of air stripping with emissions control technology. The development of this manual was part of a larger activity for the U.S. Air Force focused on the field study and demonstration of the state of the art in air stripping with emissions control technology. The intent of the guidance manual is to provide managers and engineers with necessary information so that decisions relating to the application of this technology can proceed on a rational basis.

Analysis of the lifetime operating costs for application of air stripping technology for remediation of contaminated groundwater indicates that the use of emissions control devices for systems for air stripping of VOCs from groundwater considerably increases the costs of such operations, cost considerations favor the use of lower values of the stripping factor, and the costs of the remediation of contaminated groundwater are largely controlled by operating rather than capital costs.

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EXECUTIVE SUMMARY

A. OBJECTIVE

The objective of this guidance manual is to provide a tool to U.S. Air Force engineers and decision makers for use in evaluation and selection of air stripping with emissions control technology.

B. BACKGROUND

The development of this manual was part of a larger activity for the U.S. Air Force focused on the field study and demonstration of the state of the art in air stripping with emissions control technology. The intent of the guidance manual is to provide managers and engineers with necessary information so that decisions relating to the application of this technology can proceed on a rational basis. Although the information provided in the manual is available from a number of sources, it had not been organized so that it could be readily used for air stripping technology evaluation, especially by one not very skilled in the art. In this guidance manual, the information is organized and provided to the user in an interactive spreadsheet format.

C. SCOPE

The results of the field tests for the U.S. Air Force, along with other relevant information, were translated into a computer model used to assess the design and economic aspects of relevant technology and operating parameters for groundwater remediation by air stripping with emissions control. The technology basis for the computer model and operating instructions for the spreadsheet are included in the guidance manual. Also, the spreadsheet was used to evaluate example cases of air stripping with emissions control. The results of the calculations are presented and explained in the manual.

D. METHODOLOGY

The approach used in this activity was to provide a useful computer model in an easy to use format. The economic simulation was developed as spreadsheets that may be used on a personal computer. Multiplan by MicroSoft was the software chosen because of its capability to automatically perform iterative calculations (needed when circular dependencies exist between spreadsheet cells). In the development of the computer model, information was utilized from the literature and also from the results of the field study of air stripping with emissions control conducted for the U.S. Air Force.

E. TEST DESCRIPTION

The Eglin Air Force Base air stripping field study is described in full in ESL TR 90-51, <u>Air Stripping and Emissions Control Technologies: Field Testing of Countercurrent Packings, Rotary Air</u>

<u>Stripping, Catalytic Oxidation, and Adsorption Materials</u>. Results from this study were used in the development of the computer model for this guidance manual.

F. RESULTS

Analysis of the lifetime operating costs for application of air stripping technology for remediation of contaminated groundwater indicates that the use of emissions control devices for systems for air stripping of VOCs from groundwater considerably increases the costs of such operations, cost considerations favor the use of lower values of the stripping factor, and the costs of the remediation of contaminated groundwater are largely controlled by operating rather than capital costs.

G. CONCLUSIONS

The spreadsheet-based model developed and described herein can be readily utilized by Air Force personnel for the evaluation and selection of an air stripping with emissions control technology for the remediation of VOC contaminated groundwater. If desired, the correlations for design and cost estimations can be updated as new information becomes available. By varying financial input parameters, such as depreciation period, interest rates, etc., different scenarios may be evaluated for particular operating conditions of groundwater flowrate, contaminant concentration, etc.

PREFACE

This report was prepared by the Oak Ridge National Laboratory, P. O. Box 2008, Oak Ridge, TN 37831-6044, for the Air Force Engineering and Services Center, Engineering and Services Laboratory, Tyndall Air Force Base, Florida, as partial fulfillment of the statement of work entitled "Air Stripping with Emissions Control" in accordance with DOE Interagency Agreement No. 1489-1489-A1. The period of performance of the work was from April 1987 to June 1989. Oak Ridge National Laboratory is managed by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under contract DE-AC05-84OR21400.
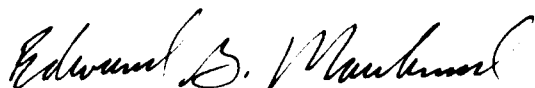
This document details the results of activities performed under Task 4.4 of the statement of work, Phase 4: IRP Phase IV Users Manual. A related document completed under the same contract is ESL TR 90-51, Air Stripping and Emissions Control Technologies: Field Testing of Countercurrent Packings, Rotary Air Stripping, Catalytic Oxidation, and Adsorption Materials. The AFESC/RDVW Project Officers for this effort were Captain R. A. Ashworth and Captain Edward Marchand.

Mention of trade names or commercial products within this document does not constitute endorsement or recommendation for use.

Copies of the VOC-2.100 and VOC-2.300 spreadsheets are available from the Chemical/Physical Treatment Technology Area Manager, HQ AFESC/RDVW, Tyndall AFB, FL. Include a diskette with your request.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.
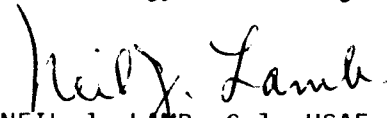
This technical report has been reviewed and is approved for publication.

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LIST OF ABBREVIATIONS

ATU	Area of a Transfer Unit
BET	Braunauer-Emmett-Teller
BTU	British Thermal Unit
CFR	Code of Federal Regulations
GAO	General Accounting Office
IAST	Ideal Adsorbed Solution Theory
IBM	International Business Machines
MS	MicroSoft
ORNL	Oak Ridge National Laboratory
TCE	Trichloroethylene
U.S.	United States
VOC	Volatile Organic Compound

LIST OF SYMBOLS[a,b]

$A_{tol.}$	Area of overall liquid-phase transfer unit, ft^2
a_c	Acceleration, $feet/s^2$
a_p	Specific area of packing per unit of packed volume, ft^2/ft^3
B	Microporosity constant, $[mol^2/cal^2]$
C_B	Cost of traditional packed tower shell and skirt, dollars
C_P	Cost of tower packing, $dollars/ft^3$
C_t	Total delivered cost of equipment, dollars
C_i	Fluid-phase concentration of component i, parts per million by weight, $[\mu g/gram]$
$C_{i,j}$	Fluid-phase concentration of component i in zone j, $[\mu g/gram]$
D	Diameter of total water piping system based on a velocity of 5 feet/second, feet
D_i	Diameter of packed tower, feet
d_p	Nominal packing diameter, feet
E_R	Carbon regeneration expense, dollars/pound
F_m	Cost factor for materials of construction, dimensionless
f	Fanning friction factor, dimensionless
G	Superficial gas molar velocity, pound $moles/ft^2$-second
G'	Air flow rate, standard $ft^3/minute$
G^*	Mass velocity of air, $pound/ft^2$-hour
g	Acceleration of gravity, $feet/s^2$
g_c	Conversion factor, pound-$feet/s^2$-$pound_F$
H	Henry's constant, ft^3 atmosphere/pound mole
H_G	Height of individual gas-phase transfer unit, feet
H_L	Height of individual liquid-phase transfer unit, feet
H_{toL}	Height of overall liquid-phase transfer unit, feet
K_i	Freundlich coefficient for component i, $[(\mu g/gram\ carbon)\ (gram\ air/\mu g)^{1/n_i}]$
L	Superficial liquid molar velocity, pound $moles/ft^2$-second
L'	Water flow rate, gallons/minute
L^*	Mass velocity of liquid, $pound/ft^2$-hour
M	Molecular weight, [gram/gram mole]
M_L	Average liquid molecular weight, pound/pound mole

LIST OF SYMBOLS
(CONTINUED)

M_s	Solute mass flow rate, pounds/hour
m	Equilibrium distribution ratio, y/x
N	Total number of components, dimensionless
N_{tol}	Number of overall liquid-phase transfer units, dimensionless
n	Refractive index, dimensionless
P_B	Brake power, hp
P_T	Total pressure, atmosphere
P_i	Partial pressure of component i, atmosphere
P_s	Saturation pressure, atmosphere
P'	Power, [kW]
Q_L	Volumetric liquid rate, ft^3/second
q_i	Loading of component i on activated carbon, μ pound/pound, [μg/gram]
$q_{i,j}$	Loading of component i on activated carbon in zone j, [μg/gram]
q_w	Working capacity of activated carbon, pound solute/pound carbon
R	Ideal gas law constant, [cal/gram mole K]
r	Radius, feet
S	Stripping factor, dimensionless
T	Absolute temperature, Rankine
T_s	Traditional packed-tower shell thickness, feet
U_G	Gas velocity, feet/second
V	Liquid velocity in water supply piping, feet/second
V_G	Superficial gas velocity, feet/second
V_F	Superficial fluid velocity, [meters/second]
V_{wi}	Adsorption wave front velocity for single component i, [meters/second]
V_{wk}	Adsorption wave front velocity for multicomponent mixture, [meters/second]
W_c	Mass of activated carbon required, pounds
W_o	Maximum space available on carbon, [cm^3/gram]
W_s	Weight of tower shell, pounds
$\dot{W}_c$	Carbon usage rate, 10^6 pound/year

x_1, x_2	Liquid-phase mole fraction exiting and entering the stripper, respectively
x	Mole fraction in the liquid phase, pound mole/pound mole
y	Mole fraction in the gas phase, pound mole/pound mole
y_1, y_2	Gas-phase mole fraction entering and exiting the stripper, respectively
Z	Calculated depth of packing, feet
Z'	Depth of packing, including safety factor, feet
Z_B''	Total static head at blower, inches of water
Z_L	Total length of water supply piping, feet
Z_T	Total hydrostatic head requirements for pump, feet
Z_p	Depth of packing between liquid redistributors, including safety factor, feet
Z_p'	Head requirement for water supply, feet-pound$_F$ /pound
$1/n_i$	Freundlich parameter for component i

Greek symbols

β	Affinity coefficient (ratio of energy of the interaction of the adsorbate molecule with the adsorbent surface to energy interaction of a reference molecule with the same adsorbent surface)
μ	Polarizability of the adsorbate, [cm^3/gram mole]
μ^*	Polarizability of the reference molecule, [cm^3/gram mole]
μ_L	Liquid-phase viscosity, pound/foot-hour
μ_G	Gas-phase viscosity, pound/foot-hour
η_B	Overall blower efficiency
η_p	Efficiency of pump
ρ_A	Adsorbate density, [gram/cm^3]
ρ_F	Fluid density, [gram/cm^3]
ρ_G	Gas density, pounds/ft^3
ρ_L	Liquid density, pounds/ft^3
ρ_c	Bulk density of activated carbon, [gram/cm^3]
ρ_{cs}	Density of carbon steel, pound/ft^3
θ_c	Carbon recycle interval, hours

LIST OF SYMBOLS
(CONCLUDED)

ϵ	Void fraction
ϕ	$(V_{wk}/V_{wi})_{C_i}$
ω	Rotational speed, rad/second

Subscripts

G	Gas
L	Liquid
M	Logarithmic average
F	Force
i	Component i

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[a]Brackets, [ ], indicate metric units.

[b]Unless otherwise specified in text, units are as given.

MANUAL FOR ESTIMATING COST OF VOC REMOVAL FROM GROUNDWATER CONTAMINATED WITH JET FUEL

SECTION I

INTRODUCTION

A. OBJECTIVE

This manual is intended to provide relevant information for persons involved in the remediation of groundwater contaminated with jet fuel or similar compounds. Developing strategies for groundwater remediation consists of four principal steps: (1) site characterization; (2) determination of treatment requirements; (3) remediation system design; and (4) system fabrication, installation, and operation. This manual is designed to be of primary benefit for item (3) of the above list; it may also be of benefit for items (2) and (4). Typical remediation technologies are identified and discussed; the costs of installed systems based on these technologies may be estimated using the enclosed software and an IBM-compatible personal computer. Much of the information provided in this manual is from a field study of air stripping with emissions control performed by the Oak Ridge National Laboratory (ORNL) for the United States Air Force (Reference 1).

Jet fuel contains a large percentage of soluble hydrocarbon compounds that are easily removed from groundwater by aeration; these compounds are called volatile organic compounds (VOCs) and have a Henry's coefficient of greater than 16 to 32 ft^3 atm/pound mole [1 to 2 m^3 atm/kmol]. Benzene is a VOC, having a Henry's coefficient estimated to be 76 ft^3 atm/pound mole [4.7 m^3 atm/kmol] at 68°F (Reference 2); naphthalene is not considered to be a VOC, having a Henry's coefficient estimated to be 6.7 ft^3 atm/pound mole [0.42 m^3 atm/kmol] at 68°F (Reference 3). Compounds with Henry's coefficient of less than 16 ft^3 atm/pound mole [1 m^3 atm/kmol], such as naphthalene, are not ordinarily removed very efficiently in aeration devices designed for VOC removal.

Stripping fuel components from water merely transfers them to another medium, usually air. Abatement of gaseous hydrocarbons by adsorption onto activated carbon has been utilized for many years; this process transfers the contaminants to another medium — activated carbon — which requires disposal or regeneration. Abatement by catalytic oxidation potentially offers a very high destruction of fuel components, producing CO_2 and H_2O.

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Information contained in this manual and accompanying software provides the user with a method of estimating unit processing costs (U.S. dollars/1000 gallons) for remediation of groundwater contaminated with jet fuel components. Two options are offered for air stripping — a traditional packed tower and a rotary air stripper. Also, two options are offered for emissions control — activated carbon adsorption and catalytic oxidation. Estimated treatment costs include fixed capital investment recovery, direct and indirect operating costs, and a method of accounting for uncertainty in any cost component. The estimates in these primary cost categories are used as inputs to an operating lifetime cost analysis. The cleanup costs are usually dominated by annual operating costs rather than fixed capital investments. Cost estimating techniques are compatible with procedures of the U.S. General Accounting Office. American units (pounds-feet-seconds) are used in this report. When not typical of supporting information, other more appropriate units, usually metric, are given in brackets, [ ].

B. BACKGROUND

Contamination of groundwater by VOCs is an important environmental problem. Sources of such contamination include accidental spills and leaking storage tanks and transport lines. Contamination of soil and groundwater from a leaking storage tank is illustrated in Figure 1. As shown in this figure, remediation of a contaminated aquifer is part of a larger problem of remediating the contaminated site, which includes the unsaturated zones. Site remediation usually involves containment of the contaminant(s). The National Oil and Hazardous Substances Contingency Plan (Reference 4) identifies three general categories of remediation activities: (1) initial, (2) source control, and (3) off-site measures. Pumping of groundwater can be useful for all three categories. Groundwater that ordinarily flows continuously through the site is an important agent for transporting soluble contaminants. Pumping activities usually involve depressing the groundwater table in the affected region by pumping from a system of wells. Contaminated water from such an operation requires treatment, as necessary, for its discharge; such treatment is the subject of this manual. A block diagram for the remediation of contaminated groundwater by air stripping with emissions control is presented in Figure 2.

A review of relevant technology was recently presented by Singh and Counce (Reference 5). Air-water contactors may be designed to give high removal of VOCs from water; contaminants of less volatility will be removed simultaneously to a lesser extent. The contaminated effluent air from the air-water contactor is often a matter of concern. If this stream is not suitable for discharge, then treatment to restore acceptable air quality will be required. During the remediation activity, the

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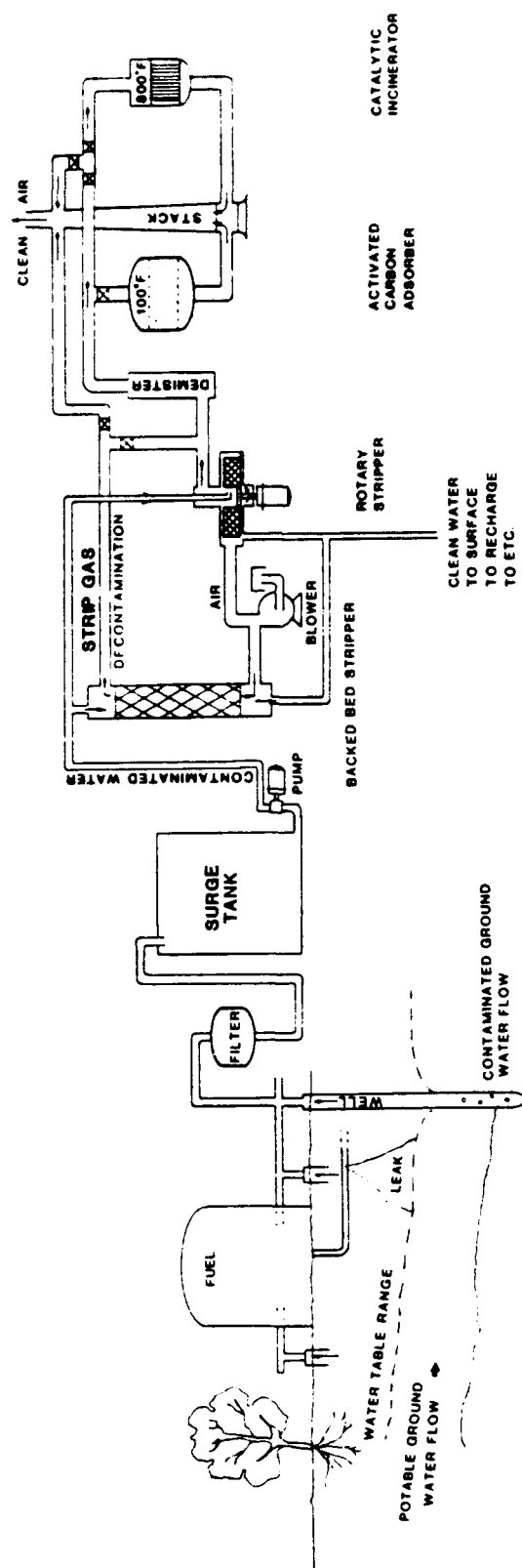
Figure. 1. Subsurface Behavior of Spilled Hydrocarbons.

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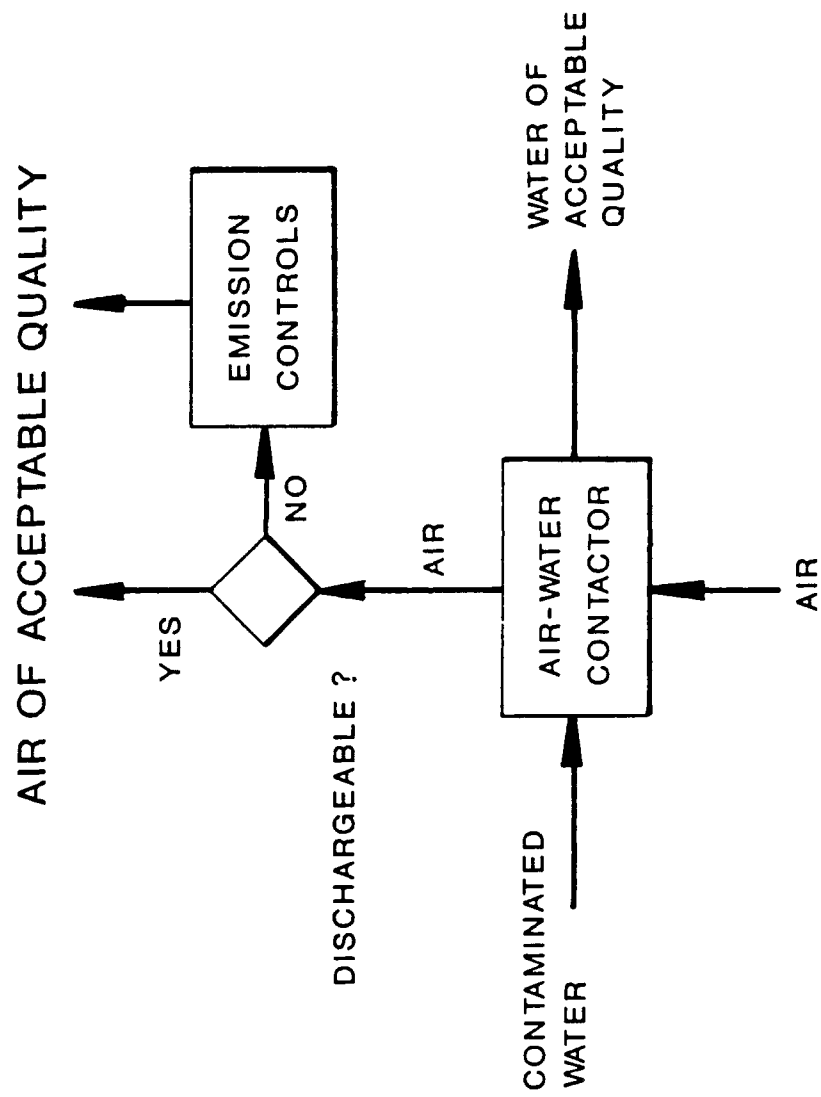
Figure 2.   Block Diagram of Remediation of Contaminated Groundwater by Air Stripping with Emissions Control.

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concentration of contaminants in the groundwater will be reduced to an acceptable level for discharge. At some point in this activity, the effluent air quality may improve to the point that any emissions control originally required is no longer necessary. The objective of an air stripper with an emissions control unit is to remove VOC contaminants from water so that the water is suitable for discharge for the life of the remediation activity; a corresponding objective is to operate the unit so that all other appropriate environmental regulations are observed for the same time period.

C. SCOPE/APPROACH

The purpose of this manual is to provide a means of assessing the unit processing costs (U.S. dollars/1000 gallons) of several configurations of an engineering system for the removal of jet fuel components from contaminated groundwater; these cost are estimated as a function of a number of key engineering and cost parameters. Some background information is also provided to give the reader a brief description of relevant technical information. The possible system configurations include an air stripper with and without emissions control. Two types of air strippers may be used: (1) a traditional packed tower for countercurrent gas-liquid contact; and (2) a centrifugal contactor, also for countercurrent gas-liquid contact. The choice of gaseous emissions control devices includes: (1) none, (2) catalytic oxidation, and (3) activated carbon adsorption. Complete computer codes and operating instructions for performing these tasks are included. The output from this assessment is an estimate of the unit processing cost for remediation of contaminated groundwater for the selected engineering and economic parameters.

SECTION II

RELEVANT TECHNICAL INFORMATION

A. AIR STRIPPING

1. Packed Air Strippers

Packed gas-liquid contactors with countercurrent gas and liquid flows provide a highly efficient means of stripping VOCs from groundwater. The design of packed towers is well developed in the chemical engineering literature (References 6, 7, and 8). A typical packed tower is shown in Figure 3, and other design details appear in Figure 4. The design process for strippers usually begins with known liquid flow rate and composition information, including that of the solute to be removed. The first step consists of the selection of the stripping medium; in this section, air is generally assumed to be the medium. The air flow rate is selected such that an adequate "driving force" for this operation can be maintained. For conditions that typically exist in air strippers, this may be satisfied by choosing a stripping factor greater than 1. The stripping factor is defined as

$$S = mG/L , \qquad (1)$$

where m is the equilibrium-phase distribution ratio, y/x, for the VOC of concern. The stripping factor also contains the ratio of gas-to-liquid superficial molar velocities, G/L; it is helpful to note that this ratio is identical to that of the molar flow rates of these two phases, since the tower cross-sectional area is not often known in the early stages of the design process. The optimum value of S is frequently found to be between 1.25 and 4.

Two general types of packing are useful for VOC removal by air stripping - random and structured - as shown in Figure 5. Random packings are available in a number of varieties, with standard saddles and slotted rings most commonly used for commercial applications. The commercial names may vary with the manufacturer, such as Flexirings® from Koch Engineering Company vs Pall rings from Chemical Processing Products Division of Norton Company; and Flexisaddles® from Koch Engineering Company vs Intalox® saddles from Norton Chemical Process Products or Novalox® saddles from Jaeger Products, Inc. Random packing is sometimes referred to as "dumped" packing due to the usual method of placement in the tower. Random packings are available in a number of nominal sizes or diameters, d_p, of up to 0.29 feet [89 mm] and in materials of ceramic, plastic, or metal. There is a tendency for maldistribution of the liquid phase in towers filled with dumped packings, especially when the packing size and depth of packing in the bed are incorrectly chosen.

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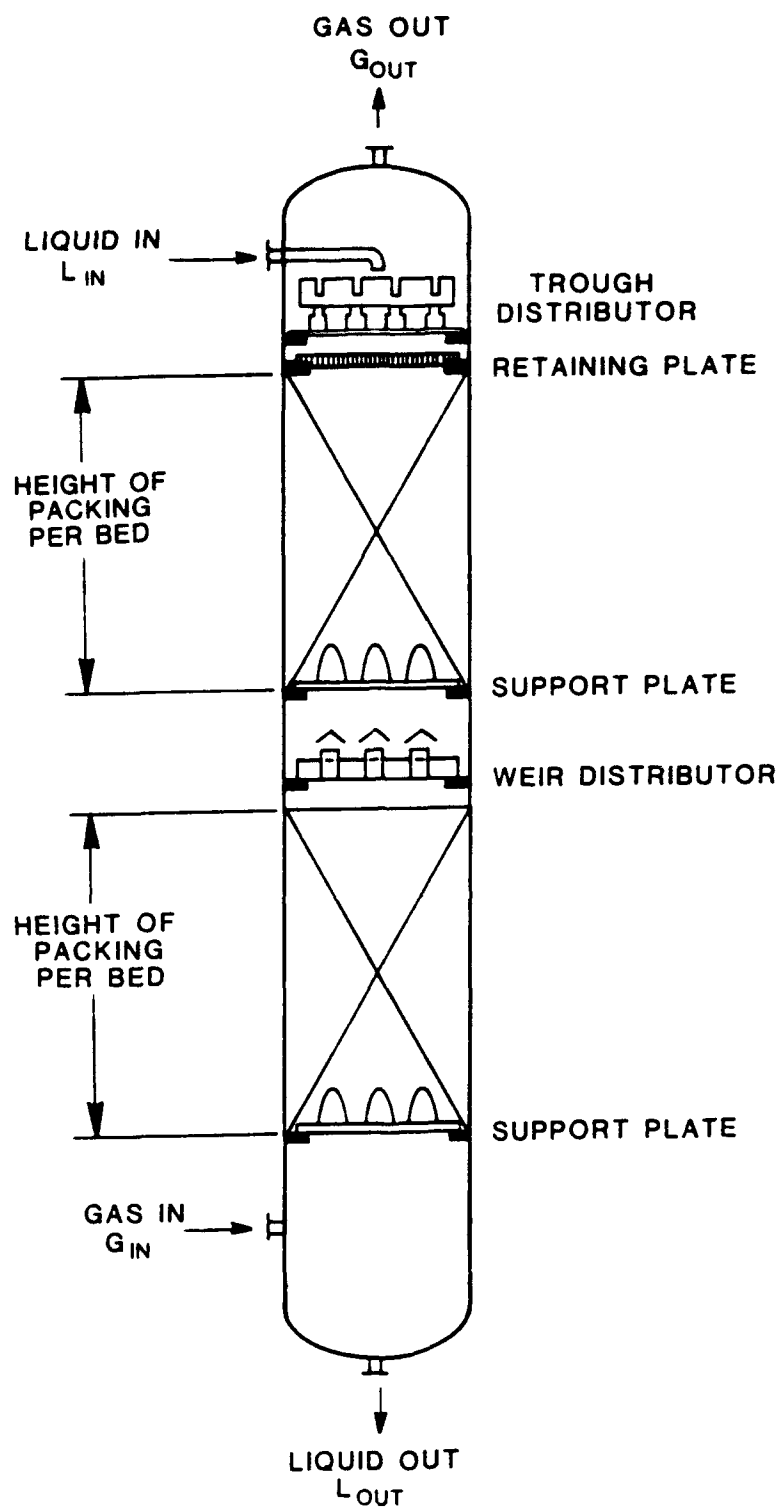
Figure 3.   Typical Packed Tower.
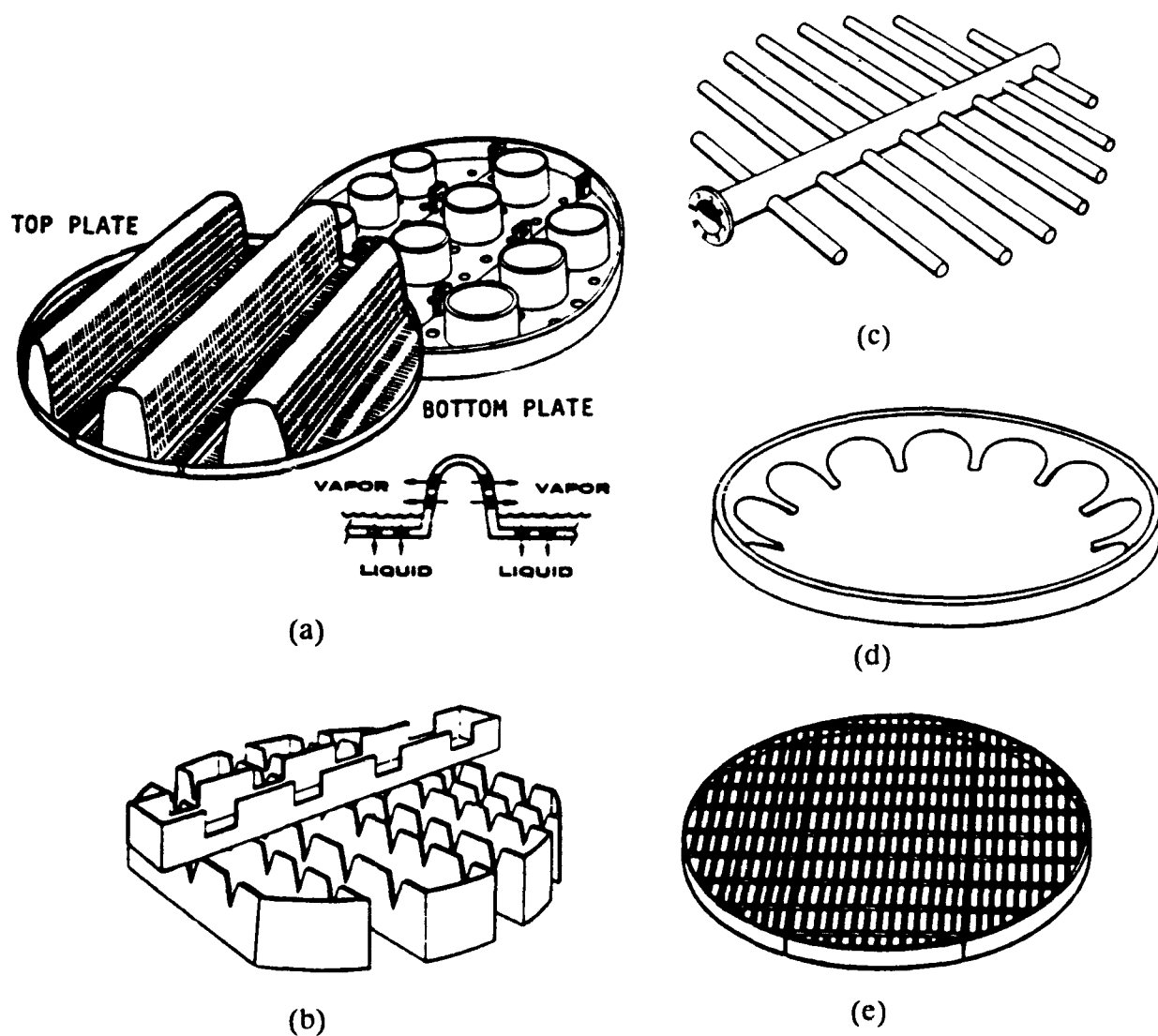
Figure 4. Packed column internals. (a) Packing support and redistributor assembly; (b) Trough-type liquid distributor; (c) Perforated pipe distributor; (d) Rosette redistributor for small towers; (e) Hold-down plate, particularly for low-density packing.

[Reproduced with permission from Stanley M. Walas, Chemical Process Equipment, (Stoneham, MA: Butterworth-Heinemann, 1988)]

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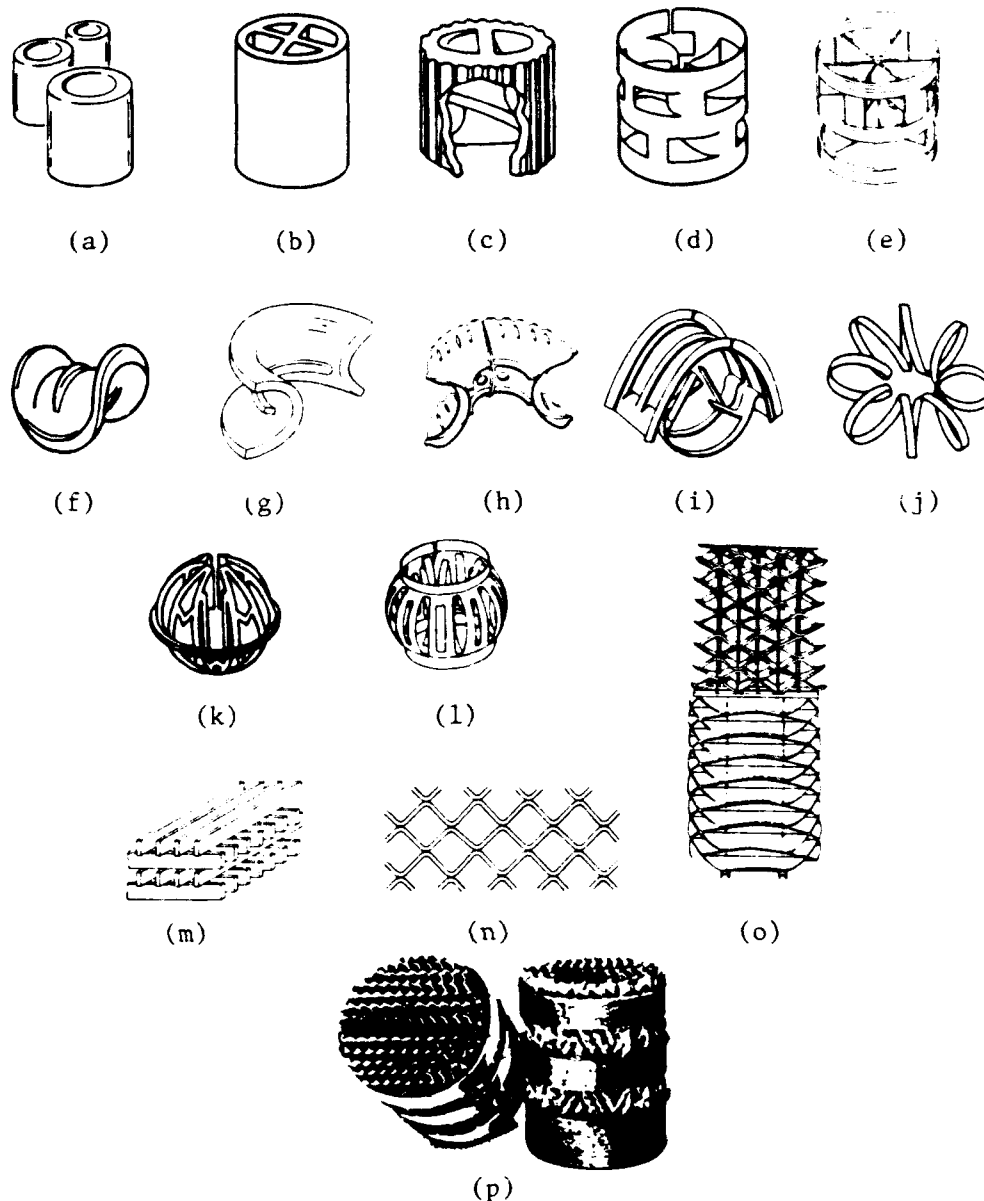
Figure 5.   Some kinds of tower packings: (a) Raschig ring; (b) partition or Lessing ring;
(c) double spiral ring; (d) metal Flexiring (*KOCH Engr. Co.*); (e) plastic pall ring;
(f) ceramic Berl saddle (*Maurice A. Knight Co.*); (g) ceramic intalox saddle
(*Norton Co.*); (h) plastic intalox saddle (*Norton Co.*); (i) metal intalox saddle
(*Norton Co.*); (j) Tellerette (*Chem-Pro Co.*); (k) plastic tripak (*Polymer Piping
and Metals Co.*); (l) metal tripak (*Polymer Piping and Metals Co.*); (m) wood
grid; (n) section through expanded metal packing; (o) sections of expanded
metal packings placed alternatively at right angles (*Denholme Co.*); (p) GEM
structured packing (*Glitsch Inc.*).

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Equipment, (Stoneham, MA: Butterworth-Heinemann, 1988)]

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This tendency is less when the ratio of column diameter to packing size, D_i/d_p, is greater than 8 (Reference 6), with the "best" value occurring at 15. Eckert (Reference 9) recommends minimum D_i/d_p values of 30 for Raschig rings, 15 for standard saddles (other than Raschig rings), and 10 to 15 for slotted rings. Because of the tendency of the liquid and gas flows to segregate in towers filled with dumped packings, it is customary to redistribute the liquid at intervals, Z_p, which vary from 2.5 to 10 times the tower diameter; Eckert (Reference 9) recommends maximum Z_p/D_i values of 2.5 to 3 for Raschig rings, 5 to 8 for standard saddles (other than Raschig rings), 5 to 10 for slotted rings, or a maximum Z_p of 20 feet, whichever is smaller. There is still speculation over the extent that good initial liquid distribution can affect the maximum Z_p/D_i ratio (Reference 10).

Structured packings offer advantages of low pressure-drop service and usually have excellent liquid distribution characteristics; it is critical, however, that the initial distribution of gases and liquids be done correctly in order to take advantage of the characteristics of these packings. The structured packings are manufactured as elements that are carefully fitted to the inside dimensions of the tower in an ordered, or structured, manner. An example of such a packing fabricated from corrugated sheets is shown in Figure 5. These sheets are commonly made of gauze (woven cloth), ceramic, or sheet metal, as well as of various plastics. The gauze packings are sometimes referred to as "high-efficiency" packing; an example of such material is the Koch-Sulzer packing. The cloth nature of the surface promotes a capillary action so that the liquid covers all the available surface even at low liquid loadings; the type of liquid flow inherent in such material appears to greatly enhance liquid-phase transport (References 11, 12, and 13). Similar packing elements fabricated of sheet metal or plastic do not appear to have the reduced liquid-phase resistance and near constant interfacial area properties of the gauze-type packings. The gauze-type structured packing is more expensive than either sheet-metal or plastic structured packing or dumped packing; its use, however, can significantly reduce design height requirements.

Discussion of typical tower intervals, distributors, packing support, etc., is presented by Treybal (Reference 6) and Perry et al. (Reference 14). The design of these items is critical for efficient packed-tower operation (References 15 and 16). They are usually manufactured and distributed by the same commercial concerns that supply tower packing. The flow-through types of packing, such as Pall® rings, metal Intalox® saddles, and structured packings, require that more attention be paid to the distribution of both gases and liquids than for older types of packings (bluff-body packings) such as Raschig rings, Berl saddles, and ceramic Intalox saddles. These older types of packings force fluids to flow around them, causing a higher pressure loss, and provide more

capacity to correct for maldistribution (Reference 17). Entrainment eliminators are not essential for VOC removal in the air stripper, but they may be very important for equipment operating downstream from the stripper tower. Knitted wire mesh is especially effective for removing entrained droplets of liquid from gas streams, although many other devices are available; further discussion on this subject is found in References 6 and 8.

Packed towers are usually circular in cross-section due to ease of construction and strength (Reference 6). The diameter of a tower for fixed gas and liquid rates is normally bounded by limits of operability. At a sufficiently small diameter, the tower will flood. At too large a diameter, the packing will not be sufficiently wetted for efficient mass transfer. Towers have operated with superficial liquid velocities as low as 0.007 inches/second [0.18 mm/second]; however, special liquid distribution systems are required (Reference 18). Usually, the tower is designed to operate at a given pressure drop per unit depth of packing; for strippers, values of 0.25 to 0.5 inches H_2O/foot [200 to 400 Pascals/meter] of packed depth are common (Reference 6). Alternately, the tower may be designed by selecting a gas velocity as a fraction of the flooding gas velocity; design values of 50 to 80 percent are common.

The height of packing required for a given separation may be conveniently calculated using the transfer unit concept,

$$Z = H_{toL} \, N_{toL} \, ,\tag{2}$$

where Z is the height of packing required, and H_{toL} and N_{toL} are the height and number of overall liquid transfer units, respectively. The above relationship may also be written in terms of overall gas transfer units; the form chosen usually indicates where the principal resistance lies. The height of an overall liquid transfer unit is calculated in the procedures used herein from estimates of heights of individual gas and liquid transfer units,

$$H_{toL} = H_L + H_G \, /S \, .\tag{3}$$

The correlations for the individual transfer unit heights H_L and H_G are based on a revised version of the Cornell equations, as presented by Fair (Reference 8).

The equilibrium distribution ratio, m, is related to Henry's constant, H, by

$$m = y/x = H(\rho_L/M_L P_T) \, ,\tag{4}$$

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where ρ_L and M_L are the density and average molecular weight, respectively, of the liquid phase and P_T is the total pressure..

The Henry's constant determines the distribution of the solute between the gas and liquid phases and depends upon the nature of the solute and the temperature. Although the Henry's constant can be estimated from the vapor pressure of pure solute and the solubility of the solute in water, experimental determination is usually recommended. For benzene, the experimentally determined expression for the variation of Henry's law constant with temperature that was used in this procedure was derived from Ashworth et al. (Reference 2) and is given as

$$H = \exp(15.216 - \frac{5749}{T}) \text{ ft}^3\text{atm/pound mole} , \tag{5}$$

where T is the absolute temperature in degrees Rankine. Further information on estimates of H_L and H_G can be found in a review by Singh and Counce (Reference 5).

The number of transfer units at conditions common to VOC removal is

$$N_{toL} = \int_{x_1}^{x_2} \frac{dx}{x - y/m} , \tag{6}$$

where x_1 and x_2 are the liquid-phase mole fractions exiting and entering the stripper, respectively.

The N_{toL} is estimated in the procedure used here by

$$N_{toL} = \frac{\ln[((x_2-y_1/m)(1-1/S)/(x_1-y_1/m)) + 1/S]}{(1 - 1/S)} , \tag{7}$$

where y_1 is the entering gas-phase mole fraction (usually equal to zero). In its simplest form, the number of transfer units is the change in liquid-phase solute composition divided by the average solute driving force composition.

The design of packed towers usually includes a substantial safety factor to account for uncertainties in the data base. Bolles and Fair (Reference 19) state that the calculated height should be multiplied by 1.7 to achieve 95 percent confidence when using their correlations for H_{toL}.

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The data base for estimation of mass transfer information is often not available for new packings. Advertisement for new packings often gives overall coefficient information; these data, however, usually involve the absorption of CO_2 into caustic solutions in which liquid-phase resistance to mass transfer is minimal and, thus, is inappropriate for general use in the design of air strippers for VOC removal.

In general, inexpensive saddles and slotted rings, which have long been reliably used in industry, appear to be cost-effective for VOC strippers (Reference 20). Specialty random packings, however, are continually being developed and marketed; these packings are usually much more costly than "standard" types of packing. The economics of the use of specialty random packings should be carefully investigated before they are specified and used. The random packing used for the performance and cost estimation in this manual is plastic Flexirings®. The major use of structured packings for VOC stripping appears to be to repack existing towers where greater efficiency or more capacity is required (Reference 20). Another use of structured packings may be to improve situations where minimum space exists for the stripper or where semivolatile components are being stripped.

2. Centrifugal Air Strippers

An alternative to the traditional packed column for countercurrent gas-liquid contact is the centrifugal contactor. A schematic of the centrifugal contactor is shown in Figure 6. The centrifugal vapor-liquid contactor is composed of two major components: the rotating packing and the stationary housing. The liquid phase is fed into the center of the rotating packing and flows outward due to the centrifugal force. After exiting the packing, the liquid phase impacts the housing wall and flows by gravity out of the unit. The vapor phase is introduced into the annular space between the packing and the housing and flows inward due to the pressure driving force. Seals are provided between the rotating packing and the housing to prevent the vapor phase from bypassing the packing. The high shear forces experienced by the liquid phase cause the formation of very thin films and rapid renewal of the interfacial surfaces. The rotation of the packing also causes considerable turbulence in the vapor phase. Both of these factors contribute to efficient mass transfer.

The concepts used to design conventional packed towers can be modified for the design of the centrifugal vapor-liquid contactors. This design is based on tests (Reference 1) of the HIGEE centrifugal contactor that is marketed by Glitch, Inc., of Dallas, Texas. Characteristics of packing material used in these tests are shown in Table 1. In designing a conventional packed tower, the diameter of the tower and the depth of packing are the two variables which need to be determined. Similarly, for the centrifugal vapor-liquid contactor, the cross-sectional area at the inner radius and
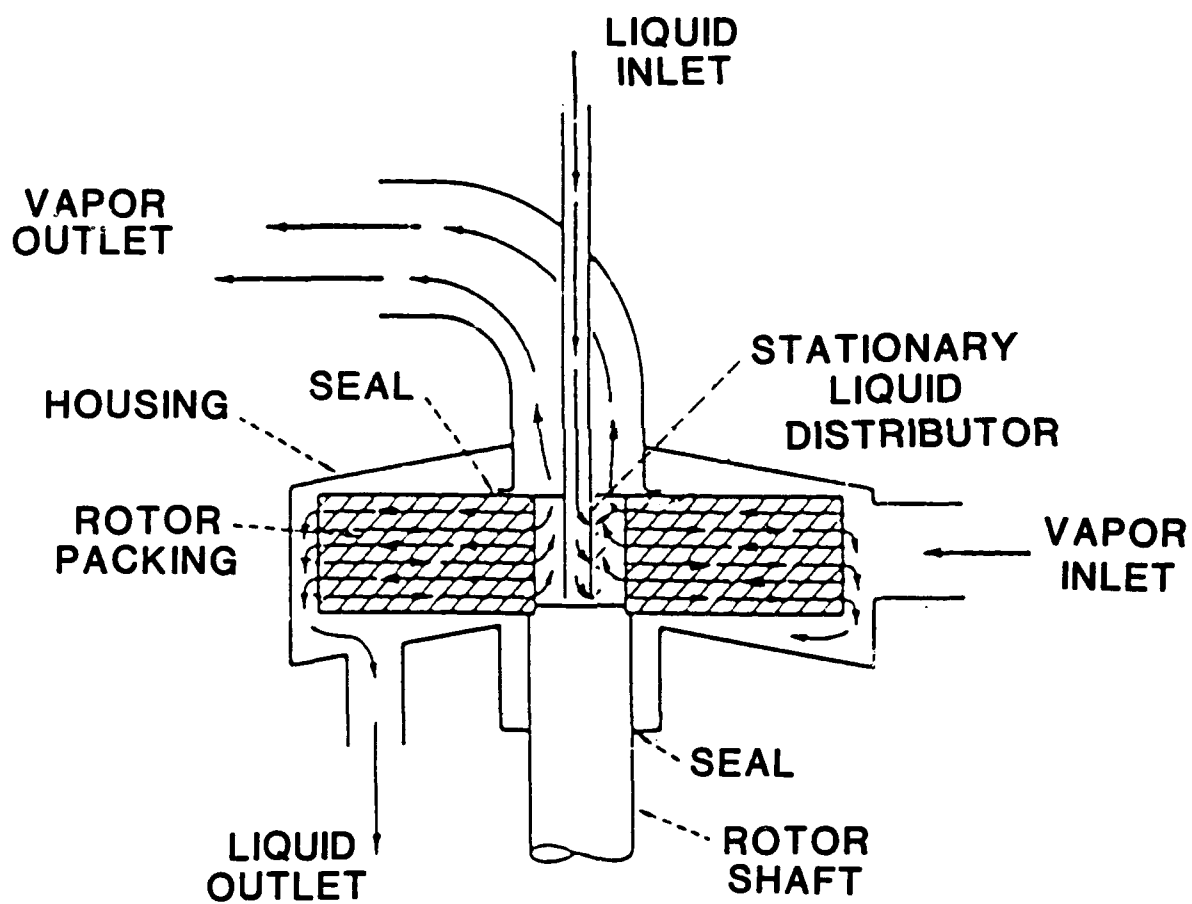
Figure 6.   A Schematic of Centrifugal Vapor-Liquid Contactor.

TABLE 1. CHARACTERISTICS OF PACKING MATERIAL USED IN TESTS OF THE
HIGEE CENTRIFUGAL CONTACTOR (REFERENCE 1)

ROTOR	SPECIFIC SURFACE AREA ft^2/ft^3	VOIDAGE (%)
1	763	95.0
2	630	93.4

Material: 85% nickel, 15% chromium (Sumitomo Electric Industries, Ltd.)

the value of the outer radius are the two critical variables. An additional complexity arises in the design of the centrifugal vapor-liquid contactor because the cross-sectional area at the inner radius can be varied by changing either the radius or the axial length. This results in an iterative design process in which the inner radius, outer radius, and axial length are varied to arrive at an optimum design solution. The maximum inner radius is thought to be approximately 0.66 feet [200 mm]; the minimum is 0.42 feet [127 mm]. The ratio of outer to inner radius should be approximately 2*.

The cross-sectional area required at the inner radius is dependent upon the desired hydraulic capacity. This design of these units should be closely coordinated with the manufacturer. The results of hydraulic capacity tests (Reference 1) are shown in Figure 7, along with the Sherwood correlation. These results indicate that the Sherwood correlation underestimated the limit of operability for the rotational speed in the case of the Sumitomo packing. However, there was good agreement for the wire gauze packing. A second-order polynomial curve fit for the experimental data is also shown in Figure 7. The equation of this curve is:

$$\log Y = -2.274484 - 1.1367\log(X) - 0.168118[\log(X)]^2 , \tag{8}$$

with a coefficient of determination (r^2) of 0.80. The Y and X in this equation are the ordinate and abscissa, respectively, for Figure 7.

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*S. P. Singh, Personal Communication with R. M. Counce, September 1989.
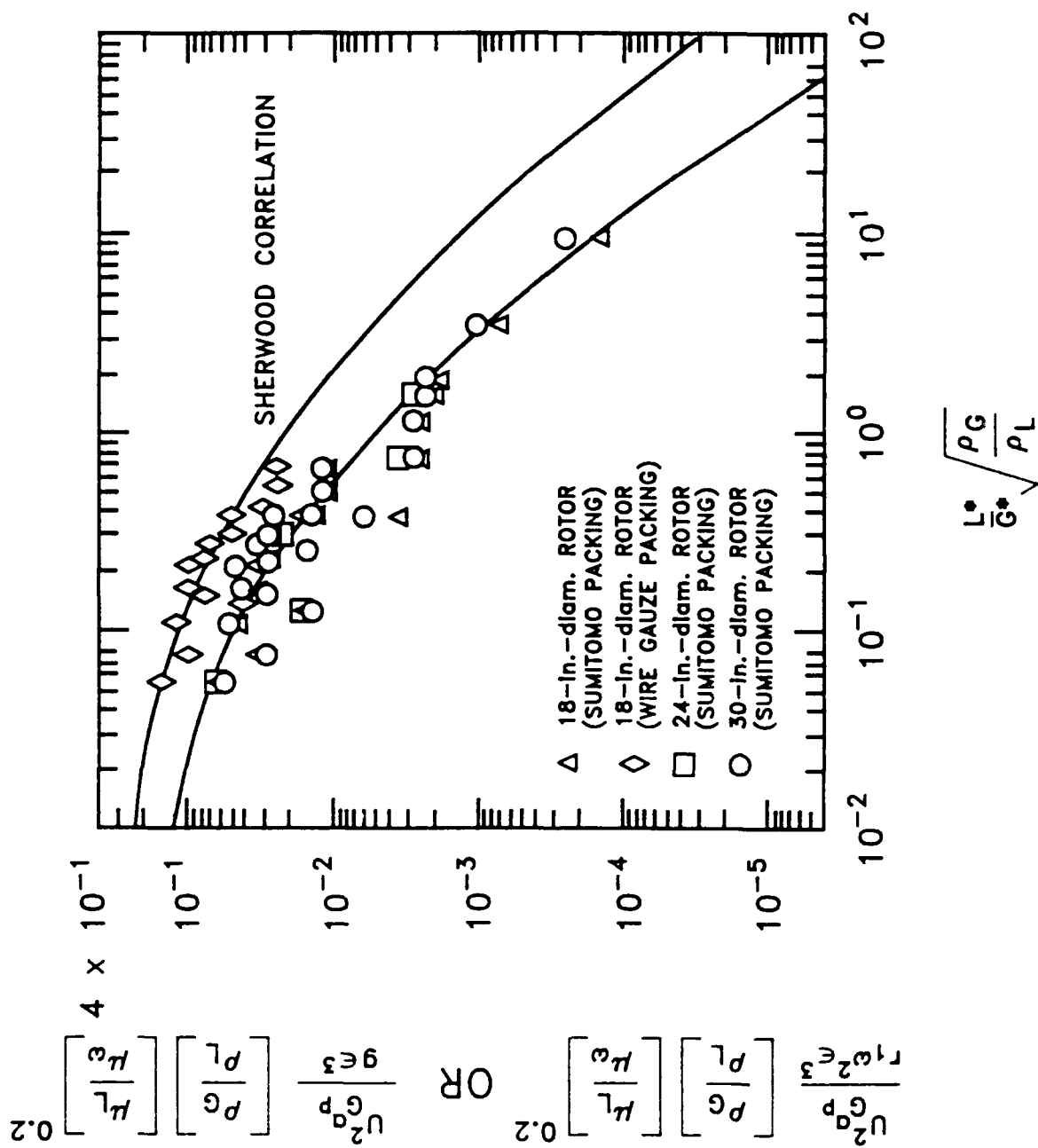
Figure 7.   Comparison of Limit of Operability Data with that Predicted by the Sherwood Flooding Correlation.

The pressure drop across the rotating packed torus of a centrifugal vapor-liquid contactor is modeled as a function of two terms. The first term accounts for the pressure drop due to rotation of the packing, and the second term accounts for pressure drop resulting from the flow of fluids through a porous media:

$$\Delta P_T = 1.356 \times 10^{-5} \rho_G \, \omega^2 (r_2^2 - r_1^2) + 1.458 \times 10^{-5} \frac{a_p}{e} \rho_G (r_2 - r_1) V_{G,avg} \quad \text{atm} \quad , \quad (9)$$

where ρ_G is the gas density in pound/ft^3, ω is the rotational speed in rad/second, r_2 and r_1 are the outer and inner radii in feet, respectively, a_p is the packing specific area in 1/feet, ϵ is the packing void fraction, and $V_{G,avg}$ is the average superficial gas velocity in feet/second. The coefficient of determination (r^2) for the regression fit is 0.94. Although the approach outlined above is a rather simple representation of a complicated system, it does a reasonable job in describing the experimental data and is convenient to use.

The mass transfer results for the HIGEE centrifugal contactor are based on a study by Wilson et al. (Reference 1); a variation of the transfer unit concept was developed by Singh (Reference 21) to represent the results of this study:

$$\pi(r_2^2 - r_1^2) = A_{toL} \, N_{toL} \quad , \quad (10)$$

where the area of an overall liquid-phase transfer unit is

$$A_{toL} = \frac{3.37 \times 10^5}{a_p^2} \, (L^*/\mu_L \, a_p)^{0.6} \, (\rho_L^2 a_c / \mu_L^2 \, a_p^3)^{-0.15} \, ft^2 \quad , \quad (11)$$

where L^* is liquid mass velocity, μ_L is liquid viscosity, ρ_L is liquid density, and a_c is acceleration. The dimensionless groups are the Reynolds number and Grashof number. Although the coefficient of determination (r^2) from regression analysis was only 0.61, the correlation predicts the area of a transfer unit (ATU) within plus or minus 20 percent, which is similar to what existing correlations predict for the conventional packed tower. The above correlation is based on the assumption that the rate of mass transfer is liquid-film controlled. The proposed correlation could be made more general by including the Schmidt number. However, since the Schmidt number in the experimental data remained constant, it may be considered to be part of the coefficient.

Power consumption for a centrifugal vapor-liquid contactor can be modeled using two distinct terms. The first term can be used to account for all the frictional losses and the second term to

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account for the power required to accelerate the liquid entering the packing torus to the rotational speed at the outer radius. The frictional losses are highly dependent upon the design of the machine and cannot be predicted without advanced knowledge of the design. The power required to accelerate the liquid, on the other hand, can be described by a theoretical model (Reference 22). An expression for the overall power consumption was obtained by Wilson et al. (Reference 1). For the three rotors tested, the experimental data for the region where the rotational speed was greater than its limit of operability gave the following equation:

$$P' = 1.22 + 4.64 \times 10^{-5} \, \rho_L r_2^2 \omega^2 \, Q_L \, , \tag{12}$$

where Q_L is the volumetric liquid rate. The coefficient of determination (r^2) for this equation was 0.92. The correlation provides a reasonable prediction of the power consumption over the operating conditions studied by Wilson et al. (Reference 1).

B. EMISSIONS CONTROL

Although air stripping is an effective technology for removing VOCs from groundwater, it simply transfers contaminant from one medium to another. In many cases, the removal of the VOCs from the air may be necessary to reduce the exposure to these chemicals. Emissions control technologies have been used by industries which use solvents or other VOCs in production processes to either recover or destroy these compounds. The three most commonly used techniques for controlling VOCs from air streams are (1) adsorption onto activated carbon, (2) catalytic oxidation, and (3) thermal oxidation. This work focuses on VOC control by means of adsorption onto activated carbon and catalytic oxidation.

1. Activated Carbon

Activated carbon can be produced from petroleum fractions, wood, coconut shells, and coal, and then given treatment by superheated steam to extend the pore network of the particles and to give activated carbon a large surface area.

The use of activated carbon to remove solvents from airstreams is well established and has been employed since the 1930s (Reference 23). The adsorption of the solvent molecules onto activated carbon is mainly due to Van der Waal forces, and no chemical reaction takes place. The adsorption of the VOCs from the gas stream onto the activated carbon bed depends upon (1) type of carbon, (2) relative humidity, (3) temperature, (4) concentration and type of VOC, and (5) regeneration steps used (Reference 24).

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Several equations are available in the literature to describe the adsorption of compounds onto activated carbon. These include the Braunauer-Emmett-Teller (BET), Freundlich, Langmuir, and Dubinin-Radushkevich equations. A commonly used isotherm describing the adsorption of single-component VOCs from gas streams is the Freundlich isotherm,

$$q_i = K_i \, C_i^{1/n_i} \, ,$$ (13)

where q_i is the component loading on the carbon for component i, K_i is the Freundlich coefficient, C_i is the gas-phase concentration, and $1/n_i$ is the Freundlich exponent.

Equilibrium information for gaseous VOCs over activated carbon is difficult to obtain from the open literature. A method for estimation of such information is presented by Crittenden et al. (Reference 25); this method is based on work by Dubinin and Radushkevich (Reference 26):

$$q_i = \left[\frac{W_o \rho_A}{10^{-6}}\right] \exp\left[\frac{-B}{\beta^2}\left(RT \, \ln\frac{P_s}{P_i}\right)^2\right] \, ,$$ (14)

where W_o is the maximum available space on the carbon, ρ_A is the liquid density of the pure adsorbate, T is temperature in Kelvin, B is the microporosity constant, β is the affinity coefficient, and P_i and P_s are the partial and saturation pressures of component i, respectively. The parameters W_o and B are characteristic of the adsorbent. These constants for the reference compound, toluene, adsorbing on a typical carbon are imbedded in the program SPEQ, which is used to estimate Freundlich parameters. This program is included in this manual in Appendix A. The affinity coefficient can be determined from the polarizabilities of the adsorbate and a reference compound by:

$$\beta = \mu/\mu^* \, .$$ (15)

The polarizability of the reference compound is also imbedded in the program SPEQ. The polarizability of any compound can be calculated from the refractive index using the following equation:

$$\mu = [(n^2 - 1)M] \, / \, [(n^2 + 2)\rho_A] \, .$$ (16)

Equation (14) may be used to generate q_i vs C_i information, which may be correlated into the form of the Freundlich equation (Reference 25).

Multicomponent gaseous VOC adsorption equilibria have been estimated by Crittenden et al. (Reference 27), using simplified ideal adsorbed solution theory (IAST). This approach utilizes single-component Freundlich isotherm information to predict loading. The velocity of the loading wave front for single-component adsorption of component i onto activated carbon is expressed as

$$V_{wi} = \frac{V_F C_{oi} \rho_F}{(q_i \rho_C + \rho_F C_{oi} \epsilon)} \quad , \tag{17}$$

where V_{wi} is the wave front velocity, V_F is the fluid superficial velocity, ρ_c is the carbon bulk density, C_{oi} is the influent concentration of i, and ϵ is the carbon void fraction. This reduces to the following equation for most cases:

$$V_{wi} = \frac{V_F C_i \rho_F}{q_i \rho_C} \quad . \tag{18}$$

The wave velocity of the kth component, for $k \geq 2$, of a multicomponent mixture adsorbing onto activated carbon is given by Speth (Reference 28):

$$V_{wk} = \frac{V_F C_{ok} \rho_F - \sum_{j=1}^{k-1} (q_{k,j} \rho_C + C_{k,j} \rho_F \epsilon)(V_{wj} - V_{wj-1}] + (q_{k,k} \rho_C + C_{k,k} \rho_F \epsilon) V_{wk-1}}{(q_{k,k} \rho_C + C_{k,k} \rho_F \epsilon)} \quad . \tag{19}$$

The subscript i,j indicates compound i in zone j, and C_{ok} is the influent concentration of component k; theoretically, there is a zone for each compound in the multicomponent adsorption model. For adsorption of N components, in which the Nth component is the least strongly adsorbed, Equation (19) is the leading wave front for all the adsorbing components when $k = N$. The concentration of the ith species in zone k may be estimated by combining Equation (19) and IAST to give:

$$C_{i,k} = \frac{q_{i,k}}{\sum_{j=k}^{N} q_{j,k}} \left[\frac{\sum_{j=k}^{N} n_j q_{j,k}}{n_i K_i} \right]^{n_i} \qquad i = 1 \text{ to } N \quad , \tag{20}$$

where N is the total number of components. Based on IAST, the ratio of carbon requirements for a given cycle time of a mixture which is composed of components in addition to component i to that of a single component of concentration C_i may be calculated by the ratio ϕ, where

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$$\phi = (V_{wk} / V_{wi})_{C_i} .$$ (21)

Thus, activated carbon requirements for a multicomponent adsorption may be estimated based on single-component isotherm information and the ratio ϕ. Component i should be one of the least strongly adsorbed components, and its inlet concentration C_i should be the same for both wave velocity calculations.

The adsorption of VOCs from the vapor phase can be affected by the relative humidity. This effect can be explained by examining the adsorption mechanism of water from the gas stream. At low relative humidity, the removal of water from the vapor phase is due mainly to adsorption onto the surface of the adsorbent. Due to a relatively low number of hydrophilic sites available on the activated carbon surface, the adsorption of water is fairly low. As the concentration of the water in the vapor phase increases, capillary condensation begins to occur in the pores of the activated carbon and the sites available for direct adsorption of the organic molecules from the vapor phase are reduced. The capillary condensation of water increases the resistance to mass transfer of other components in the pores because the compound must first dissolve in the water and then travel through the water to the adsorption site. The reduction in the adsorption of VOCs from the vapor phase decreases rapidly as the relative humidity rises above 45 to 50 percent (Reference 29). Thus, the lifetime of the adsorption bed can be extended by lowering the relative humidity of the gas stream, which can be accomplished by raising the gas stream temperature. Increasing the temperature too much, however, can also reduce the adsorption capacity. The temperature and relative humidity need to be adjusted to obtain the optimum adsorption capacity. For the calculations in the spreadsheet described in this manual, the gas stream is heated to 100°F.

a. Nonregenerative

In many cases, the amount of activated carbon used for vapor phase removal of VOCs is small enough so that disposal of the spent carbon is a viable economic option. However, other issues need to be considered, such as potential classification of the spent carbon as a hazardous waste. One option available may be the regeneration of the carbon by a commercial vendor, which may be less expensive than on-site regeneration.

b. Regenerative

Steam stripping of activated carbon is a common method of reactivating carbon when the adsorption involves concentrated solvent vapors. Decisions on steam stripping as a method of regeneration are very dependent on whether the condensate from this stripping operation will

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separate into two phases for easy removal of the organic phase. For adsorption of dilute VOC compounds onto activated carbon, the condensate from steam regeneration may not contain sufficient VOCs to form a separate phase and may require treatment of a secondary aqueous phase contaminated with dilute VOCs. To compound these problems, Crittenden et al. (Reference 29) report very high steam requirements for regeneration of activated carbon used in VOC adsorption service. Some estimated on-site costs for large-scale regeneration by multihearth, fluidized-bed, and infrared technologies are reported by Adams et al. (Reference 30). The current availability of fluidized-bed and infrared regeneration technologies is questionable.

2. Catalytic Oxidation

Another type of technology that has been used in industry to control the emission of VOCs in gas streams is catalytic oxidation. In this process, a catalyst is used to promote the oxidation of organic compounds at lower temperatures than required for thermal oxidation. The catalyst increases the rate of the reaction by bringing the reactants together or by lowering the activation energy of the reaction. Approximately 500 to 2000 catalytic oxidation units are used to control the emission of VOCs in various industries (Reference 31).

The performance of a catalytic oxidation unit depends upon temperature, type and concentration of compounds, space velocity (residence time), and type of catalyst. A typical catalytic oxidation unit is usually composed of four basic parts. A preheater is used to bring the incoming gas stream to the required temperature before entering the catalyst bed. This temperature is dependent on, for example, the contaminant concentration in the gas stream, the type of catalyst bed (fixed-bed or fluidized-bed), and the operating temperature of the catalyst bed. After the preheater, a mixing chamber is used to promote uniform temperature of the gas. The catalytic system then follows, which may be a fixed-bed or fluidized-bed system. The catalyst is usually composed of either metal oxides or finely divided precious metal on either a metal or ceramic support structure. The operating temperature of the catalyst bed is determined by the required contaminant destruction efficiency. For the same type of catalyst, some species require higher oxidation temperatures than others. Also, for the same contaminant species, the required oxidation temperature varies with the type of catalyst used. The final part of the catalytic oxidation unit is a heat recovery system, which is optional.

Spivey et al. (Reference 32) conducted a literature review on heterogeneous catalytic oxidation of potential environmentally hazardous compounds. They presented an excellent review on the mechanism of catalytic oxidation reactions and a comparison of metal oxide and precious-metal catalysts. Listed below are some findings presented in their survey report:

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1. Oxides of copper, manganese, cobalt, chromium and nickel are the most active single-metal oxide catalysts.

2. Mixed-metal oxide catalysts generally have higher activity than single-metal oxide catalysts.

3. Metal oxide catalysts are less active than precious-metal catalysts; but the metal oxide catalysts are more resistant to certain poisons, such as halogens, arsenic, lead, and phosphorus.

Palazzolo et al. (Reference 33) studied the destruction of mixtures of the halogenated hydrocarbons shown in Table 2 using fluidized-bed metal oxide catalysts and reported that the overall destruction efficiency varied from 97 to 99 percent for all the mixtures tested. They also noted that the catalyst temperature had the largest effect on the destruction efficiency, while other variables, such as mixture composition, air-to-fuel ratio, space velocity, and inlet concentration, had only a marginal effect on the destruction efficiency. The destruction efficiency of tetrachloroethylene was the lowest of all the compounds tested. The destruction efficiency across the preheater ranged from 15 to 55 percent.

In the study by Wilson et al. (Reference 1), the noble metal catalyst was poisoned almost immediately in field tests. Sulfur compounds were suspected to be the cause of the poisoning of the catalyst.

TABLE 2. MIXTURE COMPOSITIONS AND TARGET CONCENTRATIONS FOR
CATALYTIC OXIDATION TESTS (REFERENCE 33)

MIXTURE DESIGNATION	CONCENTRATION LEVEL	MIXTURE COMPOUNDS	TARGET INLET CONCENTRATION (ppmv)[a]
Mixture 1	Baseline	Trichloroethylene 1,2 dichloroethylene	6.3 8.5 14.8
Mixture 1	Low	Trichloroethylene 1,2 dichloroethylene	1.9 1.0 2.9
Mixture 2	Baseline	Trichloroethylene Benzene Ethylbenzene Pentane Cyclohexane	2.7 1.5 5.6 11.5 14.1 35.4
Mixture 3	Baseline	Vinyl chloride Trichloroethylene	7.5 1.8 9.3
Mixture 4	Baseline	1,2 dichloroethane Trichloroethylene 1,1,2-trichloroethane Tetrachloroethylene	10 10 10 10 40
Mixture 4	High	1,2 dichloroethane Trichloroethylene 1,1,2-trichloroethane Tetrachloroethylene	50 50 50 50 200

[a]ppmv = parts per million by volume of the compound.

SECTION III

EQUIPMENT DESIGN AND SIZING

In this manual, the design of air strippers for removal of soluble jet fuel components from groundwater is based on the removal of benzene. Benzene was chosen because it is an important contaminant and one of the less volatile of the soluble jet fuel VOCs. All of the soluble jet fuel VOCs of higher volatility (higher Henry's coefficient) can be assumed to be removed in the stripper with removal efficiencies at least that of benzene. It is more difficult to generalize stripper removal efficiencies for compounds of lesser volatility; one approach would be to neglect the removal of these compounds for calculation of stripper performance, while accounting for their presence in any prediction of carbon bed loading.

The cost of traditional packed-bed stripper towers is based on their physical size. The spreadsheet developed for this manual determines the size of the stripper from specification of stripping factor, fraction of gas velocity at flooding, and component removal efficiency. The selection of the stripping factor determines the ratio of gas to liquid flow rates for this contacting operation. The selection of the appropriate fraction of flooding (ratio of gas velocity to that at flooding, both at the same ratio of gas to liquid flow rates) determines the tower diameter. The internal computations of tower diameters and pressure drop across the column are based on digitalization of the Eckert flooding and pressure drop diagram as presented by Treybal (Reference 6).

The height of the overall liquid transfer unit is based on calculations of individual gas and liquid transfer units. Computation of the individual liquid and gas transfer units, H_L and H_G, is based on correlations provided by Bolles and Fair (Reference 19). The number of transfer units for a single component is calculated based on inlet and outlet mole fractions of benzene.

The algorithm for estimating the costs of centrifugal air strippers does not involve detailed design of the unit. Design of these units may be accomplished based on information presented earlier. Costing of these units in the developed spreadsheet does not require detailed design.

For application to the cleanup of jet fuel from groundwater, the design of fixed-bed carbon adsorbers is based on that for single-component adsorption of benzene and a correction factor to account for decreased single-component bed loading based on the presence of other soluble jet fuel species. The correction factor used in the spreadsheet calculations was determined from the carbon adsorption studies described in Reference 1. The humidity of the gas stream is assumed to have been reduced to less than or equal to 30 percent by heating prior to adsorption. Values of K_i and $1/n_i$ for

the Freundlich isotherm are difficult to establish for gas-phase service, but may be estimated using the computer program SPEQ developed by R. D. Cortright under the direction of J. C. Crittenden at Michigan Technological University. The theoretical background may be found in a paper by Crittenden et al. (Reference 34). A copy of this program and required input information are provided in Appendix A. This program was used to calculate the Freundlich parameters for benzene, as well as for trichloroethylene (TCE). As discussed later, the spreadsheet program includes the capability for design for cleanup of TCE-contaminated groundwater.

To correct for the presence of multiple competing species (other than water), a computer program, ETMOD, is provided in Appendix B along with a brief discussion and a sample input file, ET.DAT. This program was developed by T. F. Speth, P. H. Luft, D. W. Hand, and J. C. Crittenden; the theoretical background may be found in an article by J. C. Crittenden et al. (Reference 25). The correction factor ϕ (discussed in Section II), which is calculated by the program, accounts for the presence of multiple components and is used to estimate the size of carbon beds for multicomponent systems. In the absence of an experimentally determined correction factor, such as used for benzene in the spreadsheet, the factor ϕ may be used. For example, since the carbon usage rate is proportional to the wave front velocity, a value for ϕ of $2.7029/1.3794 = 1.96$ for n-pentane is calculated from the output results in Exhibit B-2, Appendix B.

The algorithm for calculation of the cost of catalytic oxidation units is a function of gas throughput alone. The fuel expense is a function of the operating temperature of the catalytic oxidation unit. For 90 percent destruction of benzene, an operating temperature of the catalyst bed of approximately 800°F is adequate (Reference 35). A conservative value of 900°F is used in the spreadsheet calculations. Some information on destruction of various gaseous mixtures of VOCs is presented by Tichenor and Palazzola (Reference 36). Proper selection of this operating temperature is critical to the achievement of desired removal efficiencies.

The costs of pumps, as well as operating expenses, are related to the power requirements. The total power requirements for all pumps supplying groundwater are estimated based on the head at the pump discharge. This discharge head, which is largely due to the hydrostatic head Z_T and the head loss due to friction, may be estimated as

$$Z_P' = (g/g_c) Z_T + 2fV^2 Z_L/g_c D \quad , \tag{22}$$

where f is the Fanning friction factor, g is the acceleration of gravity, g_c is the gravitional conversion factor, Z_L is the total length of water piping of diameter D, and V is the water velocity in the piping.

The velocity of water through a well-designed piping system is assumed to be 5 feet/second (Reference 37). A typical valve value of the Fanning friction factor, f, is 0.008. The required total power consumption of the pumps may be estimated as

$$P_B = \frac{L' Z_P'}{3962 \, \eta_P} \, , \tag{23}$$

where L' is the water flow rate in gallons per minute and the efficiency of centrifugal pumps may be estimated as

$$\eta_P = 0.7 \, . \tag{24}$$

The cost of the blower, as well as operating expenses, is also related to the power consumption,

$$P_B = G' \, Z_B'' / \, 6350 \, \eta_B \, , \tag{25}$$

where G' is the volumetric air flow rate in standard cubic feet per minute, $Z_B^{\cdot}$ is the total blower static head in inches of H_2O, and the overall efficiency may be estimated (Reference 38) as

$$\eta_B = 0.70 \, . \tag{26}$$

The head requirements are primarily those due to flow through the relevant major equipment items. The estimation of the gas-phase pressure loss for the traditional packed tower was mentioned earlier. The pressure drop for the centrifugal air stripper is from a correlation presented earlier in Section II. The pressure drops across the catalytic oxidation unit and the activated carbon bed were assumed to be 5 and 4 inches of water, respectively.

SECTION IV

ESTIMATION OF COSTS FOR REMOVAL OF VOCs FROM GROUNDWATER

This section focuses upon the estimation of the cost (in current year dollars/1000 gallons of water processed) of the removal of VOCs from groundwater. The estimation procedure involves the following sequence, all of which is handled on spreadsheets:

1. Engineering design characterization, making use of design algorithms as discussed in the preceding section.

2. Estimation of (1) the fixed capital costs for capital equipment and (2) annual operating costs. All costs presented for this study are adjusted to 1990 dollars using the estimates for the average inflation rate and the average annual real interest rate, as described later. The costs may be accurate to approximately plus or minus 30 percent overall.

3. Use of inputs from these two steps in the operating lifetime analysis to estimate the cleanup costs per 1000 gallons of groundwater processed.

The spreadsheet programs allow for many of the engineering and the financial parameters to be treated as input variables, which, in turn, allows for single-variable sensitivity analysis. Because of this, it is necessary to establish a set of "base case" conditions summarized in Table 3. Some special variations in the base case parameters are identified as part of the subsequent data analyses.

VOC-2.100 is a dual purpose spreadsheet that generates design parameters necessary for estimation of fixed capital and annual operating (noncapital) costs. The design information is then carried over into estimation (in 1990 dollars) of the fixed capital and the annual expense items. A government-owned (break-even, or zero-profit) scenario is stipulated. Thus, there is no consideration of the time phasing between expense and revenue, and working capital need not be included in the cost estimations. The design for cleanup of groundwater contaminated with jet fuel components is estimated using the concentration of benzene in the water and accounting for the presence of other components where necessary, as discussed previously. In addition to the calculations for removal of jet fuel components, VOC-2.100 has the capability to treat cleanup of TCE. For completeness of economic evaluation, calculations are made for catalytic oxidation of off-gas containing TCE. However, it is noted that (1) some catalysts are poisoned by halogens, and (2) an environmental issue exists as to the form in which chlorine is emitted from an oxidation unit.

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TABLE 3. INPUT DESIGN VARIABLES FOR SPREADSHEET (TABLE 1 OF SPREADSHEET VOC-2.100)

DESIGN INPUT TABLE
(Base Case Independent Design Variable Inputs)

General Inputs, Units	Value	Efficiencies	Value
Operating Temperature, Fahrenheit	60	Air Heaters	0.7
Inlet Gas Pressure, Atmospheres	1.00	Air Blowers	0.6
Groundwater Stream		Water Pumps	0.7
Water Feed Rate, Gallons/Minute	500	**Stripper Related Parameters**	
Contaminant Concentration, ppb IN	10000	Groundwater Depth, ft	30
Contaminant Cleanup Factor	0.990	Fanning Friction Factor	0.008
Stripper Tower		Horizontal Pipe Length, ft	100
Stripping Factor	4.0	Consolidated Friction Loss Coefficient for valves, elbows, etc.	15
Packing Information		**Carbon Air Stream Cleanup**	
Packing Size, mm (in)	50(2)	Carbon Recycle Interval, days	7
Packing Factor	20	Carbon Use Safety Factor	1.5
Correlation Factor Term*	1.502	Carbon Bulk Density, lb/ft^3	30
Flooding Factor	0.4	**Catalytic Incineration Air Stream Cleanup**	
Height of Each Packed Bed, ft	10	Catalytic Unit Size Safety Factor	1.5

TABLE 3. DESIGN INPUT VARIABLES FOR SPREADSHEET (TABLE 1 OF
SPREADSHEET VOC-2.100) (CONCLUDED)

Overall Operating Cycle Load Factor (365 days/year = 1.00)	0.85
Cost Parameters	
Equipment Installation Factor (Stripper)	2.20
EIF (Carbon and Catalytic)	1.60
Materials (SS) Factor, STRIPPER	1.70
Fuel Oil, 1990 $/$10^6$ BTU	6.15
Electricity Cost, 1990 $/kwh	0.060
Operations & Maintenance Factor	0.150
Overhead Rate (%) on Expense	100
Average Annual Inflation: 1977-90	0.0484

[*]Treybal (1980).

For operating lifetime financial analyses, the output values of fixed capital costs and of annual
expense from VOC-2.100 are used as inputs to spreadsheet VOC-2.300. This operating lifetime
analysis spreadsheet provides the total dollar cost per 1000 gallons of groundwater processed over
a 20-year equipment lifetime. The cost estimation procedures used are in agreement with guidelines
of the United States General Accounting Office (GAO). The operating lifetime analysis was used
because the estimation of capital and annual operating costs is, by itself, not adequate for the
economic evaluation of a proposed project. The determination of total dollar cost involves
(1) calculating the annual capital and expense costs for each year of operation and (2) summing these
yearly costs. The operating cost for each year of the operating lifetime is calculated using the annual
expense estimate for the base year and adjusting it to the current year with the assumed inflation
rate. Since the assumed depreciation period was 20 years, the annual capital cost is 5 percent of the
total capital costs of the major equipment items. The cost per 1000 gallons of groundwater processed
is then the total current year cost (the sum of the yearly costs) divided by the total amount of
groundwater processed (in thousands of gallons) during the operating lifetime of the air stripping
system.

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The components of the groundwater cleanup systems consist of:

- A packed column stripper or a centrifugal stripper. Included with this unit are the pumps and piping associated with wells to provide access to the groundwater.

- A carbon adsorption system for cleanup of off-gas from the stripper.

- Or, as an alternative, a catalytic oxidation system for cleanup of off-gas from the stripper.

Thus, six equipment configurations are possible. Other key technical design parameters used for the economic studies are summarized as follows:

- Stainless steel construction for the stripper and the submerged pump for the groundwater system, but not for any other unit operations.

- Plastic Flexiring* packing.

- Oil-fired preheating of the off-gas entering the carbon adsorption system to reduce relative humidity and improve adsorption.

- Oil-fired heating of the catalytic oxidation unit.

There are two important observations related to the groundwater cleanup costs: (1) for the entire range of sensitivity analyses evaluated, the cleanup costs are dominated by annual operating costs rather than by fixed capital costs; and (2) the cost of carbon adsorption is sensitive to the concentration of contaminants in the groundwater, whereas the cost of catalytic oxidation is not.

A. ESTIMATION OF THE FIXED CAPITAL COST

The fixed capital costs for grass roots systems are estimated by use of correlation equations from the engineering literature, as summarized in the following subsections. These values are then escalated by use of an equipment installation factor (or Lang factor) to account for additional costs such as installation, instrumentation and controls, yard improvements, piping, electrical, service facilities, etc. The adjusted amount then is the fixed capital cost used for subsequent cost analyses.

1. Equipment Installation Factors

Equipment installation factors in the range of about 1 to 6 are found in miscellaneous sources (References 37, 39, and 40). Explicit values for selected pollution control equipment, however, seem to lie in the range of about 1.6 to 2.5. The base case values used in this study were 2.0 for either of the two strippers, and 1.6 for either of the two air treatment systems. Either or both may, however, be used as input variables.

2. Fixed Capital Investment for Air Stripper and Associated Equipment

a. Stripper Air Fan and Motor

Cost data for air fans from Vatavuk & Neveril (Reference 35) were examined. The cost data, however, are presented in the form of somewhat complex combinations of graphs which are

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difficult to translate into computer algorithms. Therefore, cost values were obtained manually from their graphs as a function of the range of stripper sizes used in this manual. Since the stripper size is characterized in part by water throughput rates, it was possible to generate the following correlation:

$$C_t = F_M * 1000 * [L'/30]^{0.4} \ , \tag{27}$$

where C_t is the cost in 1977 dollars of the air fan and motor, F_M is the applicable materials factor, and L' is the water flow rate in gallons per minute.

b. Water Pump and Motor

Corripio et al. (Reference 41) use multiple equation sets for cost estimation purposes; these multiple sets are somewhat awkward to install into a spreadsheet. A few cost values were manually calculated from their sets of equations. A log-log scaling plot was then evaluated, and the following cost correlation equation was generated for a submersible centrifugal pump with a stainless steel head:

$$C_t = 1.7 * 4040 \ (L'/1440)^{0.7} \ , \tag{28}$$

where C_t is the cost of pump and motor in 1977 dollars.

The scaling factor of 0.7 is consistent with median values for many equipment systems (Reference 37). In the absence of any data for the scaling factor, a common approach is to estimate on the basis of 0.6.

c. Stripper Shell

The weight, W_s, of the total stripper shell and structural accessories was estimated on the assumption of 0.25-inch steel construction.

The C_t (Reference 42) in 1977 dollars was then estimated as:

$$C_t = C_B F_M \ , \tag{29}$$

where

F_M = 1.0 for carbon steel, 1.7 for stainless steel,

C_B = $\exp\{6.329 + 0.18255(\ln W_s) + 0.02297(\ln W_s)^2\}$,

W_s = $1.1 \ \pi \ D_i \ Z' \ T_s \ \rho_{cs}$.

d. Plastic Pall Rings

The cost of plastic Pall rings in 1990 dollars is:

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$$C_p = \$11.00/ft^3 \quad (1\text{-}inch \; plastic \; Flexirings) \tag{30}$$

$$C_p = \$5.50/ft^3 \quad (2\text{-}inch \; plastic \; Flexirings) \tag{31}$$

$$C_p = \$3.50/ft^3 \quad (3\text{-}inch \; plastic \; Flexirings) \tag{32}$$

3. Fixed Cost of Emission Control Equipment Utilizing Activated Carbon Adsorption

The size chosen for the carbon adsorption units affects the initial capital costs, the recycle interval (the length of time between regenerations), and the operating expenses. In order to size the carbon units, the number of days in a recycle interval was set up as an input variable in the spreadsheet. This allows calculation of a carbon unit size for whatever other technical specifications may have been input for costing purposes. One additional carbon unit is specified for standby and to minimize downtime during recycle. The initial purchase requirement for the carbon load is then determined by the size and number of carbon adsorption units.

The cost of the carbon units for the basic unit, fans, motors, and controls, exclusive of the initial carbon load itself, (Reference 43) is

$$C_t = F_M(3.32 \; W_c \cdot 36{,}400) \; , \tag{33}$$

where

C_t is the cost in 1977 dollars,

$W_c = 2 \; M_s \theta_c / q_w$,

$10{,}000 \leq W_c \leq 200{,}000$,

$F_M = 1.0$ (carbon steel).

The cost of the initial carbon bed load is based on the 1977 cost of carbon at $1.00/pound.

4. Fixed Costs of Emission Control Equipment Utilizing a Catalytic Oxidation Unit

Vatavuk and Neveril (Reference 35) provide a nonlinear correlation equation for catalytic oxidation units. In the size range of interest to this study, however, a good linear fit can be made to that portion of their Figure 4 of interest. For "packaged units" (which includes preheater, blower, etc.), the cost is

$$C_t = 2.25 \; G' + 24{,}000 \; , \tag{34}$$

where G' is the air flow rate in standard cubic feet per minute and C_t is in 1979 dollars.

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5. Fixed Capital Investment Cost for Centrifugal Contactor

Actual purchase prices for two centrifugal contactor units were available for 50 and 1000 gallon per minute capacities*. Log-log scaling gave the centrifugal contactor cost as

$$C_t = 189,000 \ (Q_L/2.23)^{0.31} \ , \tag{35}$$

where Q_L is the liquid flow rate in cubic feet per second and C_t is in 1990 dollars. This equation holds for $0.11 \leq Q_L \leq 2.23$. The cost figures supplied were for complete systems, including packing.

B. ESTIMATION OF OPERATING EXPENSE COSTS

1. General Assumptions for Inflation and Interest Rates

The average annual inflation rate for the 1977-1988 period in the chemicals industries has been 4.84 percent. This is a compound average of the Chemical Engineering and the Marshall & Swift annual inflation indices (provided monthly in Chemical Engineering journal). In all cases, that annual rate has been used to adjust older price bases forward to 1990 dollars.

Annual interest generally is related to annual inflation. Twenty or more years ago, applied interest rates tended to be approximately 3 percent higher than the inflation rate; i.e., the "real interest" rate was averaging around 3 percent annually. During the late 1970s, the real interest rate rose substantially. Over the past decade, it has been moving generally back down to the vicinity of 5 percent (Reference 44). A 5 percent annual real interest rate was used throughout this study, although it is treated as an input variable and other values can also be examined. The combination of the real interest rate and the inflation rate leads to an applied interest rate of slightly less than 10 percent annually as the base case.

2. General Assumptions for Overhead Rates

Cost estimation for overhead rates may well generate more diverse opinion than any other. Both a single rate/single base (References 44, 45, 46, and 47) and a multiple rate/multiple base method were evaluated. The maximum spread between the two methods was about plus or minus 10 percent, although the overall uncertainty of the total analysis may well be plus or minus 25 percent (Reference 37). Thus, it was felt that the more complex multiple-rate method was not warranted and the bulk of the evaluation was done with the single rate/single base method.

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*S. P. Singh, Personal Communication with R. M. Counce, September 1989.

In general, a high overhead of 100 percent, shown as an input variable of Table 3, was used for either the packed column stripper or the centrifugal contactor. This was done because, in all cases, all of the direct labor is loaded into the expense base for the stripper unit, as discussed below. A lower rate of 25 percent was applied to the two air treatment systems.

3. Fuel and Electricity Costs

The annual fuel and electricity requirements are provided by the design portion of the spreadsheet.

The fuel costs involve the assumption that the air stream will be preheated using No. 2 oil as the energy source. For the carbon adsorption unit, the air is preheated to 100°F. This preheating is to reduce the relative humidity of the stream and thereby improve the performance of the carbon adsorption system. For the catalytic oxidation unit, the air is preheated to 900°F.

Both fuel and electrical power costs vary around the country. The base-case values used here are typical of current costs in the southeastern United States in 1990; however, they are provided as input variables.

4. Charcoal Regeneration

The regeneration of charcoal is a major component of the annual expense base for the carbon adsorption units. This expense may be estimated by

$$E_R = 0.77 - 1.94 \left(\frac{W_c'}{10}\right) + 2.81 \left(\frac{W_c'}{10}\right)^2 - 1.38 \left(\frac{W_c'}{10}\right)^3 , \tag{36}$$

where E_R is in dollars per pound of carbon regenerated. This correlation expression was generated by curve fitting to the graphical information of Adams et al. (Reference 30) for the multihearth method of carbon regeneration. The authors indicate that the regeneration cost estimates allow for 25 percent excess capacity, about 12 percent carbon replacement during each regeneration, and for all other related costs.

5. Maintenance

Annual maintenance costs in the range 5 to 15 percent of the fixed capital investment are commonly quoted (References 37 and 39). This wide range is simply indicative of the actual wide range of true maintenance costs.

Because of such uncertainties, the maintenance cost is handled as an input variable in Table 3. A typical value is the median of 10 percent.

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6. Pall Ring "Maintenance"

Total replacement on a 4-year cycle was assumed, which leads to an annual replacement cost equal to 25 percent of the initial investment cost.

7. Labor

One full-time equivalent (FTE) engineering technician level at $24,000/year direct salary in 1990 dollars was assumed. This is somewhat higher than suggested by Neveril (Reference 39), but the higher work load was used here as a conservative approach. No labor is loaded onto the two air treatment systems. All labor is loaded onto the stripper for all technical options.

C. TECHNICAL COMBINATIONS OF EQUIPMENT

Six technical configurations were considered in this study, as shown below:

Packed-column stripper	ALONE
	PLUS carbon adsorption treatment
	PLUS catalytic oxidation
Centrifugal Contactor	ALONE
	PLUS carbon adsorption treatment
	PLUS catalytic oxidation

Both fixed capital and expense components of the processing costs were presumed to be linearly additive for any combination of the applicable unit operations. More information on capital and operating costs for these options is found in Wilson et al. (Reference 1).

D. ESTIMATION OF CLEANUP COSTS BY OPERATING LIFETIME FINANCIAL ANALYSIS

As described above, the capital and annual operating expense costs from VOC-2.100 are input into VOC-2.300 to calculate the total cost per 1000 gallons of groundwater processed over a 20-year depreciation period. The operating period is also assumed to be 20 years in the example results presented later. By changing inputs to the spreadsheet (per the instructions in Section V), the effects of independently varying the depreciation period and the operating period may be examined. For

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example, the operating period could be 5 years with the same depreciation period of 20 years. The processing costs will be seen to decrease, primarily because the effect of inflation on expense costs is less for the shorter time. If the depreciation and the operating periods are set to the same value, the capital cost will become a greater fraction of the total cost as the depreciation/operating period decreases.

SECTION V

INSTRUCTIONS FOR USE OF COST-ESTIMATING SOFTWARE

This section presents the instructions for using the cost-estimating software (available from Tyndall AFB, as detailed later). One software program may be used to generate capital and operating expense cost estimates for air stripping with emissions control processes. These estimates may then be input into the operating lifetime financial analysis program to produce estimates of the cleanup costs per 1000 gallons of groundwater processed.

In the following operational/procedural instructions, it is assumed that the user is generally familiar with spreadsheets, and specifically familiar with the MS Multip'an series of spreadsheets. For more explicit information on the spreadsheet software, refer to user manuals or to third party "user texts."

PRECAUTIONARY NOTE: The spreadsheets written for this project are in MS Multiplan Version 2.01. They may be "upward loaded" into Version 3.0 or 4.0, simply by using the TRANSFER LOAD sequence. In the process of upward loading, however, the spreadsheet will be rewritten to the disk in the higher version number and the lower version number will be lost. Thus, before executing an upward load, a backup copy in the original version number should first be made. The spreadsheet may also be exported into MS EXCEL. Refer to the MS EXCEL user manual for proper instructions. The spreadsheet may be exported into LOTUS 123; however, significant portions of the math and logic structure may be lost in the process. LOTUS and Multiplan do not use fully compatible logic, math, and naming protocols, and major portions of these may have to be rewritten if transferred to LOTUS.

The design and cost-estimating routines, as presented in the following Sections A and B, generate estimates of the fixed capital costs and of the annual operating expense costs in terms of the start-up year. These data are a necessary but not a sufficient set of information for system evaluation. For proper comparison of alternative systems, it is necessary to make use of operating lifetime analysis information, as in Section C.

A DESIGN AND COST ESTIMATING, WITHOUT SENSITIVITY ANALYSIS

A printout of the design and cost-estimating spreadsheet program, VOC-2.100, is shown in Appendix D. The variables in the spreadsheet are identified in Appendix C.

The first 12 tables of VOC-2.100 are set up to handle requisite design calculations. Seven tables, D-D1B through D-D7B, handle the cost estimating and summaries for the jet fuel spill case. As

described previously, the design is based on benzene, with factors applied as necessary to simulate the behavior of a mixture of jet fuel components. Seven other tables, D-D1T through D-D7T, handle the cost-estimating and summaries for a TCE spill case. There are 39 possible input variables, as identified in Appendix C. All inputs to the spreadsheet should be made in Table D-1.

The following instructions assume that VOC-2.100 has been loaded into MS Multiplan using the **TRANSFER LOAD** sequence. Brackets, [ ], are used to indicate variable names. When entering variable names into the spreadsheets, do NOT enter the brackets.

Before making any changes to inputs, one should temporarily suppress recalculations:

OPTIONS	RECALC	NO

When RECALC is set to NO, ITERATION can be set to YES or NO.

To locate any desired input variables of Table D-1 (or any named variables, ranges, or areas anywhere in the spreadsheet), use the GOTO NAME sequence. Using this sequence, set the variable [VNUM] equal to zero to suppress the sensitivity analysis:

GOTO	NAME	[VNUM]	0

Again using the GOTO NAME sequence, enter the appropriate alpha or numeric information for the variables of interest in Table D-1. For example,

GOTO	NAME	[WGM]	1000

will set the groundwater flowrate to 1000 gallons per minute. After setting values for the variables of interest, make certain that no variable has been set to [VAR]. Do this by checking the information in each cell in each of the two columns with the heading VALUE in Table D-1. If a variable has been set to [VAR], enter the appropriate alpha or numeric information. The spreadsheet may now be run by resetting RECALC and ITERATION:

OPTIONS	RECALC	YES	ITERATION	YES

The spreadsheet will run and generate a single set of outputs for the set of input variables as specified in Table D-1. Table D-2 summarizes those inputs plus some additional "derived values."

Any or all of the 26 tables of the spreadsheet, any range, or any single variable value may then be printed by

PRINT	OPTIONS

with the table, range, or variable specified by NAME and with other parameters, such as margins, etc., specified through the spreadsheet print menu.

B. DESIGN AND COST ESTIMATING, WITH SENSITIVITY ANALYSIS

The spreadsheet is set up to provide the option of automatic iteration through any specified sequence of values of any single numeric input variable found in Table D-1. Because of the logic structure involved in "table building" in this case, the run time will be approximately 20 minutes for an IBM XT-generation machine. The run time will be approximately 1.5 minutes for a 386-generation machine.

To perform a single-variable sensitivity analysis, proceed as already outlined above. However, before initiating calculations by resetting RECALC to YES, the following additional steps must be carried out. First, go to the variable [VI] using the GOTO sequence:

GOTO	NAME	[VI]

Enter, as an alpha entry, using the naming notation of the Table D-1, the NAME of the input variable for which the sensitivity analysis is to be performed. For example, if the groundwater flowrate is the variable of interest, then:

ALPHA	[WGM]

Enter numeric values for the next three variables, [VIN], [VSTEP], and [VNUM]. These entries will then control:

- the initial numeric value of the variable,
- the incremental value for each iteration of the sheet, and
- the total number of values to be run (maximum number for [VNUM] is 15).

Finally, before initiating calculations, the variable for which the sensitivity analysis is being done must be set to [VAR] using the VALUE command. For example, if [WGM] is the variable of interest:

GOTO	NAME	[WGM]	VALUE	[VAR]

As in the previous section, make certain that all <u>other</u> input variables in Table D-1 have been set to an appropriate numeric or alpha value, and <u>NOT</u> to [VAR]. When all variable entries are complete, initiate calculations by:

OPTIONS	RECALC	YES	ITERATION	YES

The 14 cost tables contained in Appendix D contain an illustrative sensitivity run. These tables will automatically clear and reset themselves if one subsequently wishes to run a different sensitivity analysis.

C. OPERATING LIFETIME FINANCIAL ANALYSIS

A complete illustrative printout of the program spreadsheet VOC-2.300 is provided as Appendix E. This spreadsheet is used for operating lifetime financial analyses. General procedures (i.e., the initial suppression of recalculations, subsequent printing) are the same as outlined previously.

For calculation of the processing cost per 1000 gallons of groundwater with VOC-2.300, the values for capital and operating expense costs obtained from running VOC-2.100 are used. As described previously, running VOC-1.00 without sensitivity analysis will generate one set of capital and operating expense costs, while running with sensitivity analysis can generate up to 15 sets of costs.

To run VOC-2.300 for a particular set of capital and operating expense values, first set RECALC to NO. Then, in Table E-1, enter the value for the capital cost by:

GOTO	NAME	[F]	CAP

where CAP is the numeric value for capital cost. Next, enter the operating expense cost by:

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GOTO	NAME	[E]	EXP

where EXP is the numeric value for the initial year operating expense cost. Finally, enter in Table E-1 any other numerical changes/inputs that you wish to have apply to the equipment system construction phase.

In Table E-4, set the groundwater pumping rate (in gallons per minute) to the value that corresponds to the set of capital and operating expense costs that was input in Table E-1:

GOTO	NAME	[WPR]	RATE

where RATE is the numeric value of the pumping rate. The variable [M], the number of operating years, may be set to some other value less than 20 years (the spreadsheet is set up for a maximum of 20 years), if desired. Values for other variables in Table E-4 may be entered, except for those values which are derived from previous inputs. The spreadsheet may now be run by:

OPTIONS	RECALC	YES	ITERATION	NO

since no iteration is required for the calculations of VOC-2.300.

When calculations are completed, the processing cost information may be obtained from Table E-8 of the spreadsheet. The total processing cost per 1000 gallons on a cashflow basis is found in Row 8, Column 68. On a depreciation basis, the total processing cost is found in Row 19, Column 68. The individual contributions to the total cost of the operating expense and the fixed capital depreciation are found in Row 13, Column 68 and Row 16, Column 68, respectively.

D. EXAMPLES OF DESIGN AND COST ANALYSIS RESULTS

The information presented in this section was generated by (1) running spreadsheet VOC-2.100 to perform design and cost estimation with sensitivity analysis to produce estimates of initial fixed capital cost and initial year expense cost and (2) running spreadsheet VOC-2.300, using the estimated costs from Step (1) as input, to produce the operating lifetime cost estimates. In Step (1), sensitivity analyses were performed for three variables: groundwater flow rate, stripping factor, and flooding factor. Air stripping of TCE (trichloroethylene) from groundwater was considered, where the base-case conditions were (1) 99 percent removal efficiency, (2) a stripping factor of 4, (3) a flooding

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factor of 0.4, and (4) 10 ppm of TCE in the groundwater. Figures 8 through 10 show the dollar cost per 1,000 gallons of groundwater processed as a function of groundwater flow rate, stripping factor, and flooding factor, respectively. Included on each figure are the results for the three different cases of (1) air stripping only, (2) air stripping with carbon adsorption, and (3) air stripping with catalytic oxidation.

Figure 8 demonstrates the economy of scale; the processing cost decreases with increasing water flow rate or, in effect, the size of the equipment. There is little difference between the packed stripper and the centrifugal contactor costs. As expected, the costs for the two cases with emissions control are significantly higher than for air stripping alone. For TCE, the carbon adsorption and the catalytic oxidation emissions control options produce approximately the same processing costs as a function of water flow rate. With higher concentrations of contaminant in the groundwater, the carbon cost will increase due to the higher carbon usage while the catalytic oxidation cost will be essentially unaffected. This may be seen in Wilson et al. (Reference 1), where cases are presented for different concentrations of jet fuel in groundwater.

In Figure 9, the processing cost for air stripping alone is relatively insensitive to stripping factor. However, for carbon adsorption and catalytic oxidation, the cost increases with increasing stripping factor. In the case of catalytic oxidation, the cause of the increasing cost is the larger size of the oxidation unit required as the air flow rate increases. For carbon adsorption, the capacity of the bed decreases with increasing air flow rate as a result of the lower concentration of the contaminants in the effluent air from the stripper. Figure 10 shows that, in all three cases, the processing costs are independent of flooding factor for all practical purposes.

As pointed out in Section V.A, there are 39 input variables to the cost estimation spreadsheet which may be examined for their impact upon the cost of the air stripping systems. Examples of the effects of three of these variables have been presented here. In Appendix E, results from single variable sensitivity analyses are given for installation factor, contaminant removal efficiency, the applied overhead rate, and the carbon regeneration interval.

The spreadsheets described here should be very useful for the evaluation of competing alternatives for groundwater cleanup. Quite often, the choice between alternatives is made on the basis of competitive bids for the installed capital equipment system, i.e., the low bidder on equipment. However, as may been seen in the detailed analyses presented in the Appendix, one should not overlook the significant effect of the operating expense in determining the true cost of cleanup operations.
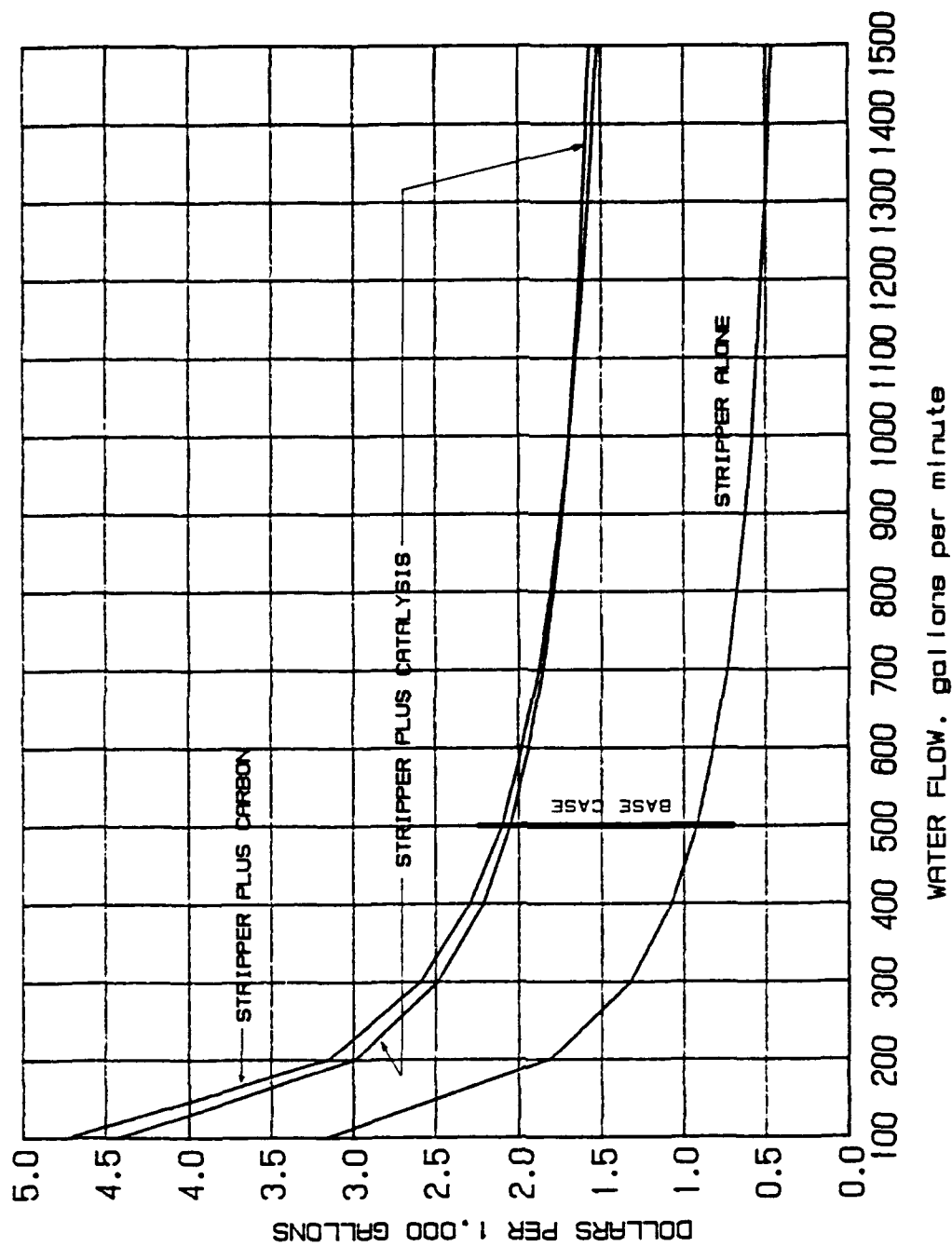
Figure 8. Processing Cost vs Water Flow Rate ior TCE Cleanup.

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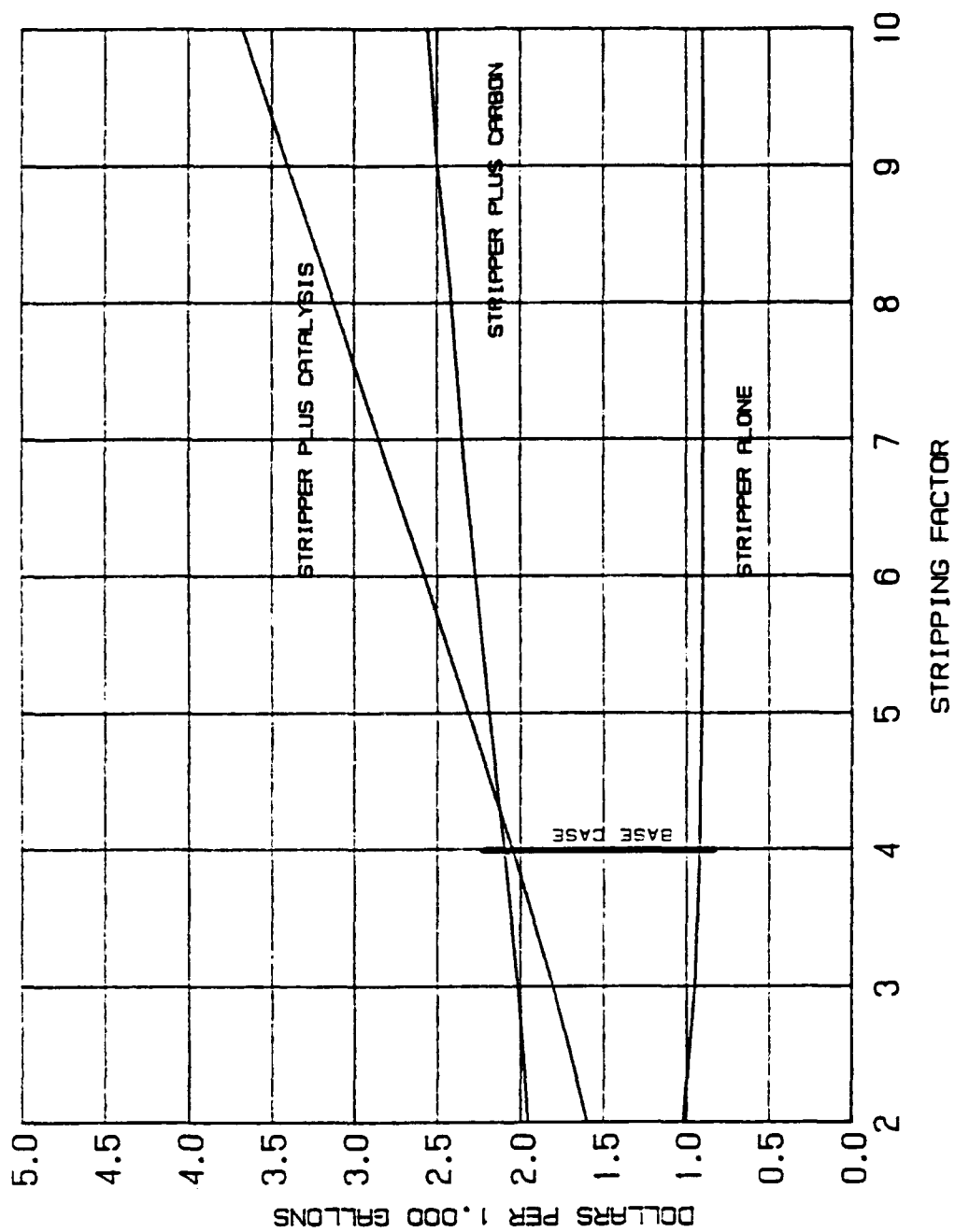
Figure 9.   Processing Cost vs. Stripping Factor for TCE Cleanup.

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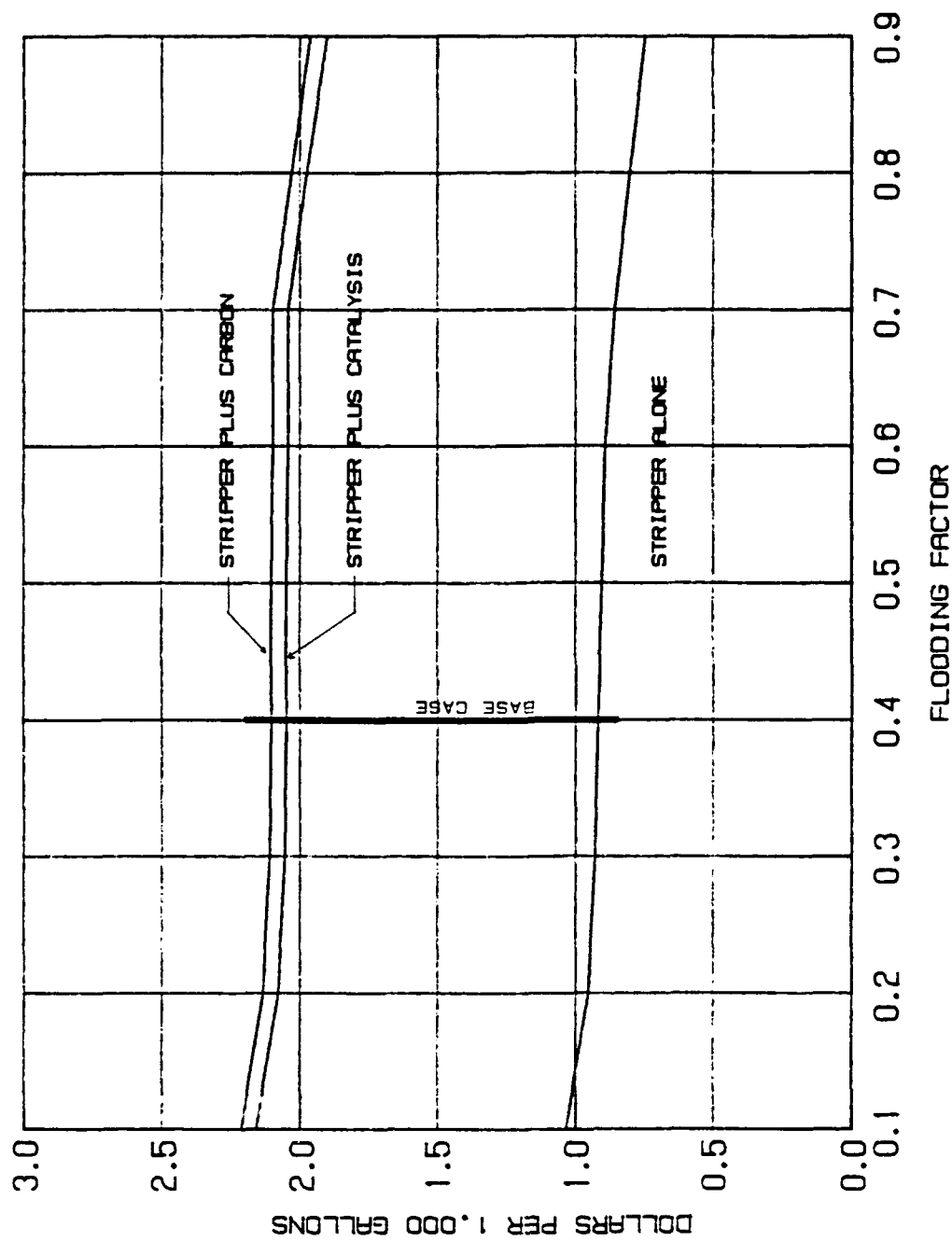
Figure 10. Processing Cost vs. Flooding Factor for TCE Cleanup.

Copies of the VOC-2.100 and VOC-2.300 spreadsheets are available from the Chemical/Physical Treatment Technology Area Manager, HQ AFESC/RDVW, Tyndall AFB, FL. Include a diskette with your request.

SECTION VI

CONCLUSIONS

The spreadsheet-based model developed and described herein can be readily utilized by Air Force personnel for the evaluation and selection of an air stripping with emissions control technology for the remediation of VOC contaminated groundwater. If desired, the correlations for design and cost estimations can be updated as new information becomes available. By varying financial input parameters, such as depreciation period, interest rates, etc., different scenarios may be evaluated for particular operating conditions of groundwater flowrate, contaminant concentration, etc.

REFERENCES

1. Wilson, J. H., Counce, R. M., Lucero, A. J., Jennings, H. L., and Singh, S. P., <u>Air Stripping and Emissions Control technologies: Field Testing of Countercurrent Packings, Rotary Air Stripping, Catalytic Oxidation, and Adsorption Materials</u>, ESL TR 90-51, Air Force Engineering and Services Center, Tyndall Air Force Base, Florida, 1991, in preparation.

2. Ashworth, R. A., Howe, G. B., Mullins, M. E., and Rogers, T. N., "Air-Water Partitioning Coefficients of Organics in Dilute Aqueous Solutions," <u>J. Haz. Mater.</u>, p 25, 1988.

3. Mackay, D. and Shiu, W. Y., "A Critical Review of Henry's Law Constants for Chemicals of Environmental Interest," <u>J. Phys. Chem. Ref. Data</u>, Vol. $10(4)$, pp 1175-1199, 1981.

4. Code of Federal Regulations, 40 CFR Part 300.

5. Singh, S. P. and Counce, R. M., <u>Removal of Volatile Organic Compounds from Groundwater: A Survey of the Technologies</u>, ORNL/TM-10724, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1989.

6. Treybal, R., <u>Mass Transfer Operations</u>, McGraw-Hill Book Company, New York, 1980.

7. Chopey, N. P. and Hicks, T. G., <u>Handbook of Chemical Engineering Calculations</u>, McGraw-Hill Book Company, New York, 1984.

8. Fair, J. R., Steinmeyer, D. E., Penny, W. R., and Croker, B. B., "Liquid-Gas Systems," <u>Chemical Engineer's Handbook, Sixth Edition</u>, Section 18, (R. H. Perry, D. W. Green, and J. O. Maloney, editors) McGraw-Hill, New York, 1984.

9. Eckert, J. S., "Design Techniques for Sizing Packed Towers," <u>Chem. Eng. Prog.</u>, Vol. 54, pp 57-59, 1961.

10. Strigle, R. E., Jr., <u>Random Packings and Packed Towers, Design and Applications</u>, Gulf Publishing Co., Houston, 1987.

11. Bravo, J. L., et al., "Mass Transfer in Gauze Packings," <u>Hydrocarbon Proc.</u>, Vol. 65(3), pp 91-95, 1985.

12. Selby, G. W. and Counce, R. M., "Aqueous Scrubbing of Dilute NO_x Gas Mixtures," <u>Ind. Eng. Chem. Res.</u> Vol. 27(10), pp 1917-1922, 1988.

13. Lucero, A. J., Wilson, J. H., Counce, R. M., Singh, S. P., Ashworth, R. A., and Elliott, M. G., "Air Stripping of VOC from Groundwater Using Towers Filled with Structured Packing," Paper presented at AIChE 1990 Spring National Meeting, Orlando, Florida, 1990.

REFERENCES
(CONTINUED)

14. Perry, R. H., and Chilton, C. H., <u>Chemical Engineer's Handbook</u>, 5th. ed., McGraw-Hill Book Company, New York, 1984.

15. Kunesh, J. G., Lahm, L., and Yanagi, T., "Commercial Scale Experiments That Provide Insight on Packed Tower Distributors," <u>Ind. Eng. Chem. Res.</u>, Vol. 26, pp. 1845-1850, 1987.

16. Kunesh, J. G., "Practical Tips on Tower Packing," <u>Chem. Engr.</u> Vol. 94(18), pp. 101-105, 1987.

17. "Distillation," Fair, J. R., Chapter 5 of <u>Handbook of Separation Process Technology</u> (R. W. Rousseau, Ed) Wiley and Sons, New York, 1987.

18. Norton Company, "Design Information for Packed Towers," Bulletin DC-11, Norton Company, Akron, Ohio, 1971.

19. Bolles, W. L. and Fair, J. R., "Improved Mass-Transfer Model Enhances Packed-Column Design," <u>Chem. Eng.</u>, Vol. 78, pp 109-116, 12 July 1982.

20. Hill, J. H., "Packings for VOC Stripper Columns," paper presented at 1987 AIChE Annual Meeting, New York, New York, 1987.

21. Singh, S. P., <u>Air Stripping of Volatile Organic Compounds from Groundwater: An Evaluation of a Centrifugal Vapor-Liquid Contactor</u>, Ph.D. Dissertation, University of Tennessee, 1989.

22. Leonard, R. A., <u>Prediction of Hydraulic Performance in Annular Centrifugal Contactors</u>, Argonne National Laboratory, ANL-80-57, July 1980.

23. Metcalf & Eddy, Inc., <u>Wastewater Engineering: Treatment, Disposal, Reuse</u>, McGraw-Hill, Inc., New York, 1979.

24. Foster, M. L., "Evaluation of Parameters Affecting Activated Carbon Adsorption of a Solvent-Laden Air Stream," paper presented at the 78th Annual Meeting of the Air Pollution Control Association, Detroit, Michigan, June 1985.

25. Crittenden, J. C., Speth, T. F., Hand, D. W., Luft, P. J., and Lykins, B., "Evaluating Multicomponent Competitive Adsorption in Fixed Beds," <u>J. Environ. Engr.</u>, Vol. 113(6), p 1363, December 1987.

26. Dubinin, M. M. and Rudushkevich, L. V., <u>Dokl. Akad. Nauk. SSSR</u>, Vol. 55, p 331, 1947.

27. Crittenden, J. C., Luft, P., Hand, D. W., Oravitz, S. W. Loner, and Arl, M., "Multicomponent Adsorption Equilibria Using Ideal Adsorbed Solution Theory," <u>Environ. Sci. & Technol.</u>, Vol. 19, p 1037, 1985.

REFERENCES
(CONTINUED)

28. Speth, T. F., <u>Predicting Equilibria for Single and Multicomponent Aqueous Phase Adsorption Onto Activated Carbon</u>, Master's Thesis, Michigan Technol. Univ., Houghton, Michigan, 1986.

29. Crittenden, J. C., Cortright, R. C., Rick, B., Tang, S.-R., Perram, D., "Using GAC to Remove VOCs from Air Stripper Off-Gas," <u>J. AWWA</u>, p 73, May 1988.

30. Adams, J. Q., Clark, R. M., Miltner, R. J., "Controlling Organics with GAC: A Cost and Performance Analysis," <u>J AWWA</u>, pp 132-140, 1989.

31. Jennings, M. S., Krohn, N. E., and Berry, R. S., <u>Control of Industrial VOC Emissions by Catalytic Incineration: Volume 1, Assessment of Catalytic Incineration and Competing Controls</u>, EPA-600/2-84-118a, Washington, D.C., July 1984.

32. Spivey, J. J., Tichener, B. A., and Ashworth, R. A., <u>Catalytic Oxidation of VOCs: A Literature Review</u>, Research Triangle Institute, Research Triangle Park, North Carolina, 1987.

33. Palazzolo, M. A., Jamgochain, C. L., Steinmetz, J. I., and Lewis, D. L., <u>Destruction of Chlorinated Hydrocarbons by Catalytic Oxidation</u>, EPA-600/2-86-079, Washington, D.C., September 1986.

34. Crittenden, J. C., Regg, T. J., Perram, D. L., and Tang, S. R., "Predicting Gas Phase Adsorption Equilibria of Volatile Organics and Humidity," <u>J. Environ. Engr.</u>, (in press).

35. Vatavuk, W. M. and Neveril, R. B., "Estimate the Size and Costs of Incinerators," <u>Chem. Engr.</u>, Vol. 89(14), pp 129-132, 12 July 1982.

36. Tichenor, B. A. and Palazzolo, M. A., "Destruction of Volatile Organic Compounds via Catalytic Incineration," <u>Environ. Prog.</u>, Vol. 6, (3), p 172, August 1987.

37. Peters, M. S. and Timmerhaus, K. D., <u>Plant Design and Economics for Chemical Engineers</u>, 3rd ed., McGraw Hill Book Co., New York, 1980.

38. Clarke, L. and Davidson, R. L., <u>Manual for Process Engineering Calculations</u>, 2nd ed., McGraw Hill, 1986.

39. Neveril, R. B., <u>Capital and Operating Cost of Selected Air Pollution Control Systems</u>, EPA 450/5-80-002, Research Triangle Park, North Carolina, 1978.

40. Walas, S. M., <u>Chemical Process Equipment Selection and Design</u>, Butterworth Publishing, New York, 1988.

REFERENCES
(CONCLUDED)

41. Corripio, A. B., Chrien, K. S., and Evans, L. B., "Estimate Costs of Centrifugal Pumps and Electric Motors," Chem. Engr., Vol. 82(4), pp 115-118, 22 February 1982.

42. Mulet, A., Corripio, A. B., and Evans, L. B., "Estimate Costs of Distillation and Absorption Towers via Correlations," Chem. Engr. Vol. 88(26), pp 77-82, 28 December 1981.

43. Vatavuk, W. M. and Neveril, R. B., "Costs of Carbon Adsorbers," Chem. Engr., Vol. 90(2), pp 131-132, 24 January 1983.

44. Thomas, C. O., "Methanol as a Carrier for Alaskan Natural Gas," Prepared for the U.S. General Accounting Office, Contract No. 3130090, Washington, D.C., November 1982.

45. Thomas, C. O., "Alaskan Methanol Concept," A policy analysis study for the Federal Energy Administration by the Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, 30 September 1975.

46. Thomas, C. O., "Alaskan Methanol Concept" Testimony for the Senate Commerce Committee and the Senate Interior and Insular Affairs Committee, Washington, D.C., by the Institute for Energy Analysis, Oak Ridge Associated Universities, Oak Ridge, Tennessee, 24 March 1976.

47. Thomas, C. O., "Alaskan Methanol," in Methanol Technology and Applications in Motor Fuels, D. K. Paul, ed., Noyes Data Corporation, Park Ridge, New Jersey, 1978.

APPENDIX A

ESTIMATION OF GAS-PHASE FREUNDLICH ISOTHERM PARAMETERS
FOR VOCS OVER ACTIVATED CARBON

To estimate the performance of gas-phase adsorption, adsorption equilibria are necessary. The program SPEQ, furnished by J. C. Crittenden of Michigan Technological University, provides estimates of such equilibria in the form of single-component Freundlich parameters. Application of this program is presented by Crittenden et al. (Reference 27). The program utilizes the Dubinin-Radushkevich equation described in Chapter 2. The program proceeds interactively and requires the following information for each component of interest:

Compound name

Antoine Equation Constant A

Antoine Equation Constant B

Antoine Equation Constant C

BETA (affinity coefficient)

Density (gram/cm^3)

Molecular Weight

System Pressure (mm Hg)

Temperature (°C)

Desired Gas Concentration (micrograms/liter at STP)

Initial concentration for integration (μgram/liter)

Integration concentration step (μgram/liter)

The latter two parameters must sometimes be determined by trial and error, but may be set at about 1/100 and 1/1000, respectively, of the desired gas concentration. The program output is found in SPEQ.OUT. This output includes the Freundlich parameters K [(μmol/gram)/(μmol/L)$^{1/n}$] and 1/n, as well as the gas concentration range for plus or minus 10 percent prediction accuracy loading. The program and sample output are shown as Exhibits A1 and A2, respectively.

53

```
C    PROGRAM NAME - SPEQ
C
C    LANGUAGE - FORTRAN
C
C    THIS PROGRAM USES THE D-R EQUATION TO PREDICT THE SURFACE LOADING FOR
C    A DESIRE GAS CONCENTRATION (ug/L STP).  THE PROGRAM WILL THEN FIND
C    THE CORRECT FREUNDLICH PARAMETER IS SUCH A MANNERS AS THE SPREADING
C    PRESSURE FOR THE CALCULATED FREUNDLICH PARAMETER WILL BE THE SAME AS
C    THE SPREADING PRESSURE CALCULATED FOR THE D-R EQUATION.
C
C    THE SPREADING PRESSURE IS FOUND BY DOING A NUMERICAL INTEGRATION THAT
C    MAKES USE OF THE TRAPEZOID RULE.
C
C    PROGRAM DEVELOPED BY:  RANDY D. CORTRIGHT, Graduate Student
C
C    DEVELOPED AT        :  MICHIGAN TECH UNIVERSITY
C                           Houghton, Michigan 49931
C
C
C    INPUT:
C
C    INPUT THE FOLLOWING PARAMETER INTO A FILE NAME SPEQ.IN
C
C    COMPOUND NAME
C    ANTOINES EQTN. A
C    ANTOINES EQTN. B
C    ANTOINES EQTN. C
C    BETA
C    DENSITY G/CC
C    MOLECULAR WEIGHT
C    SYSTEM PRESSURE IN MM HG
C    TEMPERATURE DEG C
C    DESIRE GAS CONCENTRATION IN MICROGRAMS/LITER (STP)
C
C
C    OUTPUT
C
C    OUTPUT WILL BE SENT TO THE FILE NAME SPEQ.OUT
C
C    THE OUTPUT WILL GIVE INTERMEDIATE SPREADING PRESSURE VALUES FOR
C    INTERMEDIATE GAS CONCENTRATIONS,  THE FINAL SPREADING PRESSURE,
C    THE EQUIVALENT FREUNDLICH PARAMETERS, AND THE CONCENTRATION RANGE
C    WERE THE D-R PREDICTION AND THE FREUNDLICH PREDICTION ARE WITHIN 10 %
C
C
      CHARACTER NAME*25
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DOUBLE PRECISION N,NA,NB
      OPEN(7,FILE='SPEQ.OUT')
C
C    READ IN THE INPUT DATA FROM THE SCREEN
C
      WRITE(*,101)
101   FORMAT(2X,'BEGIN EXECUTION OF PROGRAM',////)
      write(*,5000)
5000  FORMAT(2X,'ENTER THE COMPOUND NAME ?    ')
      READ(*,6500) NAME
6500  FORMAT(A25)
      WRITE(*,600)
```

```fortran
600     FORMAT(2X,'ENTER ANTOINES CONSTANT A ?    ')
        READ(*,*) A
        WRITE(*,700)
700     FORMAT(2X,'ENTER ANTOINES CONSTANT B ?    ')
        READ(*,*) B
        WRITE(*,800)
800     FORMAT(2X,'ENTER ANTOINES CONSTANT C ?     ')
        READ(*,*) C
        WRITE(*,900)
900     FORMAT(2X,'ENTER THE CONSTANT BETA ?    ')
        READ(*,*) BETA
        WRITE(*,100)
100     FORMAT(2X,'ENTER THE DENSITY OF THE COMPOUND IN GM/CM**3 ?    ')
        READ(*,*) DEN
        WRITE(*,110)
110     FORMAT(2X,'ENTER THE MOLECULAR WEIGHT OF THE COMPOUND ?    ')
        READ(*,*) WEIGHT
        WRITE(*,120)
120     FORMAT(2X,'ENTER THE SYSTEM PRESSURE IN mm HG ?     ')
        READ(*,*) PRESS
        WRITE(*,130)
130     FORMAT(2X,'ENTER THE SYSTEM TEMPERATURE IN DEG. C ?    ')
        READ(*,*) TEMPC
        WRITE(*,3434)
3434    FORMAT(2X,'ENTER THE AVERAGE INFLUENT CONC. IN UG/L ?   ')
        READ(*,*) CONIN
        WRITE(*,1111)
1111    FORMAT(2X,'ENTER THE INITIAL CONC. FOR INTEGRATION IN UG/L ? ')
        READ(*,*) CONC
        WRITE(*,1112)
1112    FORMAT(2X,'ENTER THE INTEGRATION CONC. STEP IN UG/L ? ')
        READ(*,*) H
C
C  CALCULATE THE COMPOUNDS VAPOR PRESSURE AT THE SYSTEMS PRESSURE
C  USING THE ANTOINES EQUATION
C
        TEMPK = TEMPC + 273.0
        VP = 10.0**(A - B/(TEMPC+C))
C  PRINT OUT THE DATA READ INTO THE PROGRAM
C
        WRITE(7,10) NAME,A, B,C, BETA, DEN, WEIGHT, PRESS, TEMPC,CONIN
10      FORMAT(' COMPOUND - ', A25,//
      $           ' THE ANTOINES EQTN. A IS ', F7.2, /
      $           ' THE ANTOINES EQTN. B IS ', F7.2, /
      $           ' THE ANTOINES EQTN. C IS ', F7.2,/
      $           ' THE VALUE OF BETA IS ', F7.5,/
      $           ' THE LIQUID DENSITY IN G/CC IS ', F7.5,/
      $           ' THE MOLECULAR WEIGHT IS ', F6.2,/
      $           ' THE SYSTEM PRESSURE IN MM HG IS ', F6.2, /
      $           ' THE SYSTEM TEMPERATURE IN DEG C IS ', F6.2,/
      $           ' INLET GAS CONCENTRATION IN  ug/l IS ', E12.5,//)
        WRITE(7,20)
20      FORMAT(2X,'  CONC ug/l ',3X, 'Qo umol/gram',3X,'      N     ',
      $         3X,'SPREADING PRESSURE',/)
CèC  INTIALIZE THE VALUES FOR THE NUMERICAL INTEGRATION
C
        NA = 0.0D0
        QA = 0.0D0
        SUM = 0.0D0
        EXC = 1.0D-4
        I = 1
        MAX = 10
```

```
30      IF (CONC .LE. CONIN) THEN
C
C   CALCULATE THE SURFACE LOADING AT THE GAS CONCENTRATION
C
        PP = (CONC/WEIGHT * 22.40D0 / 1.0D+06) * PRESS
        QB = 0.46D+6*DEN/WEIGHT *
     $          EXP(-1.33D-7*(TEMPK/BETA * DLOG(VP/PP))**2)
C
C   CALCULATE THE VALUE OF dln C/d ln q AT THE GAS CONCENTRATION
C   THIS IS EQUAL TO THE FREUNDLICH N
C
        NB = 1.0D0 / (2.66D-7 * DLOG(VP/PP) * (TEMPK/BETA)**2)
C
C   TRAPEZOID RULE
C
        SUM = SUM + ((QB - QA)/2.0D0) * (NB + NA)
        NA = NB
        QA = QB
C
C   INCREMENT THE GAS CONCENTRATION
C
        IF (I .LE. MAX) THEN
            I = I + 1
            CONC = CONC + H
            GO TO 30
        ELSE
C
C   PRINT OUT INTERMEDIATE VALUES OF SPREADING PRESSURE
C
            WRITE(7,40)CONC,QA,NA,SUM
            MAX = MAX + MAX
            IF (CONC .GT. EXC) THEN
                H = H * 10.0D0
                EXC = EXC * 10.0D0
            ENDIF
            CONC = CONC + H
            PRINT*, 'CONC IS ', CONC,QA
            I = I + 1
            GO TO 30
        END IF
      ELSE
        WRITE(7,40)CONC,QA,NA,SUM
40      FORMAT(2X,E12.5,3X,E12.5,3X,E12.5,3X,E12.5)
C
C   CALCULATE THE FREUNDLICH PARAMETERS AND PRINT OUT THE RESULTS
C
        N = QA/SUM
        XK = QA/ ((CONC/WEIGHT) ** N)
        WRITE(7,50) SUM,N,XK
50      FORMAT('          ',//
     $          ' THE SPREADING PRESSURE IS ',E12.5,/
     $          ' THE VALUE OF 1/N IS ',E12.5,/
     $          ' THE VALUE OF XK IS ',E12.5,//)
      ENDIF
C
C CALCULATE AND PRINT OUT THE LOWER BOUNDS FOR THE REGION WHERE THE
C ERROR IS LESS THAN 10 % BETWEEN  THE D-R PREDICTION AND THE
C FREUNDLICH PREDICTION
C
      CONC = CONIN
      QB = QA
```

```
60      IF(ABS((QB -QA)/QB) .LE. 0.10) THEN
            PP = (CONC/WEIGHT * 22.40D0 / 1.0D+6)*PRESS
            QB = 0.46D+6*DEN/WEIGHT *
     $             EXP(-1.33D-7*(TEMPK/BETA * DLOG(VP/PP))**2)
            QA = XK * (CONC/WEIGHT)**N
            CONC = CONC - 0.001
            GO TO 60
        ELSE
            WRITE(7,65) CONC,QB,QA
65          FORMAT(' LOWER CONCENTRATION BOUNDS IS ', E12.5,' ug/L',/
     $             ' D-R PREDICTED LOADING IN umol/g IS ', E12.5,/
     $             ' FREUNDLICH LOADING IN umol/g IS ', E12.5,/)
        ENDIF
C
C CALCULATE AND PRINT OUT THE UPPER BOUNDS FOR THE REGION WHERE THE
C ERROR BETWEEN THE D-R PREDICTION AND FREUNDLICH PREDICTION IS
C LESS THEN 10 %
C
        CONC = CONIN
        QB = QA
70      IF(ABS((QB -QA)/QB) .LE. 0.10) THEN
            PP = (CONC/WEIGHT * 22.40D0 / 1.0D+6)*PRESS
            QB = 0.46D+6*DEN/WEIGHT *
     $             EXP(-1.33D-7*(TEMPK/BETA * DLOG(VP/PP))**2)
            QA = XK * (CONC/WEIGHT)**N
            CONC = CONC + 0.001
            GO TO 70
        ELSE
            WRITE(7,75) CONC,QB,QA
75          FORMAT(' UPPER CONCENTRATION BOUNDS IS ', E12.5, ' ug/L',/
     $             ' D-R PREDICTED LOADING IN umol/g IS ', E12.5,/
     $             ' FREUNDLICH LOADING IN umol/g IS ', E12.5,/)
        ENDIF
        END
```

COMPOUND - m-xylene

THE ANTOINES EQTN. A IS   7.01
THE ANTOINES EQTN. B IS 1462.00
THE ANTOINES EQTN. C IS   215.00
THE VALUE OF BETA IS 1.15830
THE LIQUID DENSITY IN G/CC IS 0.86400
THE MOLECULAR WEIGHT IS 106.00
THE SYSTEM PRESSURE IN MM HG IS 760.00
THE SYSTEM TEMPERATURE IN DEG C IS   25.00
INLET GAS CONCENTRATION IN ug/l IS   0.20000E+03

CONC ug/l	Qo umol/gram	N	SPREADING PRESSURE
0.11000E+03	0.26874E+04	0.92344E+01	0.12136E+05
0.21000E+03	0.26874E+04	0.92344E+01	0.12136E+05

THE SPREADING PRESSURE IS 0.12136E+05
THE VALUE OF 1/N IS 0.22145E+00
THE VALUE OF XK IS 0.23098E+04

LOWER CONCENTRATION BOUNDS IS 0.15240E+03 ug/L
D-R PREDICTED LOADING IN umol/g IS 0.27814E+04
FREUNDLICH LOADING IN umol/g IS 0.25032E+04

UPPER CONCENTRATION BOUNDS IS 0.69497E+03 ug/L
D-R PREDICTED LOADING IN umol/g IS 0.31845E+04
FREUNDLICH LOADING IN umol/g IS 0.35029E+04

APPENDIX B

EVALUATION OF MULTICOMPONENT COMPETITIVE LOADING IN FIXED BEDS

The program ETMOD.FOR is a modification of the program ET furnished by J. C. Crittenden of Michigan Technology University. The modification enables use of the current International Machine and Statistics Library (IMSL) for the solution of a set of mathematical equations. The current IMSL routine used in this calculation is DNEQNF. The use of this program is described in Crittenden et al. (Reference 25). The necessary input data are described below:

Line 1

Number of components (N), bed void fraction, bulk density of adsorbent, flow rate of fluid (gallons per minute per square foot)

Line 2 through Line N+1

Component name, Freundlich K (micromole/gram) (liters/micromole)$^{1/n}$, Freundlich 1/n, initial concentration (micrograms/liter), molecular weight

Typical input is provided in Exhibit B-1; typical output is found in Exhibit B-2. The computer program ETMOD.FOR is shown in Exhibit B-3. Note that the input flow rate is in gallons per minute per square foot. The program was originally written for water treatment. However, the program may be used for air treatment by (1) converting typical air flow rate units (e.g., cubic feet per minute) to those specified for the input flow rate, and (2) inputting Freundlich parameters that apply for gas-phase adsorption.

TYPICAL INPUT

NOTE: This is liquid-phase data; however, gas-phase data can be used.

SAMPLE INPUT - ET.DAT

7,0.431,0.457,1.931

'M-XYLENE',1044.0,0.2458,5.2,106.17

'OP-XYLENE', 895.0,0.2587,9.3,106.17

'ETHYL BENZENE', 714.4,0.2953,4.5,106.17

'TOLUENE',475.0,0.3282,19.3,92.15

'TETRACHLOROETHENE',435.0,0.3847,37.6,165.83

'TRICHLOROETHENE',192.0,0.4382,47.9,131.29

'CIS-DICHLOROETHENE',46.9,0.5562,70.9,96.93

EQUILIBRIUM THEORY RESULTS

NUMBER OF COMPONENTS :	5
BED VOID FRACTION :	0.430
BULK DENSITY OF ADSORBENT (g/cm**3) :	0.480
FLOWRATE (gpm/ft**2) :	224.400

	BED VOLUMES FED TO BREAKTHROUGH	VELOCITY OF WAVE (cm/sec)	TREATMENT CAPACITY (mg CARBON/L WATER)
ZONE(1)	334614.5	0.45541907E-04	1.4345
ZONE(2)	312381.6	0.48783232E-04	1.5366
ZONE(3)	281513.9	0.54132259E-04	1.7051
ZONE(4)	250931.5	0.60729666E-04	1.9129
ZONE(5)	177584.1	0.85812782E-04	2.7029

COMPONENT= M,O,P-XYLENES

FREUNDLICH K (um/g)*(L/um)**1/n :	2390.00
FREUNDLICH 1/n :	0.1920
INITIAL CONCENTRATION (ug/L) :	356.0000
MOLECULAR WEIGHT :	106.1700
SINGLE SOLUTE TREATMENT CAPACITY (mg CARBON/L WATER) :	1.1122
DIMENSIONLESS BED LENGTH FOR ZONE(1) :	0.53071239

		C(ug/L)	Q(ug/g)	C/Co	DG	QAVE	Cio (ug/L)
ZONE(	1)	356.000	248172.46	1.0000	.778E+06	248172.46	0.521E+03
ZONE(	2)	0.000	0.00	0.0000	.000E+00	231683.03	0.467E+03
ZONE(	3)	0.000	0.00	0.0000	.000E+00	208789.49	0.806E+02
ZONE(	4)	0.000	0.00	0.0000	.000E+00	186107.51	0.517E+01
ZONE(	5)	0.000	0.00	0.0000	.000E+00	131708.20	0.134E-02

COMPONENT= ETHYL BENZENE

FREUNDLICH K (um/g)*(L/um)**1/n :	2481.00
FREUNDLICH 1/n :	0.2194
INITIAL CONCENTRATION (ug/L) :	178.0000
MOLECULAR WEIGHT :	106.1700
SINGLE SOLUTE TREATMENT CAPACITY (mg CARBON/L WATER) :	0.6033
DIMENSIONLESS BED LENGTH FOR ZONE(2) :	0.03777206

		C(ug/L)	Q(ug/g)	C/Co	DG	QAVE	Cio (ug/L)
ZONE(	1)	178.000	97709.62	1.0000	.613E+06	97709.62	0.662E+03
ZONE(	2)	569.459	370601.29	3.1992	.726E+06	115841.48	0.602E+03
ZONE(	3)	0.000	0.00	0.0000	.000E+00	104394.71	0.129E+03
ZONE(	4)	0.000	0.00	0.0000	.000E+00	93053.73	0.117E+02
ZONE(	5)	0.000	0.00	0.0000	.000E+00	65854.08	0.847E-02

COMPONENT= TOLUENE

FREUNDLICH K (um/g)*(L/um)**1/n :   2029.00
FREUNDLICH 1/n :   0.2779
INITIAL CONCENTRATION (ug/L) :   62.5300
MOLECULAR WEIGHT :   92.1400
SINGLE SOLUTE TREATMENT CAPACITY
(mg CARBON/L WATER) :   0.3725
DIMENSIONLESS BED LENGTH
FOR ZONE(3) :   0.06233369

		C(ug/L)	Q(ug/g)	C/Co	DG	QAVE	Cio (ug/L)
ZONE(	1)	62.530	10453.11	1.0000	.187E+06	10453.11	0.189E+04
ZONE(	2)	65.897	12800.62	1.0539	.217E+06	10609.09	0.175E+04
ZONE(	3)	498.542	294363.26	7.5654	.659E+06	38647.99	0.520E+03
ZONE(	4)	0.000	0.00	0.0000	.000E+00	34449.44	0.779E+02
ZONE(	5)	0.000	0.00	0.0000	.000E+00	24379.85	0.259E+00

COMPONENT= BENZENE

FREUNDLICH K (um/g)*(L/um)**1/n :   1427.00
FREUNDLICH 1/n :   0.4288
INITIAL CONCENTRATION (ug/L) :   45.9300
MOLECULAR WEIGHT :   78.1100
SINGLE SOLUTE TREATMENT CAPACITY
(mg CARBON/L WATER) :   0.5174
DIMENSIONLESS BED LENGTH
FOR ZONE(4) :   0.07688140

		C(ug/L)	Q(ug/g)	C/Co	DG	QAVE	Cio (ug/L)
ZONE(	1)	45.930	3555.72	1.0000	.864E+05	3555.72	0.345E+04
ZONE(	2)	46.698	4090.92	1.0167	.978E+05	3591.28	0.329E+04
ZONE(	3)	55.124	9574.93	1.1805	.194E+06	4182.55	0.150E+04
ZONE(	4)	432.583	230949.58	7.8474	.596E+06	28817.53	0.438E+03
ZONE(	5)	0.000	0.00	0.0000	.000E+00	20394.16	0.108E+02

COMPONENT= N-PENTANE

FREUNDLICH K (um/g)*(L/um)**1/n :   518.00
FREUNDLICH 1/n :   0.4876
INITIAL CONCENTRATION (ug/L) :   37.4400
MOLECULAR WEIGHT :   72.1500
SINGLE SOLUTE TREATMENT CAPACITY
(mg CARBON/L WATER) :   1.3794
DIMENSIONLESS BED LENGTH
FOR ZONE(5) :   0.29230047

		C(ug/L)	Q(ug/g)	C/Co	DG	QAVE	Cio (ug/L)
ZONE(	1)	37.440	440.13	1.0000	.131E+05	440.13	0.210E+05
ZONE(	2)	37.520	496.19	1.0021	.148E+05	443.85	0.201E+05
ZONE(	3)	38.156	909.92	1.0169	.266E+05	489.91	0.101E+05
ZONE(	4)	41.025	2592.67	1.0752	.705E+05	718.34	0.342E+04
ZONE(	5)	132.067	50186.75	3.2192	.424E+06	15177.98	0.132E+03

```
C
C
C              ********EQUILIBRIUM THEORY PROGRAM********
C
C
C      THIS PROGRAM CALCULATES MULTICOMPONENT BREAKTHROUGH FOR FIXED
C      BED ADSORBERS. THE PROGRAM ASSUMES NO MASS TRANSFER RESISTANCE.
C      IDEAL ADSORBED SOLUTION THEORY IS USED TO PREDICT COMPETITION.
C
C
C      PROGRAM WRITTEN BY:  THOMAS FRANCIS SPETH
C      PROGRAM ALTERED BY R M COUNCE NOV 29,1989
C      THANKS TO:  PAUL LUFT, DAVID HAND, AND DR. JOHN CRITTENDEN
C                  FOR THEIR PREVIOUS WORK.
C
C                         VARIABLE DEFINITIONS
C
C      BVF   = BED VOID FRACTION
C      C     = LIQUID PHASE CONCENTRATION (ug/L)
C      CH    = WORKING CHARACTER
C      CHAR  = NAME OF THE COMPONENTS (TEN LETTERS)
C      CO    = INITIAL CONCENTRATIONS (ug/L)
C      DEN   = BULK DENSITY OF ADSORBENT (g/cm**3)
C      DGX   = DIMENSIONLESS GROUP X:  USED TO FIND STRONGEST COMPONENT
C      DGY   = DIMENSIONLESS GROUP Y:  USED TO FIND STRONGEST COMPONENT
C      FCN   = SUBROUTINE THAT SETS UP THE NON-LINEAR EQUATIONS
C      FCS   = C/CO
C      FLRT  = FLOW RATE (GPM/FT**2)
C      FNORM = OUTPUT:  SUM OF THE RESIDUALS
C      I     = COUNTER
C      IAST  = SUBROUTINE TO ACCOUNT FOR COMPETITIVE EFFECTS
C      IER   = OUTPUT:  ERROR PARAMETER
C      ITMAX = MAXIMUM NUMBER OF ITERATIONS
C      IX    =: USED TO KEEP TRACK OF STRONGEST COMPONENT
C      J     = COUNTER
C      K     = COUNTER
C      L     = COUNTER FOR ERROR FIXING
C      M     = COUNTER
C      MW    = MOLECULAR WEIGHT
C      N     = NUMBER OF COMPONENTS TOTAL
C      NN    = NUMBER OF COMPONENTS IN A ZONE
C      NS    = NSIG INPUT
C      NSIG  = NUMBER OF DIGITS OF ACCURACY DESIRED IN THE COMPUTED ROOT
C      OATS  = BED VOLUMES FED
C      PAR   = PARAMETER SET
C      PAR(1 to N)= FREUNDLICH K VALUES
C      PAR(10 to 10+N)= FRUENDLICH N VALUES
C      PAR(20 to 20+N)= INITIAL CONCENTRATIONS
C      PAR(30)= VELOCITY OF THE WAVE: VW (cm/s)
C      PAR(35)= VELOCITY OF FLOW: VF (cm/s)
C      PAR(40 to 40+I)= CALCULATED LIQUID CONCENTRATIONS
C      PAR(60 to 60+I)= Q's OF THE PREVIOUS WAVE
C      PAR(80 to 80+I)= C's OF THE PREVIOUS WAVE
C      Q     = SOLID PHASE CONCENTRATION (ug/g)
C      QAVE  = AVERAGE Q IN ZONE
C      SSTC  = SINGLE SOLUTE TREATMENT CAPACITY (mg C/L WATER)
C      SUM   = USED TO CALCULATE VW AND OATS
C      VF    = VELOCITY OF FLOW (cm/s)
C      VW    = VELOCITY OF WAVE (cm/s)
C      WK    = WORK VECTOR:  LENGTH=N*(3*N+15)/2
```

```
C     X       = ONE DIMENSIONAL SOLID-PHASE CONCENTRATION (um/g)
C     XK      = FRUENDLICH K's (um/g)*((L/um)**1/N
C     XN      = FRUENDLICH 1/n 's
C     ZSQ     = COMMON BLOCK
C     ZZ      = VARIABLE USED TO CALCULATE INITIAL Q's
C     ZZZ     = DIMENSIONLESS BED LENGTH
C
C
C                       SAMPLE INPUT
C
C         N,BVF,DEN,FLRT
C         CHAR(I),XK(I),XN(I),CO(I),MW(I)
C         ....    ..    ..    ..    ..
C         CHAR(J),XK(J),XN(J),CO(J),MW(J)
C         NS
C
C                       DIMENSIONS
C
      IMPLICIT DOUBLE PRECISION (A-H, O-Z)
      CHARACTER*40 CHAR(20),CH
      DOUBLE PRECISION MW(20)
      DIMENSION XN(20),XK(20),CO(20,20),C(20,20),Q(20,20),ZZZ(20),VW(20)
     $,DGY(20,20),OATS(20),QAVE(20,20),SSTC(20),WK(200),X(20)
     $,XGUESS(20),FCS(20,20),CIO(20,20)
      EXTERNAL FCN
      COMMON /ZSQ/ BVF,DEN,M,PAR(100)
C
C                       OPEN FILES
C
      OPEN(4,FILE='ET.DAT',STATUS='OLD')
      OPEN(7,FILE='ET.OUT',STATUS='NEW')
C
C                       READ IN DATA
C
      PRINT*, 'READING DATA'
      READ(4,*) N,BVF,DEN,FLRT
      DO 10 I=1,N
       READ(4,*) CHAR(I),XK(I),XN(I),CO(I,1),MW(I)
       CO(I,1)=CO(I,1)/MW(I)
       XN(I)=1.0D0/XN(I)
10    CONTINUE
C
C                       CHANGE UNITS
C
      VF=FLRT*0.067910D0/BVF
      DEN=DEN*1000.0D0
C
C             SET ZONE ONE CONCENTRATIONS TO ZERO
C
      DO 20 I=1,N
       VW(I)=0.0D0
       PAR(60+I)=0.0D0
       PAR(80+I)=0.0D0
20    CONTINUE
C
C             SOLVE FOR EACH ZONE SEPARATELY
C
      DO 100 J=1,N
      PRINT*, 'SOLVING FOR ZONE ',J
C
```

```
      L=0
      M=J
      NS=9
      NN=N+1-J
      ZZ=1.0D0
      NSIG=NS
      SUM=0.0D0
      IRRREL=1.0E-05
C
C                 CALCULATE INITIAL GUESSES OF Q's
C
21       DO 22 I=1,N
         Q(I,J)=ZZ*XK(I)*CO(I,J)**(1.0D0/XN(I))
22       CONTINUE
C
C                 PUT Q INTO ONE-DIMENSIONAL FORM
C
         DO 24 I=1,N
         XGUESS(I)=Q(I,J)
24       CONTINUE
C
C                 SET IAST PARAMETERS
C
         DO 26 I=1,NN
         XGUESS(I)=X(M-1+I)
         PAR(I)=XK(M-1+I)
         PAR(10+I)=XN(M-1+I)
         PAR(20+I)=CO(M-1+I,J)
         PAR(60+I)=PAR(60+M-1+I)
         PAR(80+I)=PAR(80+M-1+I)
26       CONTINUE
         PAR(30)=VW(J-1)
         PAR(35)=VF
         ITMAX=100
C
      CALL DNEQNF(FCN,IRRREL,NN,ITMAX,XGUESS,X,FNORM)
C
C                      FIX ANY ERRORS
C
      IF (IERCD() .EQ. 1 .OR. IERCD() .EQ. 3) THEN
         IF (L .EQ. 0) THEN
           ZZ=2.0D0*ZZ
           L=L+1
           GOTO 21
         ENDIF
         IF (L .EQ. 1) THEN
           ZZ=3.0D0*ZZ
           L=L+1
           GOTO 21
         ENDIF
         IF (L .EQ. 2) THEN
           ZZ=ZZ/20.0D0
           L=L+1
           GOTO 21
         ENDIF
         IF (L .EQ. 3) THEN
           WRITE(7,28) J
28         FORMAT(1X,'THERE IS A PROBLEM WITH THE INITIAL CONCENTRATIONS',
     $/,'THAT THE PROGRAMS FIXING ROUTINE DID NOT HELP.  ZONE=',I2)
         ENDIF
      ENDIF
C
```

```
        IF (IERCD() .EQ. 2) THEN
         NSIG=NSIG-1
         IF (NSIG .LT. O) THEN
          WRITE(7,29) J
29        FORMAT(1X,'THE NUMBER OF SIGNIFICANT FIGURES HAS DROPPED BELOW
     $ZERO.   THERE ARE NO RESULTS FOR ZONE',I2)
         ENDIF
         GOTO 21
        ENDIF
C
C           SET X TO TWO-DIMENSIONAL OUTPUT FOR PRINT OUT
C
        IF (M .GT. 1) THEN
         DO 30 I=1,M-1
          Q(I,J)=0.0D0
30        CONTINUE
        ENDIF
        DO 31 I=1,NN
         Q(I+M-1,J)=X(I)
31      CONTINUE
C
C               CALCULATE THE LIQUID CO  ENTRATIONS
C
        IF (M .GT. 1) THEN
         DO 33 I=1,M-1
          C(I,J)=0.0D0
33        CONTINUE
        ENDIF
        DO 34 I=1,NN
         C(I+M-1,J)=PAR(40+I)
34      CONTINUE
C
C           DETERMINE THE STRONGEST COMPONENT IN ZONE J
C
        DGX=0.0D0
        DO 35 I=M,N
         DG=DEN*Q(I,J)/(C(I,J)*BVF)
         IF (DG .GT. DGX) THEN
          DGX=DG
          IX=I
         ENDIF
35      CONTINUE
C
C                   SET STRONGEST COMPONENT TO ZONE J
C
        CH=CHAR(IX)
        CHAR(IX)=CHAR(J)
        CHAR(J)=CH
C
        WM=MW(IX)
        MW(IX)=MW(J)
        MW(J)=WM
C
        XXK=XK(IX)
        XK(IX)=XK(J)
        XK(J)=XXK
C
        XXN=XN(IX)
        XN(IX)=XN(J)
        XN(J)=XXN
C
```

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         DO 37 K=1,J
          XCO=CO(IX,K)
          CO(IX,K)=CO(J,K)
          CO(J,K)=XCO
C
           XC=C(IX,K)
           C(IX,K)=C(J,K)
           C(J,K)=XC
C
           XQ=Q(IX,K)
           Q(IX,K)=Q(J,K)
           Q(J,K)=XQ
37       CONTINUE
C
C                  SET C's AND Q's FOR NEXT ZONE
C
         DO 38 I=1,N
          PAR(60+I)=Q(I,J)
          PAR(80+I)=C(I,J)
38       CONTINUE
C
C           CALCULATE VELOCITY OF THE WAVE FOR ZONE J
C
         IF (J .EQ. 1) THEN
          VW(J)=VF*BVF*CO(1,J)/(Q(1,J)*DEN+C(1,J)*BVF)
         ENDIF
         IF (J .GE. 2) THEN
          SUM=(Q(J,1)*DEN+BVF*C(J,1))*VW(1)
         ENDIF
         IF (J .GT. 2) THEN
          DO 40 K=2,J-1
           SUM=SUM+((Q(J,K)*DEN+BVF*C(J,K))*(VW(K)-VW(K-1)))
40        CONTINUE
         ENDIF
         IF (J .GE. 2) THEN
          VW(J)=(BVF*VF*CO(J,J)-SUM+(Q(J,J)*DEN+BVF*C(J,J))*VW(J-1)
     $)/(Q(J,J)*DEN+BVF*C(J,J))
         ENDIF
C
C                  SET Co FOR NEXT ZONE
C
         DO 50 I=J+1,N
          CO(I,J+1)=C(I,J)
50       CONTINUE
         DO 60 I=1,J
          CO(I,J+1)=0.0D0
60       CONTINUE
C
100      CONTINUE
C
C                  CALCULATE BED VOLUMES FED
C
         PRINT*, 'CALCULATING VARIOUS PARAMETERS'
         DO 110 I=1,N
          SUM=(Q(I,1)*DEN+C(I,J)*BVF)*VW(1)
          IF (I .GE. 2) THEN
           DO 105 K=2,I
            SUM=SUM+(Q(I,K)*DEN+C(I,K)*BVF)*(VW(K)-VW(K-1))
105        CONTINUE
          ENDIF
          OATS(I)=SUM/(CO(I,I)*VW(I))
110      CONTINUE
```

```
C
C                 CALCULATE Q  TOTAL AVERAGE FOR EACH ZONE
C
      DO 120 I=1,N
       QAVE(I,1)=Q(I,1)
120    CONTINUE
      DO 140 I=1,N
       DO 130 J=2,N
        QAVE(I,J)=(QAVE(I,J-1)*VW(J-1)+Q(I,J)*(VW(J)-VW(J-1)))/VW(J)
130    CONTINUE
140   CONTINUE
C
C                 CALCULATE DIMENSIONLESS BED LENGTH
C
      DO 150 I=1,N
       IF (I .EQ. 1) THEN
        ZZZ(1)=0.0D0
        ELSE
        ZZZ(I)=VW(I-1)/VW(N)
       ENDIF
       ZZZ(I)=VW(I)/VW(N)-ZZZ(I)
150   CONTINUE
C
C           CALCULATE SINGLE SOLUTE TREATMENT CAPACITY
C
      DO 160 I=1,N
       SSTC(I)=1000.0D0*CO(I,1)**(1.0D0-1.0D0/XN(I))/XK(I)
160   CONTINUE
C
C                 CALCULATE DG's FOR PRINT OUT
C
      DO 180 J=1,N
       DO 170 I=1,N
        DGY(I,J)=DEN*Q(I,J)/(C(I,J)*BVF)
        IF (C(I,J) .EQ. 0.0) DGY(I,J)=0.0
170    CONTINUE
180   CONTINUE
C
C                 CALCULATE C/Co FOR PRINT OUT
C
      DO 195 J=1,N
       DO 190 I=1,N
        FCS(I,J)=C(I,J)/CO(I,J)
        IF (CO(I,J) .EQ. 0.0) FCS(I,J)=0.0
190    CONTINUE
195   CONTINUE
C
C                 CALCULATE Cio
C
      DO 250 J=1,N
       CISUM=0.0D0
       DO 230 I=1,N
        CISUM=CISUM+XN(I)*Q(I,J)
230    CONTINUE
       DO 240 I=1,N
        CIO(I,J)=(CISUM/XN(I)/XK(I))**XN(I)
240    CONTINUE
250   CONTINUE
C
```

```
C                          PUT INTO ug/L UNITS
C

        DO 210 J=1,N
         DO 200 I=1,N
           CO(I,J)=CO(I,J)*MW(I)
           CIO(I,J)=CIO(I,J)*MW(I)
           Q(I,J)=Q(I,J)*MW(I)
           QAVE(I,J)=QAVE(I,J)*MW(I)
           C(I,J)=C(I,J)*MW(I)
200     CONTINUE
210     CONTINUE
C
C                          PRINT RESULTS
C
        PRINT*, 'PRINTING OUTPUT'
        WRITE(7,900)
900     FORMAT(//,1X,T10,'EQUILIBRIUM THEORY RESULTS')
        WRITE(7,910) N,BVF,DEN/1000.0D0,FLRT
910     FORMAT(1X,//,T10,'NUMBER OF COMPONENTS :',T54,I2,/,
       $T10,'BED VOID FRACTION :',T55,F5.3,/,
       $T10,'BULK DENSITY OF ADSORBENT (g/cm**3) :',T50,F10.3,/,
       $T10,'FLOWRATE (gpm/ft**2) :',T50,F10.3,//)
        WRITE(7,920)
920     FORMAT(T19,'BED VOLUMES FED',T36,'VELOCITY OF WAVE',T54,
       $'TREATMENT CAPACITY',/,
       $T19,'TO BREAKTHROUGH',T40,'(cm/sec)',T54,'(mg CARBON/L WATER)',/)
        DO 940 I=1,N
          WRITE(7,930) I,OATS(I),VW(I),DEN*1000.0D0/OATS(I)
930       FORMAT(T8,'ZONE(',T13,I2,T15,')',T17,F13.1,T35,E15.8,T52,F15.4)
940     CONTINUE
        DO 1000 I=1,N
          WRITE(7,950) CHAR(I),XK(I),1.0D0/XN(I),CO(I,1),MW(I),SSTC(I),I,
       $ ZZZ(I)
950       FORMAT(//,'COMPONENT= ',A40,//,
       $ T10,'FREUNDLICH K (um/g)*(L/um)**1/n :',T45,F10.2,/,
       $ T10,'FREUNDLICH 1/n :',T45,F10.4,/,
       $ T10,'INITIAL CONCENTRATION (ug/L) :',T45,F10.4,/,
       $ T10,'MOLECULAR WEIGHT :',T45,F10.4,/,
       $ T10,'SINGLE SOLUTE TREATMENT CAPACITY',/,
       $ T12,'(mg CARBON/L WATER) :',T40,F15.4,/,
       $ T10,'DIMENSIONLESS BED LENGTH',/,
       $ T12,'FOR ZONE(',T21,I2,T23,') :',T45,F10.8,//,
       $ T12,'C(ug/L)',T24,'Q(ug/g)',T35,'C/Co',T46,'DG',T56,'QAVE',T63,
       $ 'Cio (ug/L)')
          DO 970 J=1,N
            WRITE(7,960) J,C(I,J),Q(I,J),FCS(I,J),DGY(I,J),QAVE(I,J),
       $ CIO(I,J)
960         FORMAT('ZONE(',T7,I2,T9,')',T11,F9.3,T22,F10.2,T33,
       $F7.4,T43,E8.3,T52,F10.2,T63,E10.3)
970       CONTINUE
1000    CONTINUE
        STOP
        END
C
C
C                          SUBROUTINE FCN
C
C       THIS SUBROUTINE WILL SET UP THE EQUATIONS THAT WILL BE USED IN
C       THE ZSPOW SUBROUTINE.
C
C
```

```fortran
      SUBROUTINE FCN(X,F,NN)
C
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      DIMENSION X(NN),F(NN)
      COMMON /ZSQ/ BVF,DEN,M,PAR(100)
      PRINT*, 'M=',M
      QT=0.0D0
      QNQ=0.0D0
      DO 1010 I=1,NN
       QT=QT+X(I)
       QNQ=QNQ+PAR(10+I)*X(I)
1010  CONTINUE
C
C                   CALCULATE F(I)
C
      IF (M .EQ. 1) THEN
       DO 1020 I=1,NN
        F(I)=-PAR(20+I)+X(I)/QT*(QNQ/PAR(10+I)/PAR(I))**PAR(10+I)
1020   CONTINUE
      ENDIF
      IF (M .GT. 1) THEN
       DO 1030 I=1,NN
        F(I)=-X(I)/QT*(QNQ/PAR(10+I)/PAR(I))**PAR(10+I)+((X(I)-PAR(60+I)
     $)*DEN*PAR(30))/((PAR(35)-PAR(30))*BVF)+PAR(80+I)
1030   CONTINUE
      ENDIF
C
C                   CALCULATE LIQUID CONCENTRATION
C
      IF (M .EQ. 1) THEN
       DO 1040 I=1,NN
        PAR(40+I)=X(I)*(QNQ/(PAR(10+I)*PAR(I)))**PAR(10+I)/QT
        PRINT*, 'X(I) ',X(I),'   F(I) ',F(I)
1040   CONTINUE
      ENDIF
      IF (M .GT. 1) THEN
       DO 1050 I=1,NN
        PAR(40+I)=((X(I)-PAR(60+I))*DEN*PAR(30))/((PAR(35)-PAR(30))
     $*BVF)+PAR(80+I)
        PRINT*, 'X(I) ',X(I),'  F(I) ',F(I)
1050   CONTINUE
      ENDIF
      RETURN
      END
```

APPENDIX C

SPREADSHEET VARIABLES

The following notation table applies specifically to the terminology used in the spreadsheets for this project. It is important to recognize that the spreadsheet notation often is not the same as the notation used in the preceding sections of text. This arises because of typical software restrictions as to acceptable notation. Because of this, all of the following spreadsheet notation is clearly and explicitly defined.

TABLE C-1. NOTATION TABLE - DESIGN AND COST ESTIMATING

NAMES	[b]	ITEM DESCRIPTION [c]
CASF[a]	N	Catalytic Unit Size Safety Factor
CD[a]	N	Carbon Bulk Density, pounds/ft^3
CF[a]	N	Packing Factor (Treybal, 3rd Ed.)
CRI[a]	N	Carbon Recycle Interval, days
CSF[a]	N	Carbon Use Safety Factor
CUF[a]	N	Contaminant Cleanup Factor
EC[a]	N	Electricity Cost, $/kWh
EFFA[a]	N	Electrical Efficiency, Air Blowers
EFFH[a]	N	Electrical Efficiency, Air Heaters
EFFW[a]	N	Electrical Efficiency, Water Pumps
EIFC[a]	N	Equip. Inst. Cost Factor, Carbon & Catalysis
EIFS[a]	N	Equipment Installation Cost Factor, Stripper
F[a]	N	Fanning Friction Factor fo Water Pipe
FAF[a]	N	Freundlich Adjustment Factor (BENZENE Only)
FC[a]	N	Fuel Oil Costs, $/10^6 BTU
FF[a]	N	Flooding Factor (SEE ACCOMPANYING TEXT)
HGW[a]	N	Groundwater Depth, feet
HPB[a]	N	Height of Each Packed Bed, Feet
HPL[a]	N	Horizontal Pipe Length, feet
I[a]	N	Average Annual Inflation Rate
J[a]	N	Correlation Factor Term (Treybal, 3rd Ed.)
KF[a]	N	Consolidated Friction Loss Coefficient
LF[a]	N	Operating Cycle Load Factor
MMF[a]	N	Material (SS) Factor, Stripper
OHR[a]	N	Overhead Rate, on Expense

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TABLE C-1. NOTATION TABLE - DESIGN AND COST ESTIMATING (CONTINUED)

NAMES	[b]	ITEM DESCRIPTION [c]
OM[a]	N	Operations & Maintenance Factor
PAT[a]	N	Gas Stream Pressure, Atmospheres
PPBI[a]	N	Inlet Contaminant Concentration, ppb
PPBO	N	Outlet Contaminant Concentration, ppb
S[a]	N	Stripping Factor (Greater Than Unity)
SF[a]	N	Height Design Safety Factor
SIZE[a]	A	Size of Stripper Packing, mm (inches)
TF[a]	N	Fahrenheit Temperature
TYPE[a]	A	Name/Type of Stripper Packing
VAR[a]	N	Independent Variable, Current Value
VI[a]	A	Name of Independent Variable
VIN[a]	N	Initial Value of Independent Variable
VNUM[a]	N	Number of Parametric Steps to Run
VSTEP[a]	N	Size of Each Independent Variable Step
WGM[a]	N	Water Feed Rate, gallons/minute
ABS	N	Abscissa for Pressure Gradient (Treybal, 3rd Ed.)
ABS2	N	Treybal Abscissa, Table 5
ABSB	N	ABS Individual for Benzene
ABST	N	ABS Individual for Trichloroethylene
ACAT	N	Air Flow Rate, ft^3/minute, BENZENE
ACFM	N	Air Flow Rate, ft^3/minute
ACFM1	N	ACFM Individual for Benzene
ACFM2	N	ACFM Individual for Trichloroethylene
ACFMB	N	Copied from ACFM1
AD	N	Air Density, pounds/ft^3

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TABLE C-1. NOTATION TABLE - DESIGN AND COST ESTIMATING (CONTINUED)

NAMES	[b]	ITEM DESCRIPTION [c]
ALR	N	Air Loading Rate at Flooding, (pounds/minute)/ft^2
AMCF	N	Air, pound moles/ft^3
AORD	N	Adjusted Ordinate, FF * ORD
APM	N	Air Flow Rate, pounds/minute
APM1	N	APM Individual for Benzene
APM2	N	APM Individual for Trichloroethylene
APMB	N	Air Flow Rate BENZENE, pounds/minute
APMM	N	Air Flow Rate, pound moles/minute
AREA	N	Stripper Cross Section Area, ft^2
AV1	N	Air Viscosity, Centipoise
AV2	N	Air Viscosity, pounds/feet second
BC	N	Carbon Breakthrough Capacity, pounds/pounds
CAPCATB	N	Catalysis Unit Installed Capital Cost, BENZENE
CAPCB	N	Carbon Unit Installed Capital Costs, BENZENE
CAPRB	N	Centrifugal Contactor Installed Capital Costs, BENZENE
CAPSB	N	Packed Stripper Installed Capital Costs, BENZENE
CARR	N	Total Pounds Carbon Needed, Time Base
CCU	N	Carbon Cycle Use BENZENE, pounds/cycle
CFPD	N	Carbon Cubic Feet Required, Time Base
CMFI	N	Contaminant Mole Fraction, In
CMFO	N	Contaminant Mole Fraction, Out
CN	N	Column Number Lookup Table 9
CPD	N	Adjusted Carbon Needed. pounds, Time Base
CPD1	N	CPD, Individual for Benzene
CPD2	N	CPD, Individual for Trichloroethylene

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TABLE C-1. NOTATION TABLE - DESIGN AND COST ESTIMATING (CONTINUED)

NAMES	[b]	ITEM DESCRIPTION [c]
CPS	N	Carbon Unit Design Size BENZENE, pounds
CPV	N	Collision Function, Vapor
CRA	N	Carbon Recycled Annually BENZENE, pounds
CUP	N	Carbon Units Purchased [Number]
D1B	T	Table D1B, Area Name, BENZENE
D1T	T	Table D1T, Area Name, TCE
D2B	T	Table D2B, Area Name, BENZENE Cost Estimate
D2T	T	Table D2T, Area Name, TCE Cost Estimate
D3B	T	Table D3B, Area Name, BENZENE Cost Estimate
D3T	T	Table D3T, Area Name, TCE Cost Estimate
D4B	T	Table D4B, Area Name, BENZENE Cost Estimate
D4T	T	Table D4T, Area Name, TCE Cost Estimate
D5B	T	Table D5B, Area Name, BENZENE Cost Estimate
D5T	T	Table D5T, Area Name, TCE Cost Estimate
D6B	T	Table D6B, Area Name, BENZENE Cost Estimate
D6T	T	Table D6T, Area Name, TCE Cost Estimate
D7B	T	Table D7B, Area Name, BENZENE Cost Estimate
D7T	T	Table D7T, Area Name, TCE Cost Estimate
DAK	N	Diffusivity, m^2/second
DAKA	N	Diffusivity, ft^2/second
DALR	N	Derived Air Loading Rate, (pounds/minute)/ft^2
DIA	N	Stripper Diameter, feet
DIA1	N	Stripper Diameter, Table D1B
DIN	N	Stripper Diameter, Inches
DORD	N	Derived Ordinate

TABLE C-1. NOTATION TABLE - DESIGN AND COST ESTIMATING (CONTINUED)

NAMES	[b]	ITEM DESCRIPTION [c]
DORDB	N	DORD, Individual for Benzene
DORDT	N	DORD, Individual for TCE
EXPCATB	N	Catalysis Unit Annual Expense, BENZENE
EXPCB	N	Carbon Unit Annual Expense, BENZENE
EXPRB	N	Centrifugal Contactor Annual Expense, BENZENE
EXPSB	N	Packed Stripper Annual Expense, BENZENE
FPC	N	Flood Point Coefficient
FUEL1B	N	Carbon Air Heater Fuel, 10^6 BTU/year
FUEL2B	N	Catalysis Unit Fuel, 10^6 BTU/year
GCH	N	Gravity Acceleration, Time = Hours
GCM	N	Gravity Acceleration, Time = Minutes
GCS	N	Gravity Acceleration, Time = Seconds
H	N	Henry's Law Constants
HA	N	HTU, Air Feet
HA1	N	Height of Transfer Unit, Table D1B
HF	N	Total Friction Loss Factor
HP1	N	Air Blower, Total Horsepower
HP2	N	Water Pump, Total Horsepower
HT	N	HTU, Total Feet
HTOT	N	Total Height of Stripper Packing, Feet
HTOT1	N	Stripper Total Height, Table D1B
HTR	N	Total Stripper Height, Feet
HW	N	HTU, Water Feet
IN	N	Table Index Column, Table 8
INPD	N	Total Pressure Drop, inches of water

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TABLE C-1. NOTATION TABLE - DESIGN AND COST ESTIMATING (CONTINUED)

NAMES	[b]	ITEM DESCRIPTION [c]
INPD1	N	Total Pressure Drop, inches, Table D1B
INPD2	N	INPD, Individual for TCE
INT	N	Flooding Ordinate, Intermediate Term Calculation
INT2	N	Intermediate Calculation Factor, Table 5
INT3	N	Intermediate Calculation Factor, Table 5
INT4	N	Intermediate Calculation Factor, Table 5
K	N	Operating Ordinate
K1	N	K Individual for Benzene
K2	N	K Individual for Trichloroethylene
KW1	N	Air Blower, Total Kilowatts
KW2	N	Water Pump, Total Kilowatts
KWS	N	Total Stripper Electric Power, Kilowatts
KWS1	N	KWS, Individual for Benzene
KWS2	N	KWS, Individual for TCE
LPP	N	Liquid Packing Parameter, B&F
LPP1	N	Liquid Packing Parameter, B&F
LPP2	N	Liquid Packing Parameter, B&F
LPP3	N	Liquid Packing Parameter, B&F
LPP4	N	Liquid Packing Parameter, B&F
MASSR	N	Mass Ratio, Water/Air
MOLER	N	Mole Ratio, Water/Air
MRAT	N	Air Stream Concentration, ppm by moles
MRAT1	N	MRAT, Individual for Benzene
MRAT2	N	MRAT, Individual for TCE
MSEP	N	Molecular Separations, Air-Contaminant

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TABLE C-1. NOTATION TABLE - DESIGN AND COST ESTIMATING (CONTINUED)

NAMES	[b]	ITEM DESCRIPTION [c]
MWA	N	Molecular Weight, Air
MWK	N	Molecular Weight, Contaminant
MWW	N	Molecular Weight, Water
NTU	N	Number of Transfer Units
NTU1	N	Number of Transfer Units, Table D1B
ORD	N	Flooding Ordinate
PAGB	N	Pressure Gradient for Benzene, pounds/in^2 foot
PAGBI	N	Pressure Gradient for Benzene, inches water/foot
PAGT	N	Pressure Gradient for TCE, pounds/in^2 foot
PAGTI	N	Pressure Gradient for TCE, inches water/foot
PB	N	Pressure Gradient BENZENE, pounds/ft^2 foot
PC	N	Plastic Pall Rings, \$/ft^3
PD	N	Water Pipe Diameter, feet
PDIN	N	Water Pipe Internal Diameter, inches
PGT	N	Pressure Gradient Data Array, Table 8
PPBD	N	Contaminant Concentration Change, ppb
PPD	N	Total Pressure Drop, pounds/in^2
PT	N	Pressure Gradient TCE, pounds/ft^2 foot
PVOL	N	Packing Volume, ft^3
PVOL1	N	Packing Volume, Table D1B
RCP	N	Computation Term, Vapor HTU
RN	N	Row Number Lookup Table 9
RRPMM	N	Contaminant Removal Rate, pound moles/minute
RRPPM	N	Contaminant Removal Rate, pounds/minute
SELB	N	Benzene Value Finder, Table 8

TABLE C-1. NOTATION TABLE - DESIGN AND COST ESTIMATING (CONTINUED)

NAMES	[b]	ITEM DESCRIPTION [c]
SELORDB	N	Ordinate Selector BENZENE, Table 9
SELORDT	N	Ordinate Selector TCE, Table 9
SELT	N	Trichloroethylene Value Finder, Table 8
SENS	T	Control Setup for Sensitivity Analysis
SV	N	Schmidt Number, Vapor
SW	N	Schmidt Number, Weight
SWP1	N	Stripper Weight, Table D1B
TA	N	Treybal Abscissa, Selected for Table 8
TAB1	T	Table 1, Area Name, Design
TAB2	T	Table 2, Area Name, Design
TAB3	T	Table 3, Area Name, Design
TAB4	T	Table 4, Area Name, Design
TAB5	T	Table 5, Area Name, Design
TAB6	T	Table 6, Area Name, Design
TAB7	T	Table 7, Area Name, Design
TAB8	T	Table 8, Area Name, Design
TAB9	T	Table 9, Area Name, Design
TAB10	T	Table 10, Area Name, Design
TAB11	T	Table 11, Area Name, Design
TAB12	T	Table 12, Area Name, Design
TC	N	Celsius Temperature
TCS	N	Total Pounds Contaminant Stripped, Time Base
TK	N	Kelvin Temperature
TORD	N	Treybal Ordinate Table 9
TPL	N	Total Pipe Length for Water, feet

TABLE C-1. NOTATION TABLE - DESIGN AND COST ESTIMATING (CONCLUDED)

NAMES	[b]	ITEM DESCRIPTION [c]
TPW	N	Total Pounds Water, Time Base
TR	N	Rankine Temperature
VPP	N	Vapor Packing Parameter, B&F
VPP1	N	Vapor Packing Parameter, B&F
VPP2	N	Vapor Packing Parameter, B&F
VPP3	N	Vapor Packing Parameter, B&F
VPP4	N	Vapor Packing Parameter, B&F
W1	N	Air Blower, Total Watts
W2	N	Water Pump, Total Watts
WAK	N	Water Diffusivity, m^2/second
WAKA	N	Water Diffusivity, ft^2/second
WCFM	N	Water Feed Rate, ft^3/minute
WD	N	Water Density, pounds/ft^3
WLR	N	Water Loading Rate, (pounds/ft^2)/hour
WPM	N	Water Feed Rate, pounds/minute
WPMM	N	Water Feed Rate, pound moles/minute
WRAT	N	Air Stream Concentration, ppm by weight
WRAT1	N	WRAT, Individual for Benzene
WRAT2	N	WRAT, Individual for TCE
WV1	N	Water Viscosity, Centipoise
WV2	N	Water Viscosity, pounds/foot second
WVSI	N	Water Viscosity, Pa second
Z	N	Total Vertical Lift for Water, feet

[a] + = Designation of a variable design or cost input parameter.
[b] A = Alpha entry, N = Numeric entry, T = Table name for printing.
[c] Descriptive Comments. Names used in Tables D-D1T through D-D7T for TCE are not included since they are parallel to those used in BENZENE Tables D-D1B through D-D7B.

APPENDIX D

DESIGN AND COST-ESTIMATING SPREADSHEET

VOC-2.100

The following 26 tables make up spreadsheet VOC-2.100, which is written in MULTIPLAN 2.01. The file may be exported upward into MP 3.0 or MP 4.0 without difficulty. Tables D-1 through D-12 deal with the design parameters of a packed column, a carbon adsorption off-gas treatment system, and a catalytic oxidation off-gas treatment system. These 12 tables simultaneously handle TCE and Benzene, the latter used as a marker for jet fuel. The seven tables D-D1B through D-D7B are sensitivity analysis output summaries for the Benzene case, and the seven tables D-D1T through D-D7T are the same for the TCE case. Tables D-D1B, D-D2B, D-D1T, and D-D2T summarize requisite design information for use in single-variant sensitivity analyses. Tables D-D3B through D-D5B and D-D3T through D-D5T summarize the fixed capital and the annual operating cost estimates for the packed column stripper, the carbon adsorption off-gas treatment, and the catalytic oxidation off-gas treatment. Tables D-D6B and D-D6T consolidate the fixed capital and the annual operating cost estimates for the packed column stripper options. Tables D-D7B and D-D7T consolidate these for the centrifugal contactor option.

Fixed capital and annual operating (non-capital) cost estimates have been adjusted to 1990 dollars in the following tables. Continuing inflation adjustments for the period of the operating lifetime are handled in a separate spreadsheet, VOC-2.300, which is described in Appendix E. Further details will be found in the related body of the text.

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[TAB1]
VOC-2.100

TABLE D-1

DESIGN INPUT TABLE
Independent Design Variable Inputs

NOTE: All independent variable input names/locations indicated as +[ ]

GENERAL INPUTS

	[NAME]	VALUE			[NAME]	VALUE
Operating Temperature, F	+[TF]	60	Fahrenheit			
Inlet Gas Pressure	+[PAT]	1.00	Atmospheres			

ELECTRICAL EFFICIENCIES

			[NAME]	VALUE
Air Heaters			+[EFPH]	0.7
Air Blowers			+[EFFA]	0.6
Water Pumps			+[EFFW]	0.7

GROUNDWATER STREAM

	[NAME]	VALUE
Water Feed Rate, Gallons/Minute	+[WGM]	500
Contaminant Concentration, ppb IN	+[PPBI]	100
Contaminant Cleanup Factor	+[CUF]	0.990

STRIPPER RELATED PARAMETERS

	[NAME]	VALUE
Groundwater Depth, ft +[HGW]	+[HGW]	30
Fanning Friction Factor+[F]	+[F]	0.008
Horizontal Pipe Length, ft	+[HPL]	100
Consolidated Friction Loss Coefficient for valves, elbows, etc.	+[Kf]	15

STRIPPER

	[NAME]	VALUE
Stripping Factor (greater than unity)	+[S]	4.0

Packing Factor (Treybal, 3rd Ed.)
  For Size: mm(in)...METAL PALL RINGS ONLY

Size-->	16(5/8)	25(1)	38(1 1/2)	50(2)
Select Cf-->	70	48	28	20

	[NAME]	VALUE
Packing Size, mm (in)	+[SIZE]	50(2)
Packing Factor	+[Cf]	20
Correlation factor term *	+[J]	1.502
Flooding Factor	+[FF]	0.4
Height of Each Packed Bed, ft	+[HPB]	10

CARBON AIR STREAM CLEANUP

	[NAME]	VALUE
Carbon Recycle Interval, days	+[CRI]	75
Carbon Use Safety Factor	+[CSF]	1.5
Carbon Bulk Density, lb/ft^3	+[CD]	30
Freundlich Adjustment Factor [For BENZENE ONLY]	+[FAF]	0.20108

CATALYTIC INCINERATION AIR STREAM CLEAN UP

	[NAME]	VALUE
Catalytic Unit Size Safety Factor	+[CASF]	1.5

	[NAME]	VALUE
Height Design Safety Factor	+[SF]	1.7

OVERALL OPERATING CYCLE LOAD FACTOR +[LF]   0.85
  [365 days/year = 1.00)

* See Treybal, 3rd Ed.

COST PARAMETERS

		[NAME]	VALUE
Equip. Inst. Factor (Stripper)		+[EIFS]	2.20
E.. [Carbon, and Catalytic]		+[EIFC]	1.60
Materials [SS] Factor, STRIPPER		+[MMF]	1.70
Fuel Oil, 1990 $/10^6 BTU		+[FC]	6.15
Electricity Cost, 1990 $/kwh		+[EC]	0.060
Operations & Maintenance Factor		+[OM]	0.150
Overhead Rate (%) on Expense		+[OHR]	100
Av. Annual Inflation: 1977-90		+[I]	0.0484

SINGLE VARIABLE SENSITIVITY ANALYSIS, INPUT CONTROLS
[To suppress sensitivity iterations, set VNUM = 0]

Name of variable	+[VI]	CRI
Variable initial value	+[VIN]	5
Variable step value	+[VSTEP]	5
Number of values to run	+[VNUM]	15
Current variable value	[VAR]	75

[TAB2]
VOC-2.100

TABLE D-2
SUMMARY OF INDEPENDENT AND DEPENDENT DESIGN INPUT VARIABLES

+[ ] Indicates original location of a NAMED INDEPENDENT VARIABLE input (see Table 1).
[ ] Indicates original location of a NAMED DEPENDENT VARIABLE.
{ } Indicates a NAMED VALUE, transferred from an earlier location.

GENERAL INPUTS	[NAME]	VALUE
Operating Temperature, F		
Fahrenheit	{TF}	60
Rankine	[TR]	519.670
Celsius	[TC]	15.556
Kelvin	[TK]	288.706
Inlet Gas Pressure Atmospheres	{PAT}	1.00
GROUNDWATER STREAM		
Water Feed Rate, Gallons/Minute	{WGM}	500
Contaminant Concentration, ppb IN	{PPBI}	100
Contaminant Cleanup Factor	{CUF}	0.990
Contaminant Concentration, ppb OUT	[PPBO]	1
STRIPPER		
Stripping Factor [greater than unity]	{S}	4.0
Packing Factor [Treybal, 3rd Ed.]		
For Size: mm(in)...METAL PALL RINGS ONLY		
Size--> 16(5/8) 25(1) 38(1 1/2) 50(2)		
Select Cf--> 70 48 28 20		
Packing Size, mm (in)	{SIZE}	50(2)
Packing Factor	{Cf}	20
Correlation factor term **	{J}	1.502
Flooding Factor	{FF}	0.40
Height of Each Packed Bed, ft	{HPB}	10
Height Design Safety Factor	{SF}	1.7
** See Treybal, 3rd Ed.		

--ELECTRICAL EFFICIENCIES	[NAME]	VALUE
Air Heaters	[EFFH]	0.7
Air Blowers	{EFFA}	0.6
Water Pumps	{EFFW}	0.7
--STRIPPER RELATED PARAMETERS		
GroundWater Depth, ft	{HGW}	30
Fanning Friction Factor	{F}	0.008
Horizontal Pipe Length, ft	{HPL}	100
Pipe Internal Diameter, inches	[PDIN]	7
Consolidated Friction Loss Coefficient for valves, elbows, etc.	{Kf}	15
--CARBON AIR STREAM CLEANUP		
Carbon Recycle Interval, days	{CRI}	75
Carbon Use Safety Factor	{CSF}	1.5
Carbon Bulk Density, lb/ft^3	{CD}	30
Freundlich Factor, BENZENE	{F,F}	0.20108
--CATALYTIC INCINERATION AIR STREAM CLEAN UP		
Catalytic Unit Size Safety Factor	{CASF}	1.5
--OVERALL OPERATING LOAD FACTOR [365 days/year = 1.00]	{LF}	0.85
--COST PARAMETERS		
Fuel oil, 1990 $/10^6 BTU	{FC}	6.15
Equip. Inst. Factor (Stripper)	{EIFS}	2.20
EIF [Carbon, and Catalytic]	{EIPC}	1.60
Materials [SS] Factor, STRIPPER	{MMF}	1.70
Plastic Pall Rings, 1990$/ft^3	{PC}	5.50
Electricity Cost, 1990 $/kwh	{EC}	0.060
Operations & Maintenance Factor	{OM}	0.150
Overhead Rate (%) on Expense	{OHR}	100
Av. Annual Inflation: 1977-90	{I}	0.0484

FIXED NUMERICAL CONSTANTS

		BENZENE	TCE*
Molecular Weights			
Air	[MWA]	28.96	28.96
Water	[MWW]	18.016	18.016
Key Contaminant	[MWK]	78.11	131.39
g'c: Time base = seconds	[gcs]	3.217E+01	3.217E+01
Time base = minutes [used here]	[gcm]	1.158E+05	1.158E+05
Time base = hours	[gch]	4.170E+08	4.170E+08

```
***********************************
     STATUS OF SENSITIVITY
     ANALYSIS ITERATIONS
***********************************
SENSITIVITY ANALYSIS RUNNING    YES
NAME OF VARIABLE                CRI
```

[TAB3]
VOC-2.100

TABLE D-3
INTERIM INFORMATION SUMMARY TABLE FOR STRIPPER CALCULATIONS
* Trichloroethylene

		BENZENE	TCE*
MISCELLANEOUS			
Water Viscosity, Centipoise (in TC)	[WV1]	1.12171	1.12171
Water Viscosity, lb/ft s	[WV2]	7.538E-04	7.538E-04
Air Viscosity, Centipoise (in TF)	[AV1]	0.01736	0.01736
Air Viscosity, lb/ft s	[AV2]	1.167E-05	1.167E-05
Henry's Law Constants [Dimensionless, i.e. H = y/x, or the ratio of the mole fractions in the gas & liquid phases]	[H]	198.293	276.118
TEMPERATURES			
Operating Temperature, F	{TF}	60	60
Operating Temperature, C	{TC}	15.556	15.556
Operating Temperature, R	{TR}	519.670	519.670
Operating Temperature, K	{TK}	288.706	288.706
WATER FEED DATA, All Calculated from [WGM] input.			
Water Feed Rate, Gallons/Minute	{WGM}	500	500
Water Feed Rate, Cubic Feet/Minute	[WCFM]	66.8405	66.8405
Water Density, Pounds/Cubic Foot	[WD]	62.3582	62.3582
Water Feed Rate, Pounds/Minute	[WPM]	4168.0479	4168.0479
Water Feed Rate, Pound Moles/Minute	[WPMM]	231.3526	231.3526
AIR FEED DATA			
Air Pressure, Atm	{PAT}	1.000	1.000
Air Pound Moles/Cubic Foot ***	[AMCF]	0.002635	0.002635
Air Pounds/Cubic Foot, DENSITY ***	[AD]	0.076311	0.076311
And introduce Henry's Constant & Stripping Factor			
Air Pound Moles/Minute [makes use of S]	[APMM]	4.6669	3.3515
Air Pounds/Minute	[APM]	135.1526	97.0594
Air Cubic Feet/Minute	[ACFM]	1771.0661	1271.8857
Mass Ratio: Water/Air	[MASSR]	30.8396	42.9433
Mole Ratio: Water/Air	[MOLER]	49.5734	69.0296

*** Corrected for pressure [PAT] and temperature [TF], but
NOT humidity corrected, i.e. for moisture content of air.

[TAB4]
VOC-2.100

TABLE D-4

DIAMETER CALCULATIONS FOR PACKED STRIPPER

CALCULATE THE TREYBAL ABSCISSA = (WPM/APM)*(AD/WD)$^{0.5}$

Abscissa, [ABSB], and [ABST]	[ABS]	1.0788	1.5023
FLOODING Intermediate:(log10(ABS)+2)/2	[INT]	0.6777	0.7256
FLOODING Ordinate	[ORD]	0.03014	0.02058
Cf, for Pall Rings	{Cf}	20	20
g'c - stipulate gcs, gcm, or gch	{gcm}	1.158E+05	1.158E+05
Water Viscosity, cP	{WV1}	1.12171	1.12171
Air Viscosity, cP	{AV1}	0.01736	0.01736
J (Use only with Treybal, 3rd Ed.)	{J}	1.502	1.502
K (Treybal, 3rd Ed. Ordinate Constant)		5.520E-05	5.520E-05
Air Loading Rate AT FLOODING (lb/min)/ft^2	[ALR]	23.37	19.31
Flooding Factor	{FF}	0.4	0.4
Adjusted ORD, FF*ORD [Hylton] ##	[AORD]	0.01205	0.00823
Derived Air Loading Rate (lb/min)/ft^2	[DALR]	9.35	7.72
Derived ORD, Bolles & Fair	[DORD]	0.004822	0.003294
...Also [DORDB] for Benzene, & [DORDT] for Trichloroethylene			
Cross Section AREA, ft^2, APM/DALR	[AREA]	14.46057	12.56523
STRIPPER DIAMETER, ft	[DIA]	4.291	4.000
Stripper Diameter, inches	[din]	51.491	47.998

[TAB5]
VOC-2.100

TABLE D-5

VAPOR HTU CALCULATIONS FOR PACKED STRIPPER

Vapor Packing Parameter, VPP

For 5/8 in Pall Rings	[VPP1]	70	70.7857	70.7857
For 1 in Pall Rings	[VPP2]	48	73.2619	73.2619
For 1 1/2 in Pall Rings**	[VPP3]	28	106.0357	106.0357
For 2 in Pall Rings	[VPP4]	20	138.8095	138.8095
** Interpolated value	[VPP]		138.8095	138.8095

Taken From Earlier Entries & Calculations

Air Viscosity, lb/ft sec	{AV2}	1.167E-05	
Air Density, lb/ft^3	{AD}	0.07631	
Air Pressure, Atmospheres	{PAT}	1.00	
Temperature, Kelvins	{TK}	288.71	
Molecular Weight of Air	{MWA}	28.96	28.96
Molecular Weight of Key Comp.	{MWK}	78.11	131.39
1/MWA		0.034530	0.034530
1/MWK		0.012802	0.007611
$[1/MWA + 1/MWK]^{0.5}$ ---->	[RCP]	0.217561	0.205284

Stripper Diameter, ft ***	{DIA}	4.291	4.000

Collision Function Calculations
(Ref. Fig. 2.5 Treybal)

Abscissa	[ABS2]	1.6037	1.5594
(Log10(ABS2)+1)/3.60206	[INT2]	0.33457	0.33119
Collision Function, Vapor [Ordinate]	[CFV]	0.59265	0.59927

Molecular Separations Air-Key Contaminant	[MSEP]	0.4530	0.4658

Diffusivity, m^2/sec	[DAK]	8.9190E-06	7.8949E-06
Diffusivity, ft^2/sec	[DAKA]	9.5954E-05	8.4937E-05

Schmidt Number, Vapor	[SV]	1.59348	1.80018

HTU, AIR, ft	[HA]	1.1861	1.1588

*** This diameter value is used for calculation of the required volume of packing, and for the cross sectional area of the packed column stripper. BUT ... an artificial diameter of 2 feet appears in the calculation of the HTU [H?] in this table. (Hylton, ORNL)

[TAB6]
VOC-2.100

TABLE D-6
LIQUID HTU CALCULATIONS FOR PACKED STRIPPER

Water Loading Rate, lb/ft² hour	[WLR]	17294.120	19902.772
Intermediate: (Log10(ABS)-2.30103)/2.30103	[INT3]	0.84174	0.86826
Liquid Packing Parameter, LPP			
For 5/8 in Pall Rings 70	[LPP1]	0.1192	0.1319
For 1 in Pall Rings 48	[LPP2]	0.1002	0.1102
For 1 1/2 in Pall Rings** 28	[LPP3]	0.1193	0.1280
For 2 in Pall Rings 20	[LPP4]	0.1384	0.1459
** Interpolated value	[LPP]	0.1384	0.1459
Intermediate: (FF-0.5)/0.32	[INT4]	-0.3125	-0.3125
Flood Point Coefficient	[FPC]	1.000	1.000
Height of Packed Bed, ft	{HPB}	10	10
Water Viscosity, Centipoise	{WV1}	1.12171	1.12171
Water Viscosity, Pa sec	[WVSI]	1.122E-03	1.122E-03
Water Viscosity, lb/ft sec	{WV2}	7.538E-04	7.538E-04
Water Density, lb/ft³	{WD}	62.358	62.358
Water Diffusivity, m²/sec	[WAK]	8.0097E-10	8.0097E-10
Water Diffusivity, ft²/sec	[WAKA]	8.6171E-09	8.6171E-09
Schmidt Number - Water	[SW]	1402.73	1402.73
HTU, WATER, ft	[HW]	5.1830	5.4647

[TAB7]
VOC-2.100

TABLE D-7

OVERALL HEIGHT OF TRANSFER UNIT FOR PACKED STRIPPER

Ref. Treybal p. 311, eq. 8.56

Overall Height = (HTU, WATER, ft) + (HTU, AIR, ft)/S

Recall from previous calculations

HTU, AIR, ft	{HA}	1.1861	1.1588
HTU, WATER, ft	{HW}	5.1830	5.4647
HTU, TOTAL, ft	[HT]	5.4795	5.7544

[TAB8]
VOC-2.100   NUMBER OF TRANSFER UNITS CALCULATIONS FOR PACKED STRIPPER

TABLE D-8

Ref. Treybal p. 309, eqn. 8.51

IN WATER

Contaminant Concentration, ppb IN	{PPBI}	100	100
Contaminant Mole Fraction, IN	[CMFI]	2.306E-08	1.371E-08
Contaminant Concentration, ppb OUT	{PPBO}	1	1
Contaminant Mole Fraction, OUT	[CMFO]	2.306E-10	1.371E-10
Contaminant Concentration Change, ppb	[PPBD]	99	99
Contaminant Removal Rate, Pounds/Min	[RRPPM]	4.126E-04	4.126E-04
Contaminant Removal Rate, Pound Mols/Min	[RRPMM]	5.283E-06	3.141E-06
Number of Transfer Units Required	[NTU]	5.761	5.761

TOTAL HEIGHT OF COLUMN

Total = Total HTU * NTU

Total Height Required, ft	[HTR]	31.57	33.15
Safety Factor	{SF}	1.7	1.7
TOTAL HEIGHT OF PACKING, FT	[HTOT]	53.67	56.36

[TAB9]
VOC-2.100

TABLE D-9 [DATA LOOKUP TABLE]
CALCULATION OF PACKED STRIPPER PRESSURE GRADIENT
[See associated documentation for discussion of method]

Previously calculated Treybal Abscissa and Ordinate values for Benzene and TCE

ABSCISSA [ABSB] 1.0788 [ABST] 1.5023

ORDINATE [DORDB] / [DORDT]

Row Number [RN]	Treybal Abscissa [TA]	[SELB]	Column Number---> [SELT] [CN] [TORD] [SELORDB] [SELORDT] [PGT]----->	ORDINATE 1 0.00005 0 0	[DORDB] [DORDT] 2 0.00010 0 0	0.0048 3 0.00050 0 0	0.0033 4 0.00100 0 0	5 0.002 0 5	6 0.004 6 0
1	0.015	0	0	0.060	0.130	0.900	2.00	2	8
2	0.020	0	0	0.062	0.133	0.980	2.23	5	10
3	0.040	0	0	0.064	0.136	1.064	2.47	8	16
4	0.060	0	0	0.066	0.142	1.147	2.72	10	18
5	0.100	0	0	0.069	0.148	1.234	2.98	16	22
6	0.150	0	0	0.072	0.156	1.325	3.29	18	24
7	0.200	0	0	0.075	0.166	1.426	3.75	20	26
8	0.300	0	0	0.081	0.182	1.542	4.33	22	30
9	0.400	0	0	0.089	0.204	1.687	5.10	25	35
10	0.500	0	0	0.101	0.238	1.877	6.16	28	40
11	0.600	0	0	0.120	0.288	2.140	7.60	30	45
12	0.800	0	0	0.149	0.360	2.513	9.55	33	52
13	1.000	13	0	0.193	0.457	3.033	12.09	35	60
14	1.500	0	14	0.240	0.580	3.700	15.25	40	85
15	2.000	0	0	0.293	0.720	4.367	18.80	48	105
16	3.000	0	0	0.347	0.860	5.033	22.40	75	200
17	4.000	0	0	0.400	1.000	5.700	26.00	125	500

*** PRESSURE GRADIENTS, FROM LOOKUP TABLE [PGT]
***

	BENZENE	TCE	
*** In Pa/meter------>	60.00	40.00	<--- [PAGB] & [PAGT]
*** In lb/in² ft----->	0.0027	0.0018	<--- [PAGBI] & [PAGTI]
*** In inches H2O/ft-->	0.0734	0.0490	<--- [PAGBI] & [PAGTI

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[TAB9]
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TABLE D-9 (DATA LOOKUP TABLE) (CONCLUDED)
CALCULATION OF PACKED STRIPPER PRESSURE GRADIENT
(See associated documentation for discussion of method)

Previously calculated Treybal Abscissa and Ordinate values for Benzene and TCE

ABSCISSA	[ABSB]	1.0788	ORDINATE	[DORDB]	0.0048
	[ABST]	1.5023		[DORDT]	0.0033

Row Number [RN]	Treybal Abscissa [TA]	[SELB]	[SELT]	Column Number---> [CN] [TORD] [SELORDB] [SELORDT] [PGT]--->							
				7	8	9	10	11	12	13	14
				0.006	0.008	0.010	0.020	0.040	0.060	0.08.	0.100
1	0.015	0	0	0	0	0	0	0	0	0	0
2	0.020	0	0	15	20	0	0	0	0	0	0
3	0.040	0	0	18	25	35	80	150	230	350	490
4	0.060	0	0	22	30	40	82	155	240	360	500
5	0.100	0	0	25	35	45	85	175	275	400	580
6	0.150	0	0	30	40	48	90	185	300	440	600
7	0.200	0	0	35	45	52	95	205	380	580	750
8	0.300	0	0	40	50	60	100	250	400	680	900
9	0.400	0	0	45	60	65	125	300	500	800	1200
10	0.500	0	0	50	70	75	150	400	700	1200	
11	0.600	0	0	60	85	80	180	550	1100		
12	0.800	0	0	70	90	95	280	900			
13	1.000	13	0	80	100	115	320	1200			
14	1.500	0	14	90	125	150	490				
15	2.000	0	0	140	200	160	600				
16	3.000	0	0	200	380	300					
17	4.000	0	0	500	1100	600					

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[TAB10]

TABLE D-10

VOC-2.100   SUMMARY OF PACKED COLUMN STRIPPER GEOMETRY CALCULATIONS

OPERATING VARIABLES

Operating Temperature, F	{TF}	60.00
Inlet Gas Pressure, Atm	{PAT}	1.00
Water Feed Rate, Gallons/Minute	{WGM}	500
Contaminant Concentration, ppb IN	{PPBI}	100
Contaminant Concentration, ppb OUT	{PPBC}	1
Stripping Factor	{S}	4
Packing Type - Metal Pall Rings		
Packing Size	{SIZE}	50(2)
Packing Factor	{Cf}	20
Correlation Factor, J	{J}	1.502
Flooding Factor	{FF}	0.40
Height of Packed Bed	{HPB}	10
Height Safety Factor	{SF}	1.7

DESIGN OUTPUTS

		Benzene	TCE*
Stripper Diameter, ft	{DIA}-->	4.291	4.000
HTU AIR, ft	{HA}	1.1861	1.1588
HTU WATER, ft	{HW}	5.1830	5.4647
HTU TOTAL, ft	{HT}-->	5.4795	5.7544
Number of Transfer Units Required	{NTU}	5.761	5.761
Total Height Required, ft	{HTR}-->	31.568	33.152
Safety Adjusted Height Required, ft	{HTOT}-->	53.665	56.358
VOLUME OF PACKING, HTOT*$(\pi/4)$*DIA^2, ft^3	[PVOL]-->	776.031	708.153
PRESSURE GRADIENT, lb/in^2 ft	{PAGB, PAGT}-->	0.0026531	0.0017688

NOTE: --> in rows just above highlights the key geometrical data.

[TAB11]
VOC-2.100

TABLE D-11

AIR BLOWER & WATER PUMP CALCULATIONS FOR PACKED STRIPPER

INPUTS

Vertical Lift of Water			
GroundWater Depth, ft	{HGW}	30	30
Total Stripper Height, ft	{HTOT}	53.665	56.358
Total Vertical Lift, ft = HGW + HTOT + 10	[Z]	93.665	96.358
Friction Loss Factors			
Fanning Friction Factor	{F}	0.008	0.008
Horizontal Pile Length, ft	{HPL}	100	100
Total Pipe Length = Z + HPL, ft	[TPL]	193.665	196.358
Pipe Internal Diameter, inches	{PDIN}	7	7
Pipe Internal Diameter, ft	[PD]	0.5833	0.5833
Consolidated Friction Loss Coefficient, for Valves, Elbows, etc.	{Kf}	15	15
TOTAL FRICTION LOSS FACTOR	[HF]	25.62	25.77
AIR BLOWER CALCULATIONS			
Pressure Gradient, lb/in^2 ft,	{ACFM}	1771.07	1271.89
Pressure Gradient, lb/ft^2 ft	{PAGB, PAGT}	0.0026531	0.0017688
	[PB, PT]	0.3821	0.2547
TOTAL PRESSURE DROP, lb/in^2	[PPD]	0.1424	0.0997
Total Pressure Drop, inches of water	[INPD]	3.94	2.76
Air Density, lb/ft^3	{AD}	0.07631	0.07631
Packing Height, TOTAL, ft	{HTOT}	53.665	56.358
PUMP POWER: Horsepower, electric	[HP1]	1.83	0.55
Watts	[W1]	1367.57	412.56
Kilowatts, [KW1B], [KW1T]	[KW1]	1.37	0.41
WATER LIFT PUMP CALCULATIONS			
PUMP POWER: Horsepower, electric	[HP2]	18.19	18.68
Watts	[W2]	13570.09	13937.78
Kilowatts, [KW2B], [KW2T]	[KW2]	13.57	13.94
TOTAL STRIPPER POWER, kW, [KWSB], [KWST]	[KWS]	14.94	14.35

[TAB12]
VOC-2.100

TABLE D-12

CARBON USE CALCULATIONS FOR OFF GAS TREATMENT

AIR STREAM CALCULATIONS

Contaminant Removal Rate, Pounds/Min	{RRPPM}	4.126E-04	4.126E-04
Air Stream Rate, Pounds/Min	{APM}	135.15	97.06
AIR STREAM CONCENTRATION, ppm by WEIGHT	[WRAT]	3.05	4.25
Contaminant Removal Rate, Pound Mols/Min	{RRPMM}	5.283E-06	3.141E-06
Air Stream Rate, Pound Mols/Min	{APMM}	4.67	3.35
AIR STREAM CONCENTRATION, ppm by MOLS	[MRAT]	1.13	0.94

DATA FOR {WGM}   500

Breakthrough Capacity [Freundlich] * lb contaminant/lb carbon	[BC]	0.00520	0.03809

WATER PROCESSING, INFORMATION, PER DAY

Total Pounds Water Processed	[TPW]	6.002E+06	6.002E+06
Total Pounds Contaminant Stripped	[TCS]	0.594	0.594
POUNDS OF CARBON REQUIRED/DAY	[CARR]	114.16	15.60
Carbon Use Safety Factor	{CSF}	1.5	1.5
ADJUSTED CARBON POUNDS PER DAY	[CPD]	171.25	23.40
Carbon Bulk Density, lb/ft³ **	{CD}	30	30
ADJUSTED CARBON, CUBIC FEET PER DAY	[CFPD]	5.708	0.780

*   Compare with Eglin AFB breakthrough graphs provided by Lucero
    and Hylton, at 2 ppm benzene.
** Bulk densities vary SUBSTANTIALLY depending upon the source raw
    material and the method of preparation. The value shown is an
    approximate mean value of those reported in the Chemical Engineers
    Handbook.

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[D1B]
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TABLE D-D1B
PACKED COLUMN STRIPPER
SINGLE VARIABLE DESIGN OUTPUT INFORMATION

BENZENE

VARIABLE INPUT CRI	Treybal, 3rd Ed. ABSCISSA	ORDINATE	STRIPPER DIAMETER feet	NUMBER TRANSFER UNITS	HEIGHT VAPOR TRANSFER UNIT feet	HEIGHT LIQUID TRANSFER UNIT feet	STRIPPER HEIGHT [1] feet	STRIPPER WEIGHT [2] pounds	PACKING VOLUME [3] feet	PRESSURE GRADIENT in H2O/ft	TOTAL PRESSURE DROP, AIR [4] inches H2O
	{ABSB}	{DORDB}	{DIA1}	{NTU1}	{HA1}	{HW1}	{HTOT1}	[SWP1]	{PVOL1}	{PAGB1}	{INPD1}
5.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
10.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
15.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
20.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
25.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
30.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
35.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
40.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
45.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
50.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
55.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
60.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
65.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
70.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94
75.000	1.0788	0.004822	4.29	5.76	1.19	5.18	53.67	8041	776.03	0.0734	3.94

[1] Adjusted for HEIGHT DESIGN SAFETY FACTOR, [SF] = 1.7
[2] Based upon adjusted height, and 0.25 inch steel construction.
[3] Based upon the adjusted stripper height.
[4] Based upon the adjusted stripper height.
[5] WGM may also appear as the variable input for some sensitivity analysis runs.

TABLE D-D1B
PACKED COLUMN STRIPPER
SINGLE VARIABLE DESIGN OUTPUT INFORMATION (CONCLUDED)

BENZENE

			STRIPPER POWER DEMAND		
VARIABLE INPUT	AIR FLOW RATE ft³/min	WATER FLOW RATE [5] gal/min	AIR ********* kilowatts	WATER	TOTAL *********
	{ACFM1} [ACFMB]	{WGM}	{KW1B}	{KW2B}	{KWSB}
CRI					
5.000	1771.07	500.00	1.37	13.57	14.94
10.000	1771.07	500.00	1.37	13.57	14.94
15.000	1771.07	500.00	1.37	13.57	14.94
20.000	1771.07	500.00	1.37	13.57	14.94
25.000	1771.07	500.00	1.37	13.57	14.94
30.000	1771.07	500.00	1.37	13.57	14.94
35.000	1771.07	500.00	1.37	13.57	14.94
40.000	1771.07	500.00	1.37	13.57	14.94
45.000	1771.07	500.00	1.37	13.57	14.94
50.000	1771.07	500.00	1.37	13.57	14.94
55.000	1771.07	500.00	1.37	13.57	14.94
60.000	1771.07	500.00	1.37	13.57	14.94
65.000	1771.07	500.00	1.37	13.57	14.94
70.000	1771.07	500.00	1.37	13.57	14.94
75.000	1771.07	500.00	1.37	13.57	14.94

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TABLE D-D2B
CARBON ADSORPTION AND CATALYTIC INCINERATION
SINGLE VARIABLE DESIGN OUTPUT INFORMATION

BENZENE

| | | | | | | | | | | | CATALYSIS UNIT SIZING INFORMATION | |
| VARIABLE INPUT | AIR FLOW RATE | BENZENE MOLAR CONCENTRATION | CARBON DAILY USE [1] | CARBON CYCLE USE [2] | CARBON DESIGN SIZE [1,2] | CARBON UNITS PURCHASED [3] | CARBON CAPITAL PURCHASE [4] | CARBON RECYCLED ANNUALLY [5] | AIR FAN POWER [6] | AIR HEATER [8] | AIR FLOW [7] | AIR HEATER [8] |
CRI	lb/min {APM1} [APMB]	ppm {MRAT1}	lb/day {CPD1}	lb/cycle [CCU]	pounds [CDS]	[CUP]	pounds	pounds [CRA]	kilowatts [KWCB]	10⁶ BTU/yr [FUEL1B]	ft³/min [ACAT]	10⁶ BTU/yr [FUEL2B]
5.000	135.2	1.1	171	856	856	2	1712	53129	6.84	935	2657	26188
10.000	135.2	1.1	171	1712	1712	2	3425	53129	6.84	935	2657	26188
15.000	135.2	1.1	171	2569	2569	2	5137	53129	6.84	935	2657	26188
20.000	135.2	1.1	171	3425	3425	2	6850	53129	6.84	935	2657	26188
25.000	135.2	1.1	171	4281	4281	2	8562	53129	6.84	935	2657	26188
30.000	135.2	1.1	171	5137	5137	2	10275	53129	6.84	935	2657	26188
35.000	135.2	1.1	171	5994	5994	2	11987	53129	6.84	935	2657	26188
40.000	135.2	1.1	171	6850	6850	2	13700	53129	6.84	935	2657	26188
45.000	135.2	1.1	171	7706	7706	2	15412	53129	6.84	935	2657	26188
50.000	135.2	1.1	171	8562	8562	2	17125	53129	6.84	935	2657	26188
55.000	135.2	1.1	171	9419	9419	2	18837	53129	6.84	935	2657	26188
60.000	135.2	1.1	171	10275	10275	2	20550	53129	6.84	935	2657	26188
65.000	135.2	1.1	171	11131	11131	2	22262	53129	6.84	935	2657	26188
70.000	135.2	1.1	171	11987	11987	2	23974	53129	6.84	935	2657	26188
75.000	135.2	1.1	171	12843	12843	2	25687	53129	6.84	935	2657	26188

[1] Corrected for CARBON UNIT SIZE SAFETY FACTOR (CSF) = 1.50
[2] Adjusted for CARBON RECYCLE INTERVAL, days (CRI) = 75
[3] One spare adsorption unit purchased, for contingency and for shift of throughput during carbon regeneration.
[4] Subsequent to initial purchase of carbon, the regeneration cycle provides for adequate make up with new carbon.
[5] Based upon Load Factor [LF] = 0.85 and stipulated values of CSF and CRI.
[6] Sized at 5X the air fan requirements of stripper.

[7] Based upon CATALYTIC UNIT SIZE SAFETY FACTOR [CASF] = 1.5

[8] Air stream heating for both carbon adsorption and catalysis units.

10⁶ BTU = Millions BTU

(D3B)
VOC-2.100

TABLE D-D3B
PACKED COLUMN STRIPPER

BENZENE

	CAPITAL EXPENDITURES						ANNUAL EXPENSE					
VARIABLE INPUT	AIR FAN & MOTOR [1] 1977 $	WATER PUMP & MOTOR [1] 1977 $	STRIPPER SHELL [1] 1977 $	PLASTIC PALL RINGS [1] 1990 $	TOTAL EQUIPMENT DELIVERED [6] 1990 $	TOTAL EQUIPMENT INSTALLED [2] 1990 $ [CAPSB]	MAINTENANCE OF PALL RING PACKING [3] 1990 $	LABOR ONE FTE 1990 $	ELECTRICAL POWER COSTS 1990 $	MISC & O&M [4] 1990 $	UNLOADED TOTAL ANNUAL EXPENSE 1990 $	LOADED TOTAL ANNUAL EXPENSE [5] 1990 $ [EXPSB]
CRI												
5.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
10.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
15.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
20.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
25.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
30.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
35.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
40.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
45.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
50.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
55.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
60.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
65.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
70.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149
75.000	5238	3275	31525	4268	78285	172226	1067	24000	6674	25834	57575	115149

[1] Materials of construction costs adjusted upward via
    MATERIALS MULTIPLIER FACTOR   [MMF] =   1.70
[2] Adjusted upward via EQUIPMENT INSTALLATION
    FACTOR   [EIFS] =   2.20
[3] Pall ring maintenance at 25% of 1990 purchase cost.
[4] Factor x Installed Capital Equipment Costs [OM] =   0.15
[5] Overhead Rate on Total Annual Expense, %   [OHR] =   100
[6] Average Annual Inflation: 1977-90   [I] =   0.0484

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[D4B]
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TABLE D-D4B
CARBON ADSORPTION UNITS
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

BENZENE

	CAPITAL EXPENDITURES					ANNUAL EXPENSE				
VARIABLE INPUT	NEW CHARCOAL PURCHASED [1] 1977$	NEW CHARCOAL PURCHASED 1990$	CARBON SORPTION UNITS [2] 1982 $	CARBON SORPTION UNITS 1990 $	TOTAL EQUIPMENT INSTALLED [3] 1990 $ [CAPCB]	ANNUAL FUEL OIL COSTS [5] 1990 $	CHARCOAL RECYCLE COSTS 1990 $	ELECTRICAL POWER COSTS 1990 $	UNLOADED TOTAL ANNUAL EXPENSE 1990 $	LOADED TOTAL ANNUAL EXPENSE [4] 1990 $ [EXPCB]
CRI										
5.000	1712	3166	78485	114553	188349	5752	44368	3055	53175	66469
10.000	3425	6331	84171	122851	206691	5752	44368	3055	53175	66469
15.000	5137	9497	89856	131149	225033	5752	44368	3055	53175	66469
20.000	6850	12663	95541	139447	243375	5752	44368	3055	53175	66469
25.000	8562	15829	101227	147745	261717	5752	44368	3055	53175	66469
30.000	10275	18994	106912	156043	280059	5752	44368	3055	53175	66469
35.000	11987	22160	112598	164341	298401	5752	44368	3055	53175	66469
40.000	13700	25326	118283	172639	316743	5752	44368	3055	53175	66469
45.000	15412	28491	123968	180937	335085	5752	44368	3055	53175	66469
50.000	17125	31657	129654	189235	353427	5752	44368	3055	53175	66469
55.000	18837	34823	135339	197533	371769	5752	44368	3055	53175	66469
60.000	20550	37989	141024	205831	390111	5752	44368	3055	53175	66469
65.000	22262	41154	146710	214129	408453	5752	44368	3055	53175	66469
70.000	23974	44320	152395	222427	426795	5752	44368	3055	53175	66469
75.000	25687	47486	158081	230725	445137	5752	44368	3055	53175	66469

[1] Based upon $1.00/lb, 1977 Prices.
[2] There is a shift in the cost correlation function at a size of about 10,000 lb carbon.
[3] Using Equipment Installation Factor [EIF] as shown in Table 1.
[4] Overhead at 25% of total annual expense. The primary burden of the
    overhead is loaded on the packed column stripper.
[5] For heating of air stream to lower relative humidity before input
    to carbon adsorption units.

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TABLE D-D5B
CATALYTIC INCINERATION UNIT
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

BENZENE

| | CAPITAL EXPENDITURES | | | ANNUAL EXPENSE | | | | | |
VARIABLE INPUT	UNIT COST	UNIT COST	TOTAL EQUIPMENT INSTALLED [1]	ANNUAL FUEL OIL COSTS	ELECTRICAL POWER COSTS	ANNUAL CATALYST COST	ANNUAL CATALYST COST	TOTAL	LOADED TOTAL ANNUAL EXPENSE [2]
CRI	1979 $	1990 $	1990 $ [CAPCATB]	1990 $	1990 $	1979 $	1990 $	1990 $	1990 $ [EXPCATB]
5.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
10.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
15.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
20.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
25.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
30.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
35.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
40.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
45.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
50.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
55.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
60.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
65.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
70.000	29081	48911	78257	161058	3055	2678	4505	168618	210772
75.000	29081	48911	78257	161058	3055	2678	4505	168618	210772

[1] Using Equipment Installation Factor [EIF] as shown in Table 1.

[2] Overhead at 25% of total annual expense. The primary burden of the overhead is placed on the packed column stripper.

TABLE D-D6B
COMBINED EQUIPMENT SYSTEMS
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

BENZENE

VARIABLE INPUT	PACKED STRIPPER		CARBON SORPTION		PACKED STRIPPER & CARBON SORPTION		CATALYSIS UNIT		PACKED STRIPPER & CATALYSIS UNIT	
	TOTAL FIXED CAPITAL	TOTAL ANNUAL EXPENSE	TOTAL FIXED CAPITAL	TOTAL ANNUAL EXPENSE	COMBINED FIXED CAPITAL	COMBINED EXPENSE	TOTAL FIXED CAPITAL	TOTAL ANNUAL EXPENSE	COMBINED FIXED CAPITAL	COMBINED EXPENSE
CRI	1990 $ {CAPSB}	1990 $ {EXPSB}	1990 $ {CAPCB}	1990 $ {EXPCB}	1990 $	1990 $	1990 $ {CAPCATB}	1990 $ {EXPCATB}	1990 $	1990 $
5.000	172226	115149	188349	66469	360575	181618	78257	210772	250483	325922
10.000	172226	115149	206691	66469	378917	181618	78257	210772	250483	325922
15.000	172226	115149	225033	66469	397259	181618	78257	210772	250483	325922
20.000	172226	115149	243375	66469	415601	181618	78257	210772	250483	325922
25.000	172226	115149	261717	66469	433943	181618	78257	210772	250483	325922
30.000	172226	115149	280059	66469	452285	181618	78257	210772	250483	325922
35.000	172226	115149	298401	66469	470627	181618	78257	210772	250483	325922
40.000	172226	115149	316743	66469	488969	181618	78257	210772	250483	325922
45.000	172226	115149	335085	66469	507311	181618	78257	210772	250483	325922
50.000	172226	115149	353427	66469	525653	181618	78257	210772	250483	325922
55.000	172226	115149	371769	66469	543995	181618	78257	210772	250483	325922
60.000	172226	115149	390111	66469	562337	181618	78257	210772	250483	325922
65.000	172226	115149	408453	66469	580679	181618	78257	210772	250483	325922
70.000	172226	115149	426795	66469	599021	181618	78257	210772	250483	325922
75.000	172226	115149	445137	66469	617363	181618	78257	210772	250483	325922

Compare with Table D7B, which is for the centrifugal contactor. In D7B,
the two columns for the packed stripper are replaced by calculation
of the fixed capital and the annual [non-capital] expense for the
centrifugal contactor.

The capital and expense figures for the carbon adsorption and the
catalytic incineration are identical in D6B and D7B, however.

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TABLE D-D7B
COMBINED EQUIPMENT SYSTEMS
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

BENZENE

| VARIABLE INPUT | ROTARY STRIPPER | FANS, PUMPS, MOTORS | CENTRIFUGAL CONTACTOR | | CARBON SORPTION | | CENTRIFUGAL CONTACTOR & CARBON SORPTION | | CATALYSIS UNIT | | CENTRIFUGAL CONTACTOR & CATALYSIS UNIT | |
| | | | TOTAL FIXED CAPITAL | TOTAL ANNUAL EXPENSE | TOTAL FIXED CAPITAL | TOTAL ANNUAL EXPENSE | COMBINED FIXED CAPITAL | COMBINED EXPENSE | TOTAL FIXED CAPITAL | TOTAL ANNUAL EXPENSE | COMBINED FIXED CAPITAL | COMBINED EXPENSE |
CRI	[1] 1990 $	[2] 1990 $	[3] 1990 $ [CAPRB]	[4] 1990 $ [EXPRB]	[5] 1990 $ {CAPCB}	[5] 1990 $ {EXPCB}	1990 $	1990 $	[5] 1990 $ {CAPCATB}	[5] 1990 $ {EXPCATB}	1990 $	1990 $
5.000	153043	17027	272112	128496	188349	66469	460462	194965	78257	210772	350369	339269
10.000	153043	17027	272112	128496	206691	66469	478804	194965	78257	210772	350369	339269
15.000	153043	17027	272112	128496	225033	66469	497146	194965	78257	210772	350369	339269
20.000	153043	17027	272112	128496	243375	66469	515488	194965	78257	210772	350369	339269
25.000	153043	17027	272112	128496	261717	66469	533830	194965	78257	210772	350369	339269
30.000	153043	17027	272112	128496	280059	66469	552172	194965	78257	210772	350369	339269
35.000	153043	17027	272112	128496	298401	66469	570514	194965	78257	210772	350369	339269
40.000	153043	17027	272112	128496	316743	66469	588856	194965	78257	210772	350369	339269
45.000	153043	17027	272112	128496	335085	66469	607198	194965	78257	210772	350369	339269
50.000	153043	17027	272112	128496	353427	66469	625540	194965	78257	210772	350369	339269
55.000	153043	17027	272112	128496	371769	66469	643882	194965	78257	210772	350369	339269
60.000	153043	17027	272112	128496	390111	66469	662224	194965	78257	210772	350369	339269
65.000	153043	17027	272112	128496	408453	66469	680566	194965	78257	210772	350369	339269
70.000	153043	17027	272112	128496	426795	66469	698908	194965	78257	210772	350369	339269
75.000	153043	17027	272112	128496	445137	66469	717250	194965	78257	210772	350369	339269

[1] Based upon a Cost/Capacity scaling factor = 0.304. The purchased equipment cost includes one full charge of packing materials. It also provides for stainless steel construction materials.

[2] Uses the values previously calculated for the packed stripper water pump and air fans. Then double to allow for additional power to drive the rotors of the centrifugal contactor.

[3] Sum of two preceding columns. Equipment installation factor [EIFC] = 1.60 which is the same factor used for the carbon adsorption and the catalytic incineration units.

[4] Uses values from the packed stripper, except for the addition of extra electrical power to handle the rotational units. See [2] above.

[5] Identical to values already calculated for the carbon adsorption and for the catalytic incineration units, at corresponding operating conditions.

NOTE: Data for centrifugal contactor are calculated in this table. Data for carbon adsorption and catalytic incineration units are copied from earlier tables.

[D1T]
VOC-2.100

TABLE D-D1T
PACKED COLUMN STRIPPER
SINGLE VARIABLE DESIGN OUTPUT INFORMATION

TCE

| VARIABLE INPUT | Treybal, 3rd Ed. | | STRIPPER DIAMETER | NUMBER TRANSFER UNITS | HEIGHT VAPOR TRANSFER UNIT | HEIGHT LIQUID TRANSFER UNIT | STRIPPER HEIGHT [1] | STRIPPER WEIGHT [2] | PACKING VOLUME [3] | PRESSURE GRADIENT | TOTAL PRESSURE DROP, AIR [4] |
| | ABSCISSA | ORDINATE | feet | | feet | feet | feet | pounds | feet³ | in H2O/ft | inches H2O |
CRI (ABST)	(ABST)	(DORD)	(DIA2)	(NTU2)	(HA2)	(HW2)	(HTOT2)	(SWP2)	(PVOL2)	(PAGTI)	(INPD2)
5.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
10.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
15.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
20.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
25.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
30.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
35.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
40.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
45.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
50.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
55.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
60.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
65.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
70.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76
75.000	1.5023	0.003294	4.00	5.76	1.16	5.46	56.36	7871	708.15	0.0490	2.76

[1] Adjusted for HEIGHT DESIGN SAFETY FACTOR, [SF] = 1.7
[2] Based upon adjusted height, and 0.25 inch steel construction.
[3] Based upon the adjusted stripper height.
[4] Based upon the adjusted stripper height.
[5] WGM may also appear as the variable input for some sensitivity analysis runs.

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TABLE D-D1T (CONCLUDED)
PACKED COLUMN STRIPPER
SINGLE VARIABLE DESIGN OUTPUT INFORMATION

TCE

VARIABLE INPUT CRI	AIR FLOW RATE ft^3/min {ACFM2} [ACFMT]	WATER FLOW RATE [5] gal/min {WGM}	STRIPPER POWER DEMAND		
			AIR ********* {KW1T}	WATER ********* kilowatts {KW2T}	TOTAL ********* {KWST}
5.000	1271.89	500.00	0.41	13.94	14.35
10.000	1271.89	500.00	0.41	13.94	14.35
15.000	1271.89	500.00	0.41	13.94	14.35
20.000	1271.89	500.00	0.41	13.94	14.35
25.000	1271.89	500.00	0.41	13.94	14.35
30.000	1271.89	500.00	0.41	13.94	14.35
35.000	1271.89	500.00	0.41	13.94	14.35
40.000	1271.89	500.00	0.41	13.94	14.35
45.000	1271.89	500.00	0.41	13.94	14.35
50.000	1271.89	500.00	0.41	13.94	14.35
55.000	1271.89	500.00	0.41	13.94	14.35
60.000	1271.89	500.00	0.41	13.94	14.35
65.000	1271.89	500.00	0.41	13.94	14.35
70.000	1271.89	500.00	0.41	13.94	14.35
75.000	1271.89	500.00	0.41	13.94	14.35

[D2T]
VOC-2.100

TABLE D-D2T
CARBON ADSORPTION AND CATALYTIC INCINERATION
SINGLE VARIABLE DESIGN OUTPUT INFORMATION

TCE

VARIABLE INPUT	AIR FLOW RATE	BENZENE MOLAR CONCENTRATION	CARBON DAILY USE [1]	CARBON CYCLE USE [2]	CARBON DESIGN SIZE [1,2]	CARBON UNITS PURCHASED [3]	CARBON CAPITAL PURCHASE [4]	CARBON RECYCLED ANNUALLY [5]	AIR FAN POWER [6]	AIR HEATER [8]	CATALYSIS UNIT SIZE INFORMATION	
											AIR FLOW [7]	AIR HEATER [8]
CRI	lb/min {APM2} [APMT]	ppm {MRAT2}	lb/day {CPD2}	lb/cycle [CCUT]	pounds [CDST]	[CUPT]	pounds	pounds [CRAT]	kilowatts [KWCT]	10^6 BTU/yr [FUEL1T]	ft³/min [ACATT]	10^6 BTU/yr [FUEL2T]
5.000	97.1	0.9	23	117	117	2	234	7260	2.06	672	1908	18807
10.000	97.1	0.9	23	234	234	2	468	7260	2.06	672	1908	18807
15.000	97.1	0.9	23	351	351	2	702	7260	2.06	672	1908	18807
20.000	97.1	0.9	23	468	468	2	936	7260	2.06	672	1908	18807
25.000	97.1	0.9	23	585	585	2	1170	7260	2.06	672	1908	18807
30.000	97.1	0.9	23	702	702	2	1404	7260	2.06	672	1908	18807
35.000	97.1	0.9	23	819	819	2	1638	7260	2.06	672	1908	18807
40.000	97.1	0.9	23	936	936	2	1872	7260	2.06	672	1908	18807
45.000	97.1	0.9	23	1053	1053	2	2106	7260	2.06	672	1908	18807
50.000	97.1	0.9	23	1170	1170	2	2340	7260	2.06	672	1908	18807
55.000	97.1	0.9	23	1287	1287	2	2574	7260	2.06	672	1908	18807
60.000	97.1	0.9	23	1404	1404	2	2808	7260	2.06	672	1908	18807
65.000	97.1	0.9	23	1521	1521	2	3042	7260	2.06	672	1908	18807
70.000	97.1	0.9	23	1638	1638	2	3276	7260	2.06	672	1908	18807
75.000	97.1	0.9	23	1755	1755	2	3510	7260	2.06	672	1908	18807

[1] Corrected for CARBON UNIT SIZE SAFETY FACTOR (CSF) = 1.50
[2] Adjusted for CARBON RECYCLE INTERVAL, days (CRI) = 75
[3] One spare adsorption unit purchased, for contingency and for shift of throughput during carbon regeneration.
[4] Subsequent to initial purchase of carbon, the regeneration cycle provides for adequate make up with new carbon.
[5] Based upon Load Factor [LF] = 0.85 and stipulated values of CSF and CRI.
[6] Sized at 5X the air fan requirements of stripper.

[7] Based upon CATALYTIC UNIT SIZE SAFETY FACTOR [CASF] = 1.5

[8] Air stream heating for both carbon adsorption and catalysis units.

10^6 BTU = Millions BTU

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TABLE D-D3T
PACKED COLUMN STRIPPER

TCE

	CAPITAL EXPENDITURES						ANNUAL EXPENSE					
VARIABLE INPUT	AIR FAN & MOTOR [1] 1977 $	WATER PUMP & MOTOR [1] 1977 $	STRIPPER SHELL [1] 1977 $	PLASTIC PALL RINGS [1] 1990 $	TOTAL EQUIPMENT DELIVERED [6] 1990 $	TOTAL EQUIPMENT INSTALLED [2] 1990 $ [CAPST]	MAINTENANCE OF PALL RING PACKING [3] 1990 $	LABOR ONE FTE 1990 $	ELECTRICAL POWER COSTS 1990 $	MISC & O&M [4] 1990 $	UNLOADED TOTAL ANNUAL EXPENSE 1990 $	LOADED TOTAL ANNUAL EXPENSE [5] 1990 $ [EXPST]
CRI												
5.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
10.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
15.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
20.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
25.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
30.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
35.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
40.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
45.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
50.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
55.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
60.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
65.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
70.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707
75.000	5238	3275	31128	3895	77178	169791	974	24000	6411	25469	56853	113707

[1] Materials of construction costs adjusted upward via
    MATERIALS MULTIPLIER FACTOR   [MMF] = 1.70
[2] Adjusted upward via EQUIPMENT INSTALLATION
    FACTOR   [EIFS] = 2.20
[3] Pall ring maintenance at 25% of 1990 purchase cost.
[4] Factor x Installed Capital Equipment Costs   [OM] = 0.15
[5] Overhead Rate on Total Annual Expense, %   [OHR] = 100
[6] Average Annual Inflation: 1977-90   [I] = 0.0484

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[D4T]
VOC-2.100

TABLE D-D4T
CARBON ADSORPTION UNITS
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

TCE

	CAPITAL EXPENDITURES					ANNUAL EXPENSE				
VARIABLE INPUT	NEW CHARCOAL PURCHASED [1] 1977$	NEW CHARCOAL PURCHASED 1990$	CARBON SORPTION UNITS [2] 1982$	CARBON SORPTION UNITS 1990$	TOTAL EQUIPMENT INSTALLED [3] 1990$ [CAPCT]	ANNUAL FUEL OIL COSTS [5] 1990$	CHARCOAL RECYCLE COSTS 1990$	ELECTRICAL POWER COSTS 1990$	UNLOADED TOTAL ANNUAL EXPENSE 1990$	LOADED TOTAL ANNUAL EXPENSE [4] 1990$ [EXPCT]
CRI										
5.000	234	433	73577	107388	172514	4131	6133	922	11186	13982
10.000	468	865	74354	108522	175020	4131	6133	922	11186	13982
15.000	702	1298	75131	109656	177527	4131	6133	922	11186	13982
20.000	936	1730	75908	110790	180033	4131	6133	922	11186	13982
25.000	1170	2163	76685	111924	182540	4131	6133	922	11186	13982
30.000	1404	2596	77462	113058	185046	4131	6133	922	11186	13982
35.000	1638	3028	78238	114192	187553	4131	6133	922	11186	13982
40.000	1872	3461	79015	115326	190059	4131	6133	922	11186	13982
45.000	2106	3893	79792	116460	192566	4131	6133	922	11186	13982
50.000	2340	4326	80569	117594	195072	4131	6133	922	11186	13982
55.000	2574	4759	81346	118728	197579	4131	6133	922	11186	13982
60.000	2808	5191	82123	119862	200085	4131	6133	922	11186	13982
65.000	3042	5624	82900	120996	202591	4131	6133	922	11186	13982
70.000	3276	6056	83677	122130	205098	4131	6133	922	11186	13982
75.000	3510	6489	84454	123264	207604	4131	6133	922	11186	13982

[1] Based upon $1.00/lb, 1977 Prices.
[2] There is a shift in the cost correlation function at a size of about 10,000 lb carbon.
[3] Using Equipment Installation Factor [EIF] as shown in Table 1.
[4] overhead at 25% of total annual expense. The primary burden of the
    overhead is loaded on the packed column stripper.
[5] For heating of air stream to lower relative humidity before input
    to carbon adsorption units.

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TABLE D-D5T
CATALYTIC INCINERATION UNIT
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

TCE

CAPITAL EXPENDITURES				ANNUAL EXPENSE					
VARIABLE INPUT	UNIT COST	UNIT COST	TOTAL EQUIPMENT INSTALLED [1]	ANNUAL FUEL OIL COSTS	ELECTRICAL POWER COSTS	ANNUAL CATALYST COST	ANNUAL CATALYST COST	TOTAL	LOADED TOTAL ANNUAL EXPENSE [2]
CRI	1979 $	1990 $	1990 $ [CAPCATT]	1990 $	1990 $	1979 $	1990 $	1990 $	1990 $ [EXPCATT]
5.000	27649	46502	74403	115664	922	1958	3293	119879	149848
10.000	27649	46502	74403	115664	922	1958	3293	119879	149848
15.000	27649	46502	74403	115664	922	1958	3293	119879	149848
20.000	27649	46502	74403	115664	922	1958	3293	119879	149848
25.000	27649	46502	74403	115664	922	1958	3293	119879	149848
30.000	27649	46502	74403	115664	922	1958	3293	119879	149848
35.000	27649	46502	74403	115664	922	1958	3293	119879	149848
40.000	27649	46502	74403	115664	922	1958	3293	119879	149848
45.000	27649	46502	74403	115664	922	1958	3293	119879	149848
50.000	27649	46502	74403	115664	922	1958	3293	119879	149848
55.000	27649	46502	74403	115664	922	1958	3293	119879	149848
60.000	27649	46502	74403	115664	922	1958	3293	119879	149848
65.000	27649	46502	74403	115664	922	1958	3293	119879	149848
70.000	27649	46502	74403	115664	922	1958	3293	119879	149848
75.000	27649	46502	74403	115664	922	1958	3293	119879	149848

[1] Using Equipment Installation Factor (EIF) as shown in Table 1.

[2] Overhead at 25% of total annual expense. The primary burden of the overhead is placed on the packed column stripper.

[D6T]
VOC-2.100

TABLE D-D6T
COMBINED EQUIPMENT SYSTEMS
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

TCE

	PACKED STRIPPER		CARBON SORPTION		PACKED STRIPPER & CARBON SORPTION		CATALYSIS UNIT		PACKED STRIPPER & CATALYSIS UNIT	
VARIABLE INPUT	TOTAL FIXED CAPITAL 1990 $ (CAPST)	TOTAL ANNUAL EXPENSE 1990 $ (EXPST)	TOTAL FIXED CAPITAL 1990 $ (CAPCT)	TOTAL ANNUAL EXPENSE 1990 $ (EXPCT)	COMBINED FIXED CAPITAL 1990 $	COMBINED EXPENSE 1990 $	TOTAL FIXED CAPITAL 1990 $ (CAPCATT)	TOTAL ANNUAL EXPENSE 1990 $ (EXPCATT)	COMBINED FIXED CAPITAL 1990 $	COMBINED EXPENSE 1990 $
CRI										
5.000	169791	113707	172514	13982	342305	127689	74403	149848	244194	263555
10.000	169791	113707	175020	13982	344811	127689	74403	149848	244194	263555
15.000	169791	113707	177527	13982	347317	127689	74403	149848	244194	263555
20.000	169791	113707	180033	13982	349824	127689	74403	149848	244194	263555
25.000	169791	113707	182540	13982	352330	127689	74403	149848	244194	263555
30.000	169791	113707	185046	13982	354837	127689	74403	149848	244194	263555
35.000	169791	113707	187553	13982	357343	127689	74403	149848	244194	263555
40.000	169791	113707	190059	13982	359850	127689	74403	149848	244194	263555
45.000	169791	113707	192566	13982	362356	127689	74403	149848	244194	263555
50.000	169791	113707	195072	13982	364863	127689	74403	149848	244194	263555
55.000	169791	113707	197579	13982	367369	127689	74403	149848	244194	263555
60.000	169791	113707	200085	13982	369876	127689	74403	149848	244194	263555
65.000	169791	113707	202591	13982	372382	127689	74403	149848	244194	263555
70.000	169791	113707	205098	13982	374889	127689	74403	149848	244194	263555
75.000	169791	113707	207604	13982	377395	127689	74403	149848	244194	263555

Compare with Table D7T, which is for the centrifugal contactor. In D7T, the two columns for the packed stripper are replaced by calculation of the fixed capital and the annual (non-capital) expense for the centrifugal contactor.

The capital and expense figures for the carbon adsorption and the catalytic incineration are identical in D6T and D7T, however.

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TABLE D-D7T
COMBINED EQUIPMENT SYSTEMS
CAPITAL AND ANNUAL EXPENSE COST ESTIMATES

TCE

			CENTRIFUGAL CONTACTOR		CARBON SORPTION		CENTRIFUGAL CONTACTOR & CARBON SORPTION		CATALYSIS UNIT		CENTRIFUGAL CONTACTOR & CATALYSIS UNIT	
VARIABLE INPUT	ROTARY STRIPPER [1] 1990 $	FANS, PUMPS, MOTORS [2] 1990 $	TOTAL FIXED CAPITAL [3] 1990 $ [CAPRT]	TOTAL ANNUAL EXPENSE [4] 1990 $ [EXPRT]	TOTAL FIXED CAPITAL [5] 1990 $ (CAPCT)	TOTAL ANNUAL EXPENSE [5] 1990 $ (EXPCT)	COMBINED FIXED CAPITAL 1990 $	COMBINED EXPENSE 1990 $	TOTAL FIXED CAPITAL [5] 1990 $ (CAPCATT)	TOTAL ANNUAL EXPENSE [5] 1990 $ (EXPCATT)	COMBINED FIXED CAPITAL 1990 $	COMBINED EXPENSE 1990 $
CRI												
5.000	153043	17027	272112	126529	172514	13982	444626	140512	74403	149848	346516	276378
10.000	153043	17027	272112	126529	175020	13982	447133	140512	74403	149848	346516	276378
15.000	153043	17027	272112	126529	177527	13982	449639	140512	74403	149848	346516	276378
20.000	153043	17027	272112	126529	180033	13982	452146	140512	74403	149848	346516	276378
25.000	153043	17027	272112	126529	182540	13982	454652	140512	74403	149848	346516	276378
30.000	153043	17027	272112	126529	185046	13982	457159	140512	74403	149848	346516	276378
35.000	153043	17027	272112	126529	187553	13982	459665	140512	74403	149848	346516	276378
40.000	153043	17027	272112	126529	190059	13982	462172	140512	74403	149848	346516	276378
45.000	153043	17027	272112	126529	192566	13982	464678	140512	74403	149848	346516	276378
50.000	153043	17027	272112	126529	195072	13982	467184	140512	74403	149848	346516	276378
55.000	153043	17027	272112	126529	197579	13982	469691	140512	74403	149848	346516	276378
60.000	153043	17027	272112	126529	200085	13982	472197	140512	74403	149848	346516	276378
65.000	153043	17027	272112	126529	202591	13982	474704	140512	74403	149848	346516	276378
70.000	153043	17027	272112	126529	205098	13982	477210	140512	74403	149848	346516	276378
75.000	153043	17027	272112	126529	207604	13982	479717	140512	74403	149848	346516	276378

[1] Based upon a Cost/Capacity scaling factor = 0.304
The purchased equipment cost includes one full charge of packing materials.
It also provides for stainless steel construction materials.

[2] Uses the values previously calculated for the packed stripper water pump and air fans.
Then double to allow for additional power to drive the rotors of the centrifugal contactor.

[3] Sum of two preceding columns. Equipment installation factor [EIFC] = 1.60
which is the same factor used for the carbon adsorption and the catalytic
incineration units.

[4] Uses values from the packed stripper, except for the addition of extra
electrical power to handle the rotational units. See [2] above.

[5] Identical to values already calculated
for the carbon adsorption and for the
catalytic incineration units, at
corresponding operating conditions.

NOTE: Data for centrifugal contactor are
calculated in this table. Data for carbon
adsorption and catalytic incineration
units are copied from earlier tables.

APPENDIX E

OPERATING LIFETIME FINANCIAL ANALYSIS SPREADSHEET

VOC-2.300

The following eight tables make up spreadsheet VOC-2.300 written in MULTIPLAN 2.01. The file may be exported upward into MP 3.0 or MP 4.0 without difficulty. Table E-1 is for inputs to the construction phase, and Table E-4 is for inputs to the operating lifetime phase. For the analyses in this report, the construction phase is assumed to be zero years, so that Tables E-1 and E-4 are essentially identical. Table E-8 contains the output information, in terms of lifetime current dollars cost per 1000 gallons of groundwater processed. Annual adjustments for inflation are included, using the input inflation projection shown in Table E-4. The analyses are handled as 100 percent debt financing to simulate a government-owned and operated activity. At 100 percent debt financing and at zero salvage on the capital equipment, the lifetime processing costs per 1000 gallons of water should be identical for a cash flow analysis and for a depreciation analysis. This identity is shown in Table E-8. For cash flow analysis, the costs include the total capital costs and the sum of the yearly operating expenses. For the depreciation analysis, the operating expenses are the same as for the cash flow analysis. The capital costs, though, are the sum of the yearly depreciation amounts. Thus, if the capital equipment is depreciated to a zero salvage value, the two analyses are identical. The operating lifetime financial analysis is discussed in the related body of the text.

The lifetime processing costs shown in Table E-8 are for a particular set of input variables. In Section V of the text, examples were presented which showed how processing costs were affected by variations in certain variables. Additional examples of such sensitivity analyses are presented in Figures E-1 through E-4, which show the effects of variations in overhead rate, carbon recycle interval, contaminant removal efficiency, and equipment installation factor.

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TABLE E-1
INITIAL COST ESTIMATES AND OTHER
KEY PARAMETERS

	INPUT ITEM	NAME		INPUT
	BASE YEAR	[Y]	=	1990
	CURRENCY UNITS (1E+3, 1E+6, etc.)	[CU]	=	1.0E+06
	NUMBER OF CONSTRUCTION YEARS TO STARTUP	[N]	=	0
F	INITIAL FIXED CAPITAL, F	[F]	=	0.632401
	CONTINGENCY ADD-ON ADJUSTMENT	[AF]	=	0.00
FC	INITIAL FC, PLUS CONTINGENCY C--->	[FC]	=	0.632401
W	INITIAL WORKING CAPITAL, W	[W]	=	0.000000
	CONTINGENCY ADD-ON ADJUSTMENT	[AW]	=	0.00
WC	INITIAL WC, PLUS CONTINGENCY C--->	[WC]	=	0.000000
E	INITIAL ANNUAL EXPENSE, E	[E]	=	0.581721
	CONTINGENCY ADD-ON ADJUSTMENT	[AE]	=	0
EC	INITIAL EC, PLUS CONTINGENCY C--->	[EC]	=	0.581721
	FIRST YEAR FC INPUT FRACTION	[f1]	=	1.00
	SECOND YEAR FC INPUT FRACTION	[f2]	=	0.00
	THIRD YEAR FC INPUT FRACTION	[f3]	=	0.00
	FOURTH YEAR FC INPUT FRACTION	[f4]	=	0.00
	FIFTH YEAR FC INPUT FRACTION	[f5]	=	0.00

{ NOTE: f1 thru f5 must add to 1.00 }

	DEBT FRACTION [MAX = 1.000]	[D]	=	1.000
	ANNUAL INFLATION DURING CONSTRUCTION	[IF]	=	0.0484
	REAL INTEREST DURING CONSTRUCTION	[RIR]	=	0.0500
	INTEREST DURING CONSTRUCTION C--->	[IN]	=	0.0984

C---> These are COMPUTED items. Others inserted as appropriate.

[ ] Means a NAMED cell, range, or area, at its initially named location.

{ } Means an item copied from the earlier named cell or range, at an earlier location.

[PF], PF ---> PRINT FILE MACRO, FOR ALL TABLES IN SPREADSHEET

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TABLE E-2

INTERIM INFORMATION

BEFORE & AFTER INFLATION ADJUSTMENTS, & WITH DEBT FRACTION ADJUSTMENT AS WELL, BUT ... WITH NO INTEREST INCLUDED.
===

CALENDAR YEAR [CALY]	CONSTRUCTION YEAR [CONY]	YEARS OF INFLATION [INFY]	ANNUAL * INPUTS REQUIRED [AIR]	INFLATED ANNUAL ** INPUTS REQUIRED [IAIR]	DEBT *** PORTION [DP]	EQUITY *** PORTION [EP]
1990	1	0	0.6324	0.6324	0.6324	0.0000
1991	2	1	0.0000	0.0000	0.0000	0.0000
1992	3	2	0.0000	0.0000	0.0000	0.0000
1993	4	3	0.0000	0.0000	0.0000	0.0000
1994	5	4	0.0000	0.0000	0.0000	0.0000
1995	6	5				

CONSTRUCTION PERIOD TOTALS =   0.6324   0.6324   0.6324   0.0000

DEBT FRACTION VERIFICATION =   1

* UNINFLATED DISTRIBUTION OF THE INITIAL FCC ESTIMATE
** INFLATION ADJUSTED ANNUAL DISTRIBUTION OF THE INITIAL FCC ESTIMATE
***COMPARE THESE TWO COLUMNS WITH DISTRIBUTION CALCULATED IN THE FOLLOWING TABLE C. NOTE -- THAT IN THIS TABLE B THERE HAS BEEN NO INTEREST CALCULATED ON DEBT, WHICH IS DONE IN TABLE C.

ALSO NOTE THAT SOME INTERNAL SUMMATION CHECKS ARE PROVIDED ABOVE.

READ NOTES BELOW

NOTE THAT TABLE B ABOVE IS FOR INTERIM INFORMATION DISPLAY, ONLY, AND COULD READILY BE CONSOLIDATED INTO TABLE C.

TABLE E-3

CONSTRUCTION YEARS: ANALYSIS OF FIXED CAPITAL STRUCTURE

ANNUAL REQUIRED INPUTS

CALENDAR YEAR	CONST. YEAR	ANNUAL TOTALS	EQUITY PORTION	DEBT PORTION	CUMULATIVE TOTAL	CUMULATIVE DEBT	INTEREST ON CUMULATIVE DEBT
1990	1	0.632401	0.632401	0.000000	0.632401	0.000000	0.00000
1991	2	0.000000	0.000000	0.000000	0.000000	0.000000	0.00000
1992	3	0.000000	0.000000	0.000000	0.000000	0.000000	0.00000
1993	4	0.000000	0.000000	0.000000	0.000000	0.000000	0.00000
1994	5	0.000000	0.000000	0.000000	0.000000	0.000000	0.00000
1995	6	0.000000	0.000000	0.000000	0.000000	0.000000	0.00000
COLUMN TOTALS		0.63240	0.63240	0.00000			0.00000

D + E TOTAL--->	0.632401	(FCC)	<<------ NAME OF VALUE BELOW
			RESULTING DEBT FRACTION AT START UP = 0

THE COLUMN TOTALS FOR 'ANNUAL REQUIRED INPUTS' GIVE (1) THE TOTAL FCC ESTIMATE IN
START UP YEAR DOLLARS, FOR THE INPUTS SPECIFIED IN TABLE A, AND (2) THE DEBT AND EQUITY
PORTIONS FOR THE DEBT FRACTION ALSO SPECIFIED IN TABLE A. ALL OF THE DOLLAR VALUES
HAVE BEEN ADJUSTED FOR THE STIPULATED INTEREST AND INFLATION DURING THE CONSTRUCTION
YEARS ... THUS WE HAVE THE FCC ESTIMATE IN START UP YEAR DOLLARS THAT WILL BE USED
DURING SUBSEQUENT OPERATING YEARS ANALYSIS. EMPHASIS...WE DO HOLD
THE STATED DEBT FRACTION CONSTANT DURING THE CONSTRUCTION YEARS.

AS IN MOST TABLES OF THIS SPREAD SHEET, CLOSURE CHECKS ARE PROVIDED.
NOTE ALSO THAT THE FCC IS A NAMED VARIABLE AS INDICATED IN THE TABLE FOOTNOTES.

NOTE: THE LAST YEAR IN THE ABOVE TABLE IS NOT A CONSTRUCTION YEAR, BUT ACTUALLY IS THE
YEAR OPERATIONS START. IT IS INCLUDED SO THAT WE HAVE A PLACE TO DISPLAY AND USE
THE ACCRUED BUT UNPAID INTEREST AT THE END OF THE CONSTRUCTION PERIOD.

ALSO....REMEMBER THAT THIS CONSTRUCTION PERIOD SPREADSHEET IS SET UP SO THAT
WE ARE ABLE TO HOLD THE SPECIFIED DEBT FRACTION CONSTANT.

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TABLE E-4

INPUT TABLE FOR OPERATING YEARS, STARTING --- 1990

NUMBER OF OPERATING YEARS [M] = 20

FIXED CAPITAL COST ESTIMATE AT START UP {FCC} = 0.632401
SALVAGE FRACTION [SF] = 0.00
SALVAGE AMOUNT C---> [SA] = 0.000000

WORKING CAPITAL FACTOR [WCF] = 0.00
INITIAL YEAR WORKING CAPITAL COST ESTIMATE C---> [WCC] = 0.000000

NON-CAPITAL EXPENSE FACTOR [EXPF] = 0.000
INITIAL YEAR NON-CAPITAL EXPENSE EST. C---> [EXP] = 0.581721

OPERATING YEARS DEBT FRACTION * [DO] = 1.000

INFLATION RATE DURING OPERATIONS * [IFO] = 0.0484
REAL INTEREST RATE DURING OPERATIONS * [RIRO] = 0.0500
INTEREST RATE DURING OPERATIONS C---> [INO] = 0.0984

TAX RATE ON PROFITS [T] = 0.00

PRODUCTION FACTORS: L = 1.00 FOR 365 DAYS PER YEAR
FIRST YEAR FACTOR [L1] = 0.85
SECOND YEAR FACTOR [L2] = 0.85
THIRD YEAR FACTOR [L3] = 0.85
FOURTH YEAR FACTOR ** [L4] = 0.85

GROUNDWATER PUMPING RATE, gal/min [WPR] = 1500
WATER ANNUAL PROCESSING (FOR L = 1)
in gal/yr C---> [AWPR] = 7.884E+08

NUMBER OF DEPRECIATION YEARS *** [DY] = 20
(STRAIGHT LINE METHOD)

C---> These are COMPUTED values...don't set anything here.
{ } DON'T SET NEW VALUE...COPIED FROM PREVIOUS LOCATIONS.
* May set equal to values from Table-A, OR... may set
  new values here.

** L4 value continues for all subsequent years.
*** Normally set = M, the total operating lifetime.

ALL OTHER VALUES MAY BE INSERTED AS APPROPRIATE.

TABLE E-5

ANNUAL WATER PROCESSING LEVELS

OPERATING YEAR [OY]	BASE CASE PROCESSING gal/year {AWPR}	PROCESSING LOAD FACTORS {fl, etc.}	ACTUAL PROCESSING gal/year [AP]
1	7.884E+08	0.85	6.701E+08
2	7.884E+08	0.85	6.701E+08
3	7.884E+08	0.85	6.701E+08
4	7.884E+08	0.85	6.701E+08
5	7.884E+08	0.85	6.701E+08
6	7.884E+08	0.85	6.701E+08
7	7.884E+08	0.85	6.701E+08
8	7.884E+08	0.85	6.701E+08
9	7.884E+08	0.85	6.701E+08
10	7.884E+08	0.85	6.701E+08
11	7.884E+08	0.85	6.701E+08
12	7.884E+08	0.85	6.701E+08
13	7.884E+08	0.85	6.701E+08
14	7.884E+08	0.85	6.701E+08
15	7.884E+08	0.85	6.701E+08
16	7.884E+08	0.85	6.701E+08
17	7.884E+08	0.85	6.701E+08
18	7.884E+08	0.85	6.701E+08
19	7.884E+08	0.85	6.701E+08
20	7.884E+08	0.85	6.701E+08

LIFETIME PROCESSING =   [SUMW] = 1.340E+10
in gallons

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TABLE E-6

CASHFLOW EXPENSE ANALYSIS, WITH INFLATION ADJUSTMENTS ALLOWED

							DEBT SERVICE WORKING TABLE		
OPERA YEAR [OY]	LEVELIZED PAYMENT FACTOR [LPF]	LEVELIZED ANNUAL PAYMENT ON FCC [LAP]	TOTAL* WORKING CAPITAL [TWC]	ANNUAL INTEREST ON WCC [IWCC]	ANNUAL NON-CAP EXPENSE [ANE]	TOTAL CASHFLOW EXPENSE [TCE]	ANNUAL INTEREST PAID ON FCC [FCCI]	ANNUAL PAID ON FCC PRINCIPAL [APOP]	END OF YEAR UNPAID FCC DEBT [FCCD]
									0.63240
1	0.11618	0.07347	0.00000	0.00000	0.58172	0.65519	0.06223	0.01124	0.62116
2	0.11618	0.07347	0.00000	0.00000	0.60988	0.68335	0.06112	0.01235	0.60881
3	0.11618	0.07347	0.00000	0.00000	0.63939	0.71287	0.05991	0.01357	0.59524
4	0.11618	0.07347	0.00000	0.00000	0.67034	0.74381	0.05857	0.01490	0.58034
5	0.11618	0.07347	0.00000	0.00000	0.70279	0.77626	0.05711	0.01637	0.56398
6	0.11618	0.07347	0.00000	0.00000	0.73680	0.81027	0.05550	0.01798	0.54600
7	0.11618	0.07347	0.00000	0.00000	0.77246	0.84593	0.05373	0.01975	0.52625
8	0.11618	0.07347	0.00000	0.00000	0.80985	0.88332	0.05178	0.02169	0.50456
9	0.11618	0.07347	0.00000	0.00000	0.84905	0.92252	0.04965	0.02382	0.48074
10	0.11618	0.07347	0.00000	0.00000	0.89014	0.96361	0.04730	0.02617	0.45457
11	0.11618	0.07347	0.00000	0.00000	0.93322	1.00669	0.04473	0.02874	0.42583
12	0.11618	0.07347	0.00000	0.00000	0.97839	1.05186	0.04190	0.03157	0.39426
13	0.11618	0.07347	0.00000	0.00000	1.02574	1.09922	0.03880	0.03468	0.35958
14	0.11618	0.07347	0.00000	0.00000	1.07539	1.14886	0.03538	0.03809	0.32150
15	0.11618	0.07347	0.00000	0.00000	1.12744	1.20091	0.03164	0.04184	0.27966
16	0.11618	0.07347	0.00000	0.00000	1.18201	1.25548	0.02752	0.04595	0.23371
17	0.11618	0.07347	0.00000	0.00000	1.23922	1.31269	0.02300	0.05048	0.18323
18	0.11618	0.07347	0.00000	0.00000	1.29919	1.37267	0.01803	0.05544	0.12779
19	0.11618	0.07347	0.00000	0.00000	1.36207	1.43555	0.01257	0.06090	0.06689
20	0.11618	0.07347	0.00000	0.00000	1.42800	1.50147	0.00658	0.06689	0.00000
21						VERIFY PAYDOWN OF FCC DEBT PORTION ------------^			
TOTALS =	1.46944		0.00000	0.00000	18.91309	20.38253 [STCE]	0.83704	0.632401	

(FCC) = 0.632401

CHECK SUM FROM DEBT SERVICE AT RIGHT 1.46944

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TABLE E-7

DEPRECIATION BASED COST ANALYSIS

OPERATING YEAR {OY}	ANNUAL NON-CAP EXPENSE {ANE}	ANNUAL INTEREST ON FCC {FCCI}	ANNUAL INTEREST ON WCC {IWCC}	ANNUAL DEPRECIATION [AD]	EXPENSE FOR TAX PURPOSES [EFTP]
1	0.58172	0.06223	0.00000	0.03162	0.67557
2	0.60988	0.06112	0.00000	0.03162	0.70262
3	0.63939	0.05991	0.00000	0.03162	0.73092
4	0.67034	0.05857	0.00000	0.03162	0.76053
5	0.70279	0.05711	0.00000	0.03162	0.79151
6	0.73680	0.05550	0.00000	0.03162	0.82392
7	0.77246	0.05373	0.00000	0.03162	0.85781
8	0.80985	0.05178	0.00000	0.03162	0.89325
9	0.84905	0.04965	0.00000	0.03162	0.93031
10	0.89014	0.04730	0.00000	0.03162	0.96906
11	0.93322	0.04473	0.00000	0.03162	1.00957
12	0.97839	0.04190	0.00000	0.03162	1.05191
13	1.02574	0.03880	0.00000	0.03162	1.09616
14	1.07539	0.03538	0.00000	0.03162	1.14239
15	1.12744	0.03164	0.00000	0.03162	1.19069
16	1.18201	0.02752	0.00000	0.03162	1.24115
17	1.23922	0.02300	0.00000	0.03162	1.29383
18	1.29919	0.01803	0.00000	0.03162	1.34884
19	1.36207	0.01257	0.00000	0.03162	1.40627
20	1.42800	0.00658	0.00000	0.03162	1.46620
21					

[SUMEXP] -----------> 19.75013   [SUMD] 0.63240   20.3825 [SEFTP]

TEST, (1 - SF)*FCC = 0.63240

USING STRAIGHT LINE DEPRECIATION

==

SALVAGE FRACTION   [SF] = 0
NUMBER OF DEPRECIATION YEARS   [DY] = 20

[INO] = 0.098
[IFO] = 0.048

[D] = 1.000
[DO] = 1.000

TABLE E-8

[A] DOLLAR COST PER 1,000 GALLONS, BASED UPON CASHFLOW ANALYSIS = 1.5208

     DOLLAR COST PER 1,000 GALLONS, CONTRIBUTION OF NON-CAPITAL ANNUAL EXPENSES = 1.4736

     DOLLAR COST PER 1,000 GALLONS, CONTRIBUTION OF FIXED CAPITAL DEPRECIATION = 0.0472

[B] CONSOLIDATED DOLLAR COST PER 1,000 GALLONS, AS SUM OF CAPITAL AND NON-CAPITAL COSTS = 1.5208

NOTE: For construction and operating lifetime debt fractions = 1.000 or zero equity, the costs per 1,000 gallons of water process as shown in [A] and [B] should be identical.

NOTE: THESE ARE BASED UPON LIFETIME INFLATION ADJUSTMENTS, STARTING WITH INITIAL ESTIMATES, AND THUS ARE CURRENT DOLLAR AVERAGES FOR THE OPERATING LIFETIME.

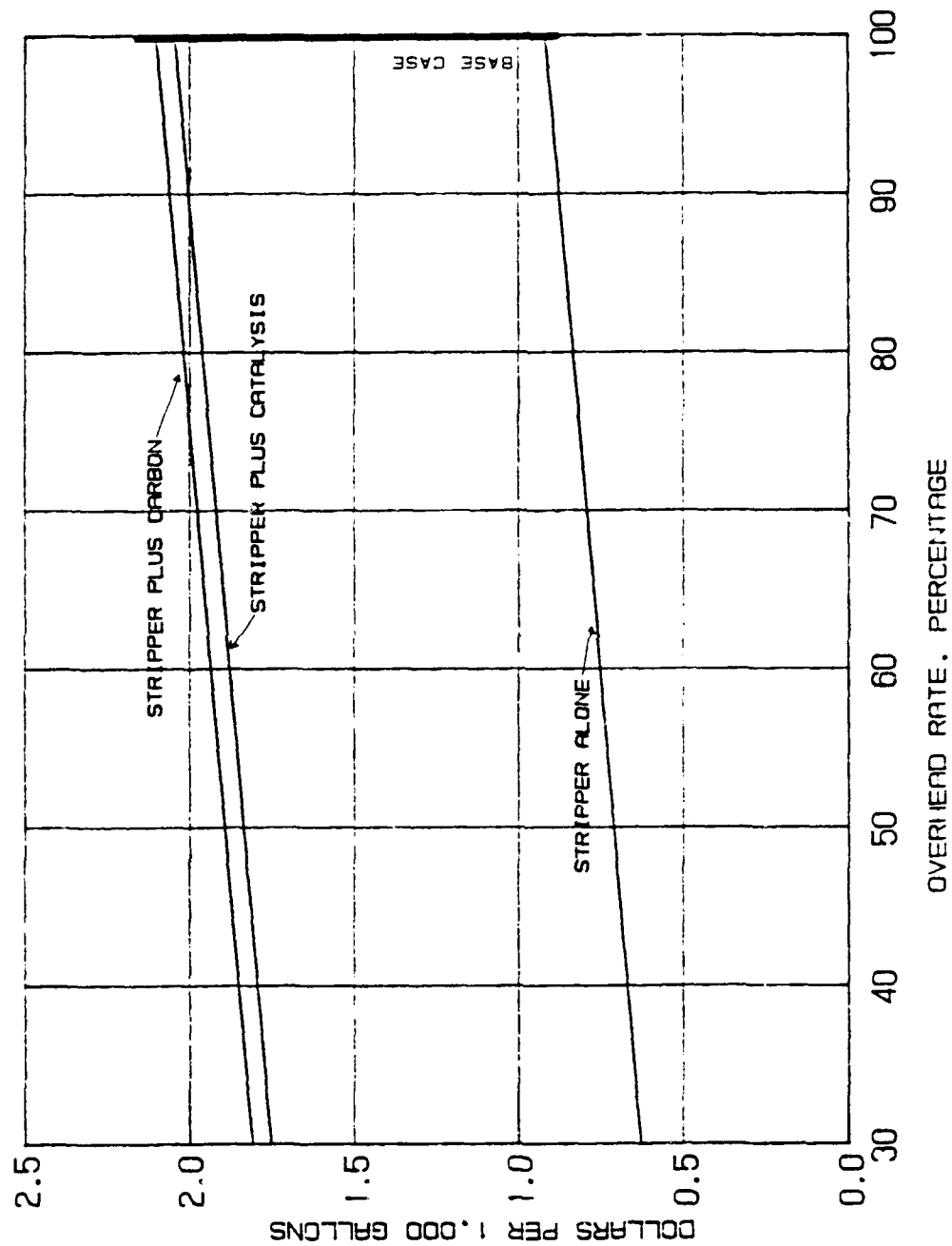| CONSTRUCTION PHASE		OPERATIONS PHASE	
CU =	1.00E+06	M =	20
N =	0	FCC =	0.6324
F =	0.6324	SF =	0.0000
AF =	0.0000	SA =	0.0000
FC =	0.6324	WCF =	0.0000
f1 =	1.00	WCC =	0.0000
f2 =	0.00	EXPF =	0.0000
f3 =	0.00	EXP =	0.5817
f4 =	0.00	DO =	1.00
f5 =	0.00	IFO =	0.0484
D =	1.00	RIRO =	0.0500
IF =	0.0484	INO =	0.0984
RIR =	0.0500	T =	0.000
IN =	0.0984	L1 =	0.850
		L2 =	0.850
WPR =	1500	L3 =	0.850
AWPR =	7.884E+08	L4 =	0.850
		DY =	20

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Figure E-1.   Operating Lifetime Processing Costs as a Function of Overhead Rate for an Air Stripper System Featuring a Traditional Packed Tower for TCE Removal from Groundwater.
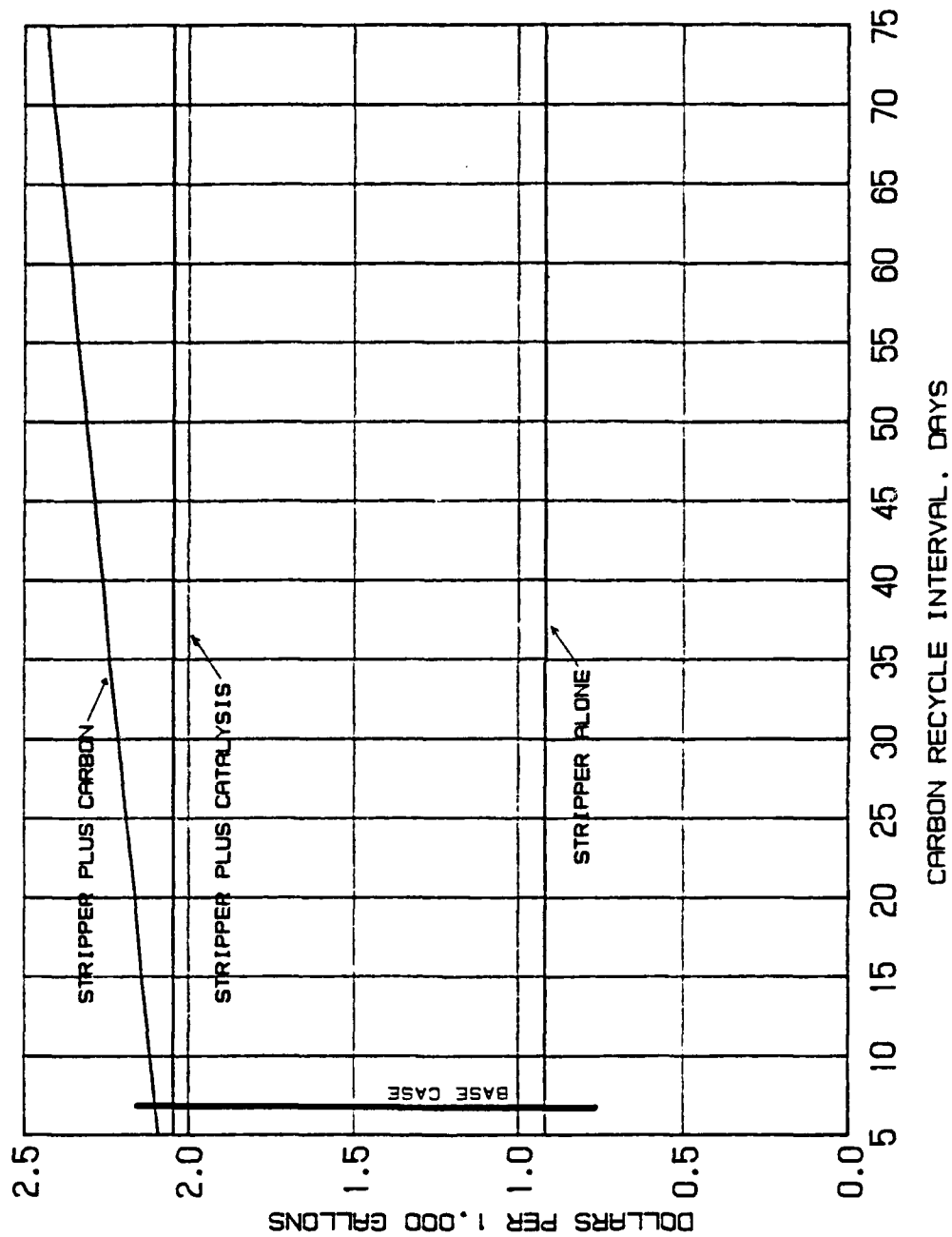
Figure E-2. Operating Lifetime Processing Costs as a Function of Carbon Recycle Interval for an Air Stripping System Featuring a Traditional Packed Tower for TCE Removal from Groundwater.
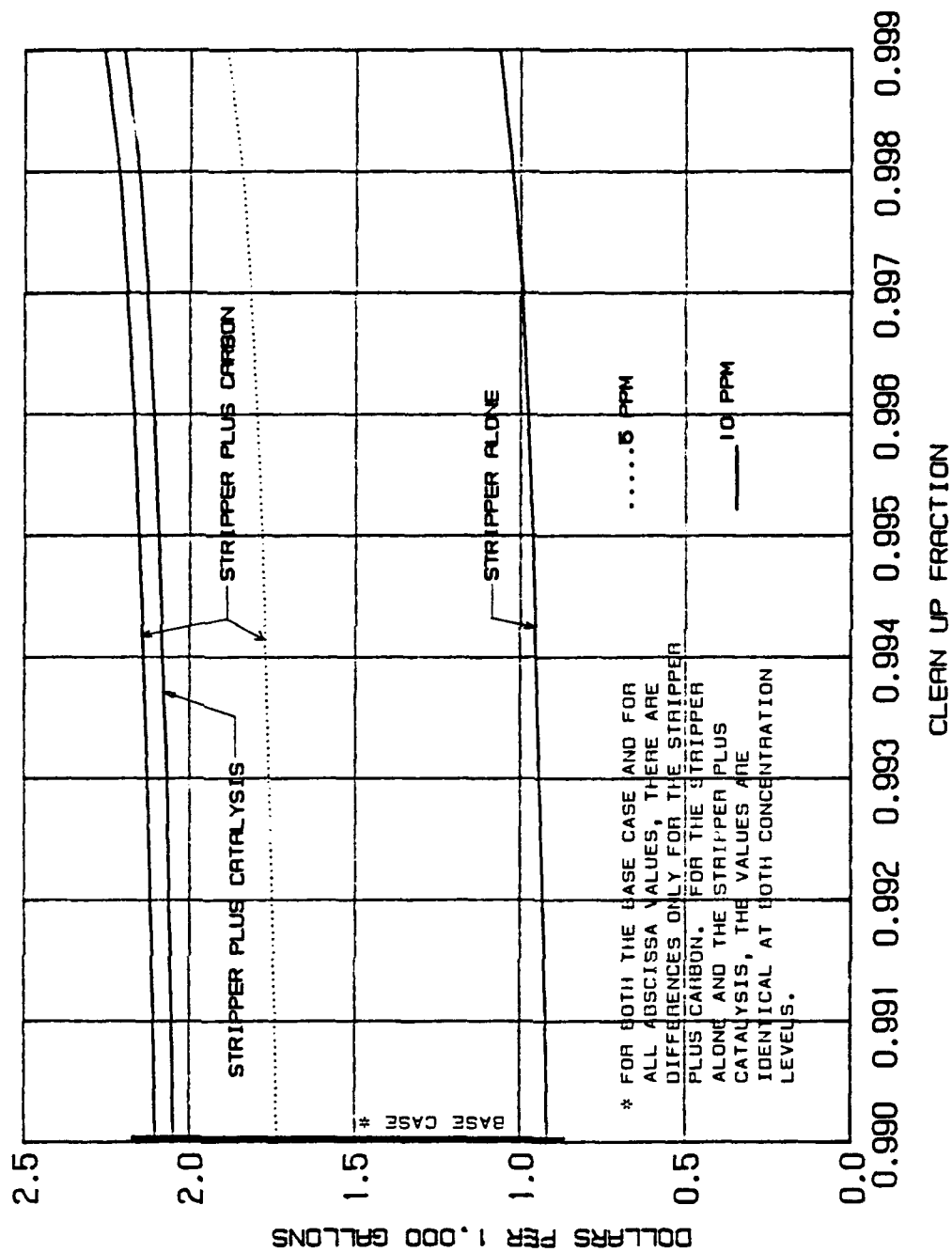
Figure E-3. Operating Lifetime Processing Costs as a Function of the Cleanup Fraction of TCE from Groundwater in an Air Stripper System Featuring a Traditional Packed Tower.
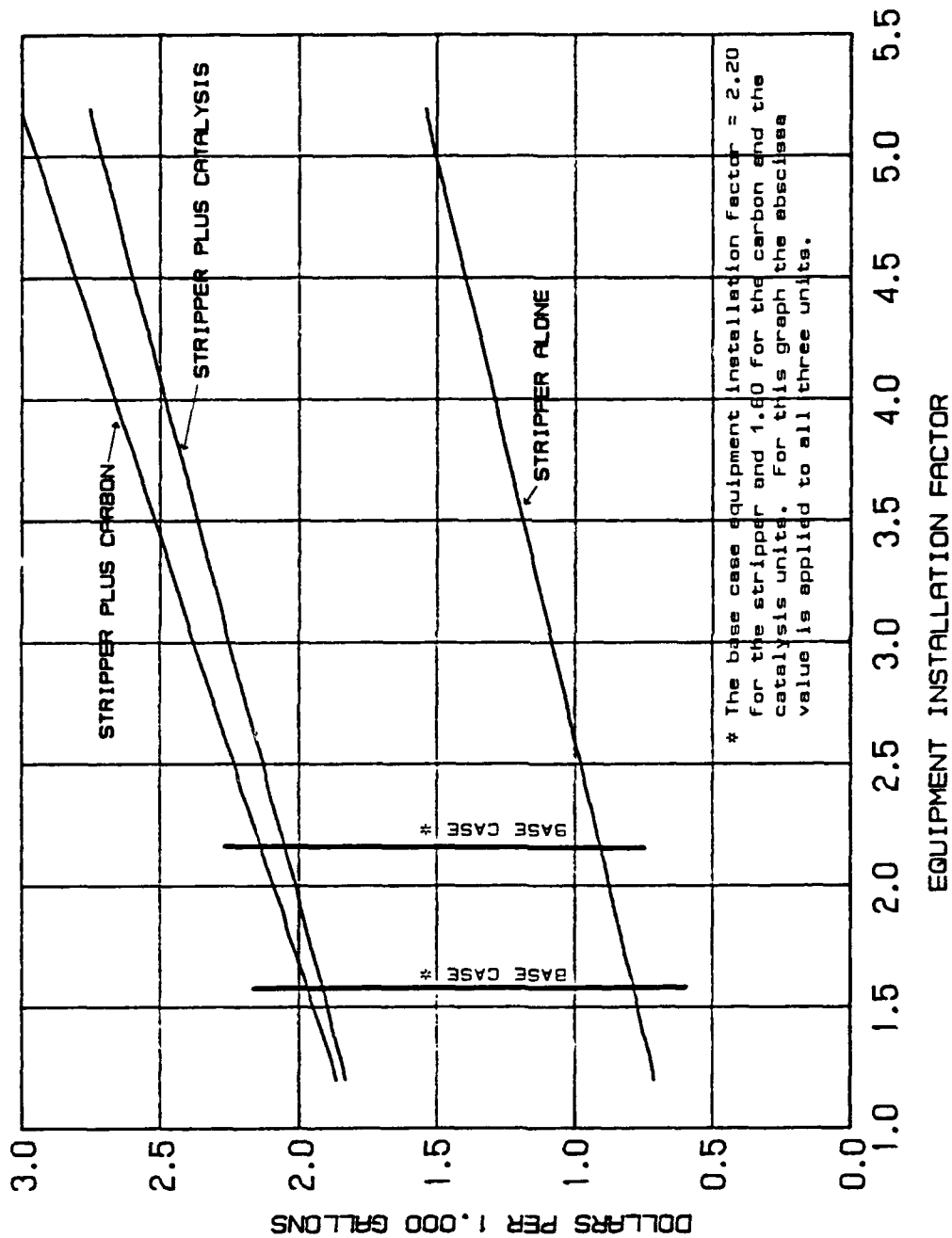
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Figure E-4. Operating Lifetime Processing Costs as a Function of Equipment Installation Factor for an Air Stripper System Featuring a Traditional Air Stripper for TCE Removal from Groundwater.