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ASDC: A MICROCOMPUTER-BASED PROGRAM FOR AIR STRIPPER DESIGN AND COSTING

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Packed-tower, counter-current air stripping is a treatment process that can be employed for removal of volatile organic compounds (VOCs) from water and wastewater. The design of an air stripper is performed using a well-developed mathematical model of the process. However, the number of variables involved exceeds the number of constraining equations by two, with the result that a number of alternative air stripper designs exist for a particular water treatment goal. In selecting the optimum design among the various alternatives, it is important to consider the capital and operating costs associated with each alternative. This report describes an interactive, microcomputer-based program - the Air Stripper Design and Costing (ASDC) program - that enables rapid evaluation of alternative air stripper designs and approximate costs associated with these designs for user-specified treatment scenarios. The various components of the program are described in detail, a guide to program operation is provided along with example applications, and results of some verification tests are presented.

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EXECUTIVE SUMMARY

A. OBJECTIVE

The objective of this project was to develop an interactive, microcomputer-based program for air stripper design that enables cost optimization and incorporates some other features not currently included in the few available programs. This report describes the resulting Air Stripper Design and Costing (ASDC) program which will be distributed as public domain software and is intended to serve as an aid to the U.S. Air Force and the environmental engineering community in the design and evaluation of air-stripping units.

B. BACKGROUND

Packed tower, countercurrent air stripping is being employed with increasing frequency for removal of volatile organic compounds (VOCs) from water supplies, wastewaters, contaminated groundwaters, and leachate from waste disposal sites. Several studies have shown that air stripping, even with off-gas treatment, can be a cost effective method for removal of VOCs from water.

Design of an air-stripping unit is performed using a well-developed mathematical model of the process which is based on principles of mass transfer. Because the number of variables involved exceeds the number of constraining equations, however, a variety of air stripper designs can be employed to achieve a desired removal for a particular compound. An air stripper is typically designed by assuming values for the extra variables (usually the stripping factor, R, which reflects the air:water ratio, and the gas pressure drop ΔP across the column), generating designs for different assumed values, estimating costs for various designs, and then selecting the optimum design by considering process requirements and costs. The air stripper design process is amenable to implementation on a computer, but only a few programs are readily available, and of these only one attempts to estimate capital and operating costs.

C. SCOPE

This report describes the air stripper design and cost estimation components of the ASDC program in detail and presents a guide to program operation. The guide contains descriptions of the function and invocation of on-screen menus, and the structure and format of input and output. An example application which exercises the major options in ASDC is also presented and includes reproductions of the corresponding input and output screens. In the final section of the report, results of selected program verification tests are presented. Performance and cost predictions for the model are compared to performance and/or cost data for some operating air-stripping units.

D. METHODOLOGY

The ASDC program was developed for implementation on IBM and IBM-compatible microcomputers. It is written in C language and is menu-driven.

Air stripper design is performed in the program using a well-established mathematical model for mass transfer in countercurrent gas-liquid flow in a packed tower. The stripping factor (R) and gas pressure drop (ΔP) are considered as the two design variables. The overall mass transfer coefficient is estimated using the widely-accepted Onda Model. Values for all other design parameters are specified by the user. Databases containing properties for a wide range of compounds and packing materials are included with the program.

The cost model incorporated in ASDC enables comparison of approximate costs for different designs. Major capital and operating costs are evaluated for each design by summing individual-component capital and operating costs. Features that enable modification of some cost factors (e.g., packing material unit cost, electricity rate) and adjustment for inflation are included in the program.

A graphical analysis option is also included in ASDC to enable the user to examine results of cost calculations on two-dimensional plots of cost (annual, total capital, etc.) versus R or ΔP, or on three-dimensional plots of cost versus R and ΔP. Generation of these on-screen plots makes it possible to assess visually the sensitivity of a particular cost item to ranges of R and/or ΔP values and facilitates search for minimum cost designs.

E. TEST DESCRIPTION

The various components of ASDC and the program as a whole have been subjected to verification tests to ensure that the software correctly represents the design and cost models employed. Tests for some critical subroutines in the program (e.g., the variation of Henry's Law constant with temperature) are outlined in the report. In addition, ASDC predictions of air stripper performance and cost are compared to performance and cost data for some actual air-stripping units in the last section of the report.

F. RESULTS

The ASDC program was constructed in accordance with initial objectives. A cost model for air-stripping units was developed and linked with the well established design procedure for this process. The resulting program is easy to use and contains contaminant and packing-material databases. It also includes graphical analysis tools that enable identification of designs associated with minimum costs. While the databases supporting parts of the cost model are not as detailed as originally planned (many manufacturers of air stripper components were reluctant to provide cost information), sufficient cost data and estimation formulae were assembled to enable construction of a component-by-component model for estimation of approximate system costs.

Limited tests of ASDC against performance and cost data for a few operating air-stripping units indicate that the design and cost submodels yield reasonable predictions. It proved difficult to obtain detailed capital and operating cost breakdowns for existing systems from the literature and from contacts with operators of a number of units. Breakdowns of major cost items were obtained for several operating units, however, and these data served as the basis for the tests cited above.

G. CONCLUSIONS

ASDC is a user-friendly program that will serve as a tool to assist with the design and evaluation of air-stripping units for the removal of VOCs from water and wastewater. Various studies have demonstrated that air stripping can be an economical treatment method for VOC removal, but assessment of the most cost effective designs is difficult because of the significant effort required to estimate costs associated with a large number of alternative designs. ASDC is intended to facilitate this task. For a specified treatment scenario, ASDC can generate up to 144 alternative designs simultaneously and approximate costs for each of these designs.

The cost model incorporated in ASDC is not intended to provide highly accurate cost estimates for a particular system, but rather to enable comparison of approximate costs for different designs on a consistent basis. Designs less than optimal with respect to total costs may be needed to provide operational flexibility or to meet other goals. In the design of air stripping units for groundwater treatment applications, for example, the probable decline of influent contaminant concentrations with time after the initiation of pumping needs to be considered. However, capital and operating costs will almost always be design considerations, if for no other reason than to quantify the price of meeting noneconomic design criteria.

While the ASDC program has been constructed with care, it is furnished "as is" and with absolutely no warranty, expressed or implied.

H. RECOMMENDATIONS

The ASDC program addresses air stripper design and costing only and does not include any design and cost calculations for possible auxiliary processes such as influent water preheating or treatment of off-gas. Increasing attention is being given to auxiliary processes in air stripper design, particularly for off-gas treatment. ASDC users should recognize that costs associated with these processes can be significant. Extension of the ASDC program to include one or more auxiliary processes may be warranted in the future if their usage becomes widespread.

PREFACE

The project under which the ASDC program was developed was sponsored by the Headquarters Air Force Civil Engineering Support Agency (HQ AFCESA/RAVW), Tyndall AFB, FL 32403-6001, under contract no. FO 8635-90-C-0099 to Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA 15213-3890.

Dr. David A. Dzombak was the Principal Investigator for the project, which was conducted from March 12, 1990 to July 11, 1991. Captain Edward G. Marchand of HQ AFCESA/RAVW at Tyndall AFB served as Project Officer.

A number of commercial products related to air stripping processes are mentioned in this report and in the ASDC computer program. No endorsement or rejection of any particular product for Air Force or other use should be inferred.

The report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and approved for publication.

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CONDITIONS OF SOFTWARE USE

ASDC is a public domain program. Carnegie Mellon University allows free use of the ASDC software in its "as is" condition. Carnegie Mellon disclaims any liability of any kind for any damages whatsoever resulting from use of the ASDC software.

Users of the ASDC software agree to return to Carnegie Mellon any improvements or extensions that they make and grant Carnegie Mellon the rights to redistribute these changes.

Export of the ASDC software is permitted only after complying with the regulations of the U.S. Department of Commerce relating to the Export of Technical Data.

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SECTION I

INTRODUCTION

A. OBJECTIVE

The objective of this project was to develop an interactive, microcomputer-based program for air stripper design which enables cost optimization and incorporates some other features not currently included in available programs. The Air Stripper Design and Costing (ASDC) program is menu-driven and designed to run on IBM microcomputers and on IBM-compatible microcomputers. For a specified water treatment scenario, ASDC can generate up to 144 alternative designs simultaneously and estimate approximate capital and operating costs associated with each design. Various two- and three-dimensional plots of costs versus design parameter values can then be displayed on-screen for rapid assessment of optimal designs with respect to cost.

B. BACKGROUND

Packed tower, countercurrent air stripping has long been used in chemical process industries and this technology is being employed with increasing frequency for removal of volatile organic compounds (VOCs) from water supplies, wastewaters, contaminated groundwaters, and leachate from waste disposal sites. The packed tower air-stripping process is illustrated schematically in Figure 1. Water contaminated with VOCs is pumped to the top of the column and evenly distributed over the cross-sectional area of the column which is filled with a porous packing material. Air is introduced at the bottom of the column and flows upward, counter to the downward water flow. The packing material serves to maximize the water surface area in the column, and exchange of VOCs from water to air occurs at the air/water interfaces in the column. Water with reduced VOC concentrations exits at the bottom of the column and air containing VOCs is discharged at the top of the column. Treatment of the off-gas is sometimes required. Several studies have shown that air stripping, even with off-gas treatment, can be a cost-effective method for removal of VOCs from water, particularly when compared with treatment by adsorption on granular activated carbon (References 1-4).

Design of an air-stripping unit is performed using a well-developed mathematical model of the process which is based on principles of mass transfer. Because the number of variables involved exceeds the number of constraining equations, however, a variety of air stripper designs can be employed to achieve a desired removal for a particular compound. An air stripper is typically designed by assuming values for the extra variables (usually the stripping factor, which reflects the air:water ratio, and the gas pressure drop across the column), generating designs for different assumed values, estimating costs for the various designs, and then selecting the optimum design by considering process requirements and costs. Air stripper design calculations are relatively straightforward but numerous. As the design procedure is iterative, design via manual calculation can be tedious and subject to mathematical errors. Because of this, and because cost data are difficult to assemble, design of air-stripping units in the past has often involved generation of only a few feasible designs and use of engineering judgment to select the final configuration. As a result, designs for many existing air-stripping units in use for water treatment are not optimal with respect to cost (e.g., Reference 5). The air stripper design process is amenable to implementation on a computer, but only a few programs are nonproprietary and readily available (References 6-9). Of these, only the program released by Clark and Adams (Reference 9) includes features that enable consideration of capital and operating costs associated with different designs.

C. SCOPE

In the following sections of the report, the design and cost estimation components of the ASDC program are described in detail and a guide to operation of the program is presented. The program operation guide contains descriptions of the function and invocation of menus, and the structure and format of input and output. An example application which exercises the major options in ASDC is also presented and includes reproductions of the corresponding input and output screens. In the final section of the report, results of selected program verification tests are presented. Performance and cost predictions from the model are compared to performance and/or cost data for actual air stripping systems.

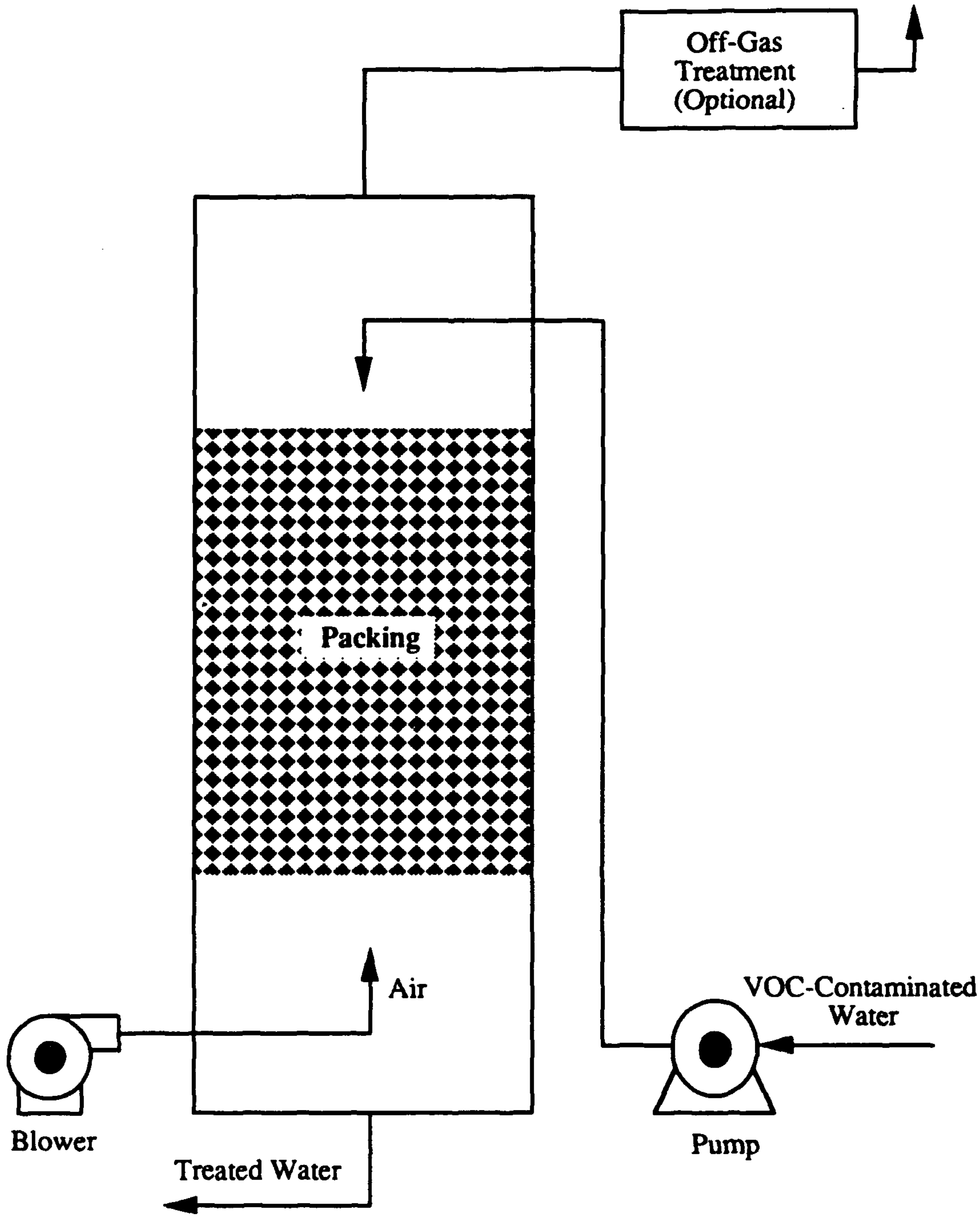


Figure 1. Schematic of an Air-Stripping Unit

SECTION II

AIR STRIPPER DESIGN

The theory of countercurrent packed-tower operation for gas/liquid absorption and stripping applications is well developed in the chemical engineering mass transfer literature (e.g., References 10 and 11). A number of excellent papers have been published which describe the application of this theory to the design of air-stripping units for water and wastewater treatment (References 12-14). In addition, USEPA has sponsored development of a process design manual (Reference 15) for air and steam stripping which summarizes the design methods, and air stripper design is described in several U.S. Air Force reports (References 16,17). The air stripper design procedure described in the cited articles is employed in the ASDC program. A summary of the design procedure is provided below, followed by detailed explanations of how certain aspects of the design procedure are implemented in ASDC.

A. OVERVIEW OF DESIGN METHODOLOGY

In designing an air-stripping unit, the goal is to determine the packed-tower configuration (diameter and height of packing material), air loading rate (moles/area-time), and water loading rate (moles/area-time) that will enable reduction of a given influent concentration C_i of a volatile contaminant to a desired effluent concentration C_e at minimum cost for a specific inflow rate Q and set of environmental conditions (air and water temperatures, atmospheric pressure). The designer must determine values or ranges of values for C_i, C_e, Q, the air and water temperatures (T_{air}, T_{water}), and the atmospheric pressure (P_{atm}), and then select some candidate packing materials. Air stripper design theory (References 10-14) can then be employed to identify a number of alternative designs.

The Henry's Law constant, H, is a compound property that provides an indication of the relative volatility of the compound. It expresses the ratio of a compound's abundance in the gas phase to that in the aqueous phase at equilibrium and is an important parameter in air stripper design. If $H < 10^{-7}$ atm·m^3/mol, the compound is considered to exhibit low volatility, while at H values greater than 10^{-7} but less than 10^{-5} atm·m^3/mol, the compound will volatilize from water slowly. Compounds with H values in the range $10^{-5} < K_H < 10^{-3}$ atm·m^3/mol are moderately to highly volatile and most easily removed by air stripping. Values of H exceeding 10^{-3} atm·m^3/mol indicate that volatilization will proceed rapidly.

The methodology of air stripper design is based on four basic equations derived from mass transfer theory:

$$Z = \text{Packing Height (m)} = HTU \times NTU \tag{1}$$

$$HTU = \text{Height of Transfer Unit (m)} = \frac{L}{K_L \, a \, \rho_w} \tag{2}$$

$$NTU = \text{Number of Transfer Units} = \frac{R}{R-1} \times \ln \frac{(C_i / C_e)(R-1) + 1}{R} \tag{3}$$

$$R = \text{Stripping Factor} = \left(\frac{G}{L}\right) \times \frac{H}{P_T} \tag{4}$$

where K_L is the overall liquid phase mass transfer coefficient (m/s), a is the specific interfacial area for the packing (m^2/m^3), ρ_w is the molar density of water (55.6 $kmol/m^3$), R is the stripping factor (dimensionless), H is the Henry's Law constant for the VOC of interest (atm), P_T is the atmospheric pressure (usually 1 atm), C_i and C_e are the influent and effluent concentrations, and L and G are the liquid and gas loading rates ($kmol/m^2$-s). Thus, the design is constrained by four equations and there are six unknown variables - *Z*, *HTU*, *NTU*, *R*, *G*, *L*. Substitution of equations (2) and (3) in equation (1) yields:

$$Z = \left(\frac{L}{(K_L a)\rho_W}\right)\left(\frac{R}{R-1}\right) \ln\left(\frac{(C_i / C_e)\ (R-1)\ +\ 1}{R}\right) \tag{5}$$

This equation can be used in design calculations to estimate the height of packing material needed to achieve a given treatment objective, but values for R (and hence the air: water ratio, G/L) and G (needed to obtain L) must be fixed arbitrarily for this calculation. The overall liquid phase mass transfer factor, $K_L a$, for the contaminant is obtained from available data or by experiment. As G, the gas loading rate, is related directly to the pressure drop, ΔP, the design variables are usually considered to be R and ΔP. Thus, the design engineer must assume a desirable pressure drop value for gas flow across a packed column corresponding to a particular value for the gas loading rate. Choosing a particular set of values for R and ΔP fixes the value of G and all other variables.

The general design procedure for an air stripper for one set of $R-\Delta P$ values is as follows:

[1] Identify contaminants of interest and choose a packing material.

[2] Specify system design parameters (influent concentrations; required effluent concentrations; water inflow rate; water temperature; atmospheric pressure; $K_L a$, if available)

[3] Choose values for R and ΔP.

[4] Calculate G/L using Equation (4).

[5] Determine G for specified ΔP value using Eckert relationships.

[6] Calculate L.

[7] Estimate $K_L\, a$ using Onda model (Reference 22) if pilot data are not available.

[8] Calculate *HTU* and *NTU* using Equations (2) and (3).

[9] Calculate *Z* using Equation (1).

[10] Calculate the tower diameter based on the known water inflow rate, *Q*, and *L*.

Thus, with the specification of *R* and ΔP the design is fixed. The design problem is to find the set of *R* and ΔP values that corresponds to minimum total cost for the unit and that is consistent with other noncost constraints or goals. Key components of the design procedure, including use of the Eckert relationships and the Onda model, are described in the following subsections.

B. ESTIMATION OF MASS TRANSFER COEFFICIENT

The two-phase resistance or two-film theory is generally accepted and widely used for description of mass transfer in gas-liquid exchange processes (References 11,18). In the two-phase resistance theory, a solute is considered to be transported from the bulk of one phase to the interface, and then from the interface to the bulk of the second phase. A stagnant film of finite thickness exists on each side of the interface, and the solute molecules must diffuse through these films before passing from the liquid phase to the gas phase, as illustrated in Figure 2. The two-phase resistance theory assumes that the only resistance to interphase exchange are the diffusional resistances in the stagnant films and that solute transfer across the interface itself is governed by Henry's Law of vapor-liquid equilibrium. The overall resistance to mass transfer is the sum of two separate resistances, a liquid-phase and a gas-phase resistance:

$$R_T = R_L + R_G \tag{6}$$

In accordance with two-phase resistance theory, these resistances R_L and R_G are defined as the reciprocals of their respective phase transfer rate constants. With the assumption that phase equilibrium exists at the interface, the following equation is obtained:

$$\frac{1}{K_L a} = \frac{1}{k_L a} + \frac{1}{H(k_G a)} \tag{7}$$

where K_L is the overall liquid-phase mass transfer coefficient, k_L is the individual liquid phase coefficient, k_G is the individual gas phase coefficient, and a is the effective interfacial area per unit volume of liquid. From the above equation, the significance of each phase in controlling the rate of gas-liquid mass transfer can be evaluated. For highly volatile contaminants which have larger H values, the gas-phase resistance is negligible and liquid-phase control of mass transfer exists. For compounds of moderate to low volatility, both

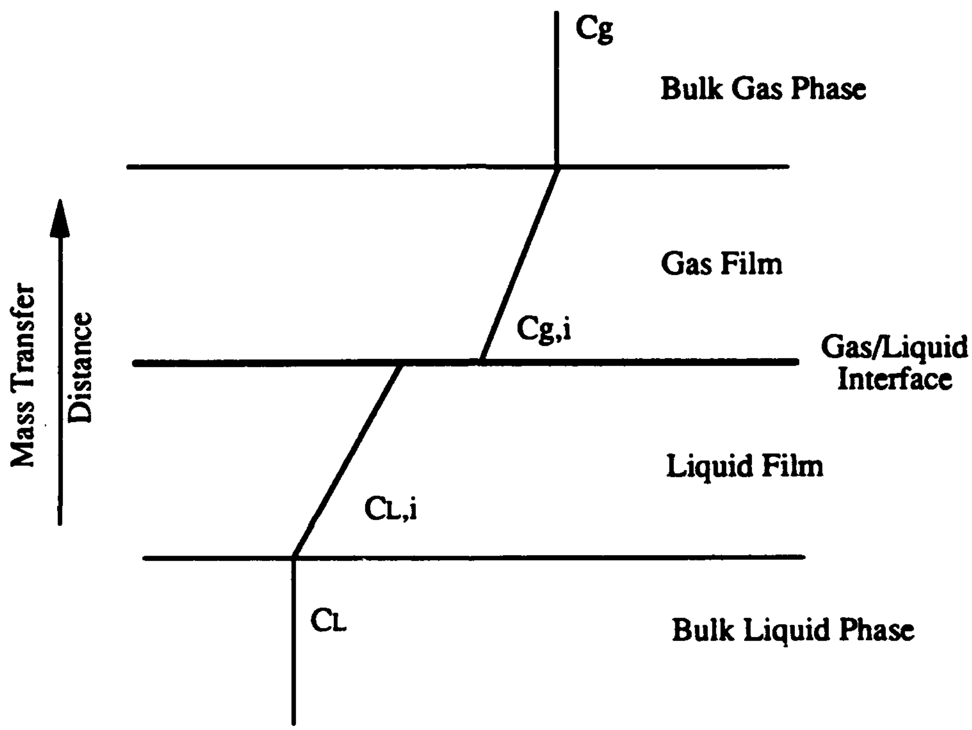


Figure 2. Two-Phase Resistance Model for Chemical Exchange at the Gas/Liquid Interface

phase resistances must be taken into account for predicting and interpreting mass transfer rates.

Overall liquid-phase mass transfer coefficients for specific applications can be determined experimentally in pilot tests (Reference 13) or can be estimated using one of several available models. The three leading models for prediction of mass transfer coefficients in countercurrent packed columns are those by Sherwood-Holloway, Shulman, and Onda. These models are reviewed by Roberts et al. (Reference 19).

The Sherwood-Holloway model (Reference 20) was developed from a study of the desorption of hydrogen, carbon dioxide, and oxygen from water into a countercurrent air flow in packed column tests involving several sizes of Raschig ring and Berl saddle packing materials. As the gaseous solutes tested by Sherwood and Holloway have sufficiently large Henry's Law constants that liquid-phase resistance controls, the overall mass transfer rate predicted with the Sherwood-Holloway correlation is governed by liquid resistance only. In addition, the correlation does not consider the effective interfacial area explicitly. This estimation method is difficult to apply to a new type of packing material.

The Shulman and Onda models (References 21, 22) estimate both gas and liquid phase resistance values, and estimation of interfacial contact area is also included. These models are, therefore, valid for a wider range of contaminants, regardless of volatility. The main item of concern for the Shulman model lies in the correlation used for prediction of interfacial area. It is not general and applies only to specific situations. This is a critical deficiency since the original work involved only a limited number of packing types. Therefore, without further information on the appropriate values of interfacial area for use with modern packings, this model is extremely limited in terms of potential applications.

The correlation developed by Onda et al. (Reference 22) entails separate estimation of the individual phase resistance values, k_L and k_g and the interfacial area, a. The specific interfacial area is taken to be the specific wetted packing area, a_w, which is estimated as a function of the liquid flow rate, packing properties, and liquid properties according to the following equation:

$$\frac{a_w}{a_t} = 1 - \exp\left[-1.45 \left(\frac{\sigma_c}{\sigma_L}\right)^{0.75} \times \left[\frac{L_M}{a_t \mu_L}\right]^{0.1} \times \left[\frac{L_M{}^2 a_t}{\rho_L{}^2 g}\right]^{-0.05} \times \left[\frac{L_M{}^2}{\rho_L \sigma_L a_t}\right]^{0.2}\right] \qquad (8)$$

where

a_t = total specific surface area of packing
σ_c = critical surface tension of packing material
σ_L = surface tension of the liquid
L_M = liquid mass loading rate
μ_L = liquid viscosity
ρ_L = liquid density
g = gravitational constant (9.81 m/s^2)

The last three factors within the argument of the exponential in Equation (8) are the Reynolds, Froude, and Weber numbers, all dimensionless. According the original developers, Equation (8) is accurate within ±20 percent. For a given packing material, liquid, and temperature, the specific interfacial area increases with increasing liquid loading rate and asymptotically approaches a_t as L_M becomes very large.

In the Onda model, the correlation for the liquid-phase coefficient, k_L, was determined from interpretation of a large data base (including the data of Sherwood and Holloway), encompassing packed tower tests with rings, spheres, rods, and saddles from 4 to 50 mm size, covering the liquid flow range $0.8 < L_M < 43$ kg $\cdot m^{-2} \cdot s^{-1}$. The correlation is given in dimensionless form as :

$$k_L \left(\frac{\rho_L}{\mu_L g}\right)^{\frac{1}{3}} = 0.0051 \left(\frac{L_M}{a_w \mu_L}\right)^{\frac{2}{3}} \left(\frac{\mu_L}{\rho_L D_L}\right)^{-0.5} (a_t d_p)^{0.4} \tag{9}$$

where d_p is the nominal packing size and D_L is diffusivity of the contaminant in the liquid. The accuracy of the estimate of k_L is reported to be ±20 percent.

For the gas-phase resistance, Onda et al. correlated mass- transfer data for absorption and stripping in the gas flow range $0.014 < L_G < 1.7$ kg $\cdot m^{-2} \cdot s^{-1}$ and various packing shapes in the size range 4 to 50 mm. They obtained the following relationship for k_G in dimensionless form:

$$\frac{k_G}{a_t D_G} = 5.23 \left(\frac{G_M}{a_t \mu_G}\right)^{0.7} \left(\frac{\mu_G}{\rho_G D_G}\right)^{\frac{1}{3}} (a_t d_p)^{-2} \tag{10}$$

where D_G is the diffusivity of the contaminant in the gas phase, and G_M is the air mass loading rate. The value of the constant in Equation (10) is changed for small packing ($d_p <$ 15 mm) from 5.23 to 2.0. The overall accuracy for the k_G correlation was placed at ±20 percent in the original work.

The ASDC program incorporates the Onda model for estimation of the overall mass transfer factor, $K_L a$, as well as an option to specify a safety factor for the estimated value. Gosset et al. (Reference 16), Roberts et al. (Reference 19), and Hand et al. (Reference 14) have validated the Onda correlation in pilot and field studies. These and other studies reported in the environmental engineering literature have found the Onda correlation to be the most accurate of the three available models for estimation of $K_L a$ in packed-tower stripping of VOCs. Implementation of the Onda model requires property data for the water (μ_L, ρ_L, σ_L), the air (μ_G, ρ_G), the packing material (a_t, d_p) and the contaminant of interest (H, D_L, D_G), as well as the water and air mass loading rates (L_M, G_M).

In the ASDC program, property data for the contaminant, the packing material, water and air are accessed from data bases while L_M and G_M are calculated. Property data for the water and air are adjusted for the appropriate temperature as discussed later in the report. Contaminant diffusion properties, namely D_L and D_G, are estimated using methods recommended by Lyman et al. (Reference 23, Chapter 17). For D_L, the estimation equation of Hayduk and Laudi (Reference 24) is employed:

$$D_L = \frac{13.26 \times 10^{-5}}{\mu_L^{1.14} V_B^{0.589}} \tag{11}$$

where μ_L is the water viscosity (centipoise) at the temperature of interest, V_B is the molar volume (cm^3/mol) of the contaminant, and D_L has units of cm^2/sec. The estimation method of Fuller et al. (Reference 25) is used for D_G:

$$D_G = \frac{10^{-3} T^{1.75} \sqrt{M_r}}{P (V_A^{1/3} + V_B^{1/3})^2} \tag{12}$$

where T is the temperature in ^oK, P is the pressure in atm, V_A and V_B are the molar volumes (cm^3/mol) for air and the contaminant of interest, M_r is a weighted average molecular weight, and D_G has units of cm^2/sec. The parameter M_r is defined as

$$M_r = (M_A + M_B)/M_A M_B \tag{13}$$

where M_A is the molecular weight of air and M_B is that of the contaminant.

C. ESTIMATION OF AIR LOADING RATE

The VOC removal efficiency of air stripping units is enhanced at higher air flow rates through the packed column, but, with greater air flows, larger pressure drops result and operating energy requirements increase. Pressure drop occurs in a packed tower as a result of frictional resistance of the gas to the liquid as it flows over the packing material and over the column equipment (i.e., air duct, support plate, distributor, and mist eliminator, etc.). The frictional resistance increases as the velocity of the countercurrent flowing gas increases. In air stripper design, the task is to select as high an air loading rate as possible for a particular packing and a specified maximum allowable gas pressure drop across the column.

Pressure drops associated with different gas loading rates in countercurrent flow packed towers have been measured for various types of random packing. These data have been summarized in "generalized pressure drop curves" relating G and ΔP which enable estimation of acceptable gas loading rates for a wide range of conditions. Sherwood et al. (Reference 20) performed experiments with a Raschig ring random packing and a variety of gases (air, hydrogen, carbon dioxide) and liquids (water, aqueous glycerol, methanol, aqueous butyric acid). They published a correlation to predict "flooding" (pressure drop so high that gas cannot flow through the tower) as a function of column dimensions and physical characteristics of the gas and liquid. However, Lobo et al. (Reference 26) observed that the Sherwood packed-bed geometry factor, a/E^3 (the area of the packing in square feet per cubic foot divided by the cube of the fractional void space) was not useful for accurate prediction of gas flow capacity for ΔP values at nonflooding conditions. Later, Leva (Reference 27) introduced the parameter of constant pressure drop and a further correction for the ratio of the density of water to the density of the liquid in the packed bed. Eckert (Reference 28) used a modification of the capacity factor of Lobo and called it the "packing factor," F. Eckert's packing factor was set by averaging the observed capacities of the bed under the conditions outlined by Lobo et al., with the exception that they were measured at pressure drops of 0.5, 1.0 and 1.5 inch H_2O per foot of packed height rather than at the flooding point. The generalized pressure drop correlation of Eckert is accepted today by most designers and recommended by Perry's Chemical Engineers' Handbook (Reference 29) as the best tool for estimating acceptable gas loading rates. An updated set of generalized pressure drop curves (Figure 3), obtained from the Norton Company (Akron, Ohio), are used for estimation of G in the ASDC program.

On the Eckert correlation plot of Figure 3, the abscissa is known as the flow parameter:

$$H' = \frac{L}{G}\left(\frac{\rho_G}{\rho_L}\right)^{0.5} \tag{14}$$

and the ordinate is the capacity parameter:

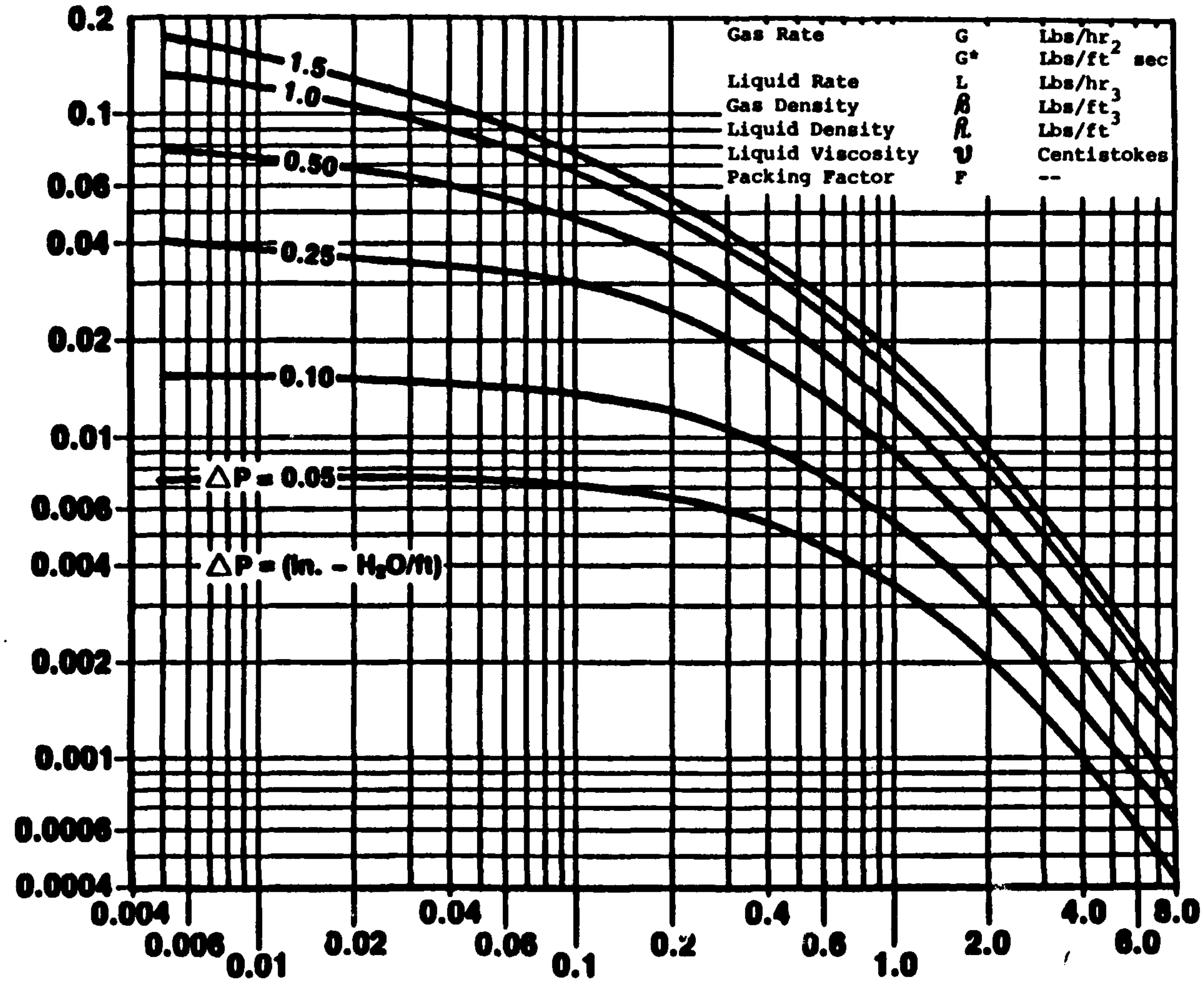
$$V = \frac{G^2 F \mu_L^{0.1}}{g\, \rho_G\, (\rho_L - \rho_G)} \tag{15}$$

where g is the gravitational constant (32.2 ft/s^2), ρ_G is the gas density (lb/ft^3), ρ_L is the liquid density (lb/ft^3), μ_L is the liquid viscosity (Centipoise), and F is the packing factor (ft^{-1}). To facilitate use of the Eckert correlation curves, the linearization method developed by Prahl (Reference 30) and employed by Boadway (Reference 31) was adopted. The Prahl method provides a means to represent the nonlinear Eckert correlation curves with simple linear equations. It was implemented in the ASDC program via the following steps:

[1] Numerical values of the flow parameter H' and the capacity parameter V were read with a digitizer from the generalized pressure drop curves for different pressure drops.

[2] Values for $\Delta P/V$ were calculated for values of H'.

[3] $\Delta P/V$ was plotted versus ΔP for different values of H'. Straight lines (with slope = m and y-intercept = n) were fitted to these points as shown in Figure 4.



$$V = \frac{G^{*2} F \nu^{0.1}}{32.2\, \rho_G [\rho_L - \rho_G]}$$

$$H' = \frac{L}{G}\left[\frac{\rho_G}{\rho_L}\right]^{0.5}$$

Figure 3. Generalized Pressure Drop Curves (Norton Company, 1988)

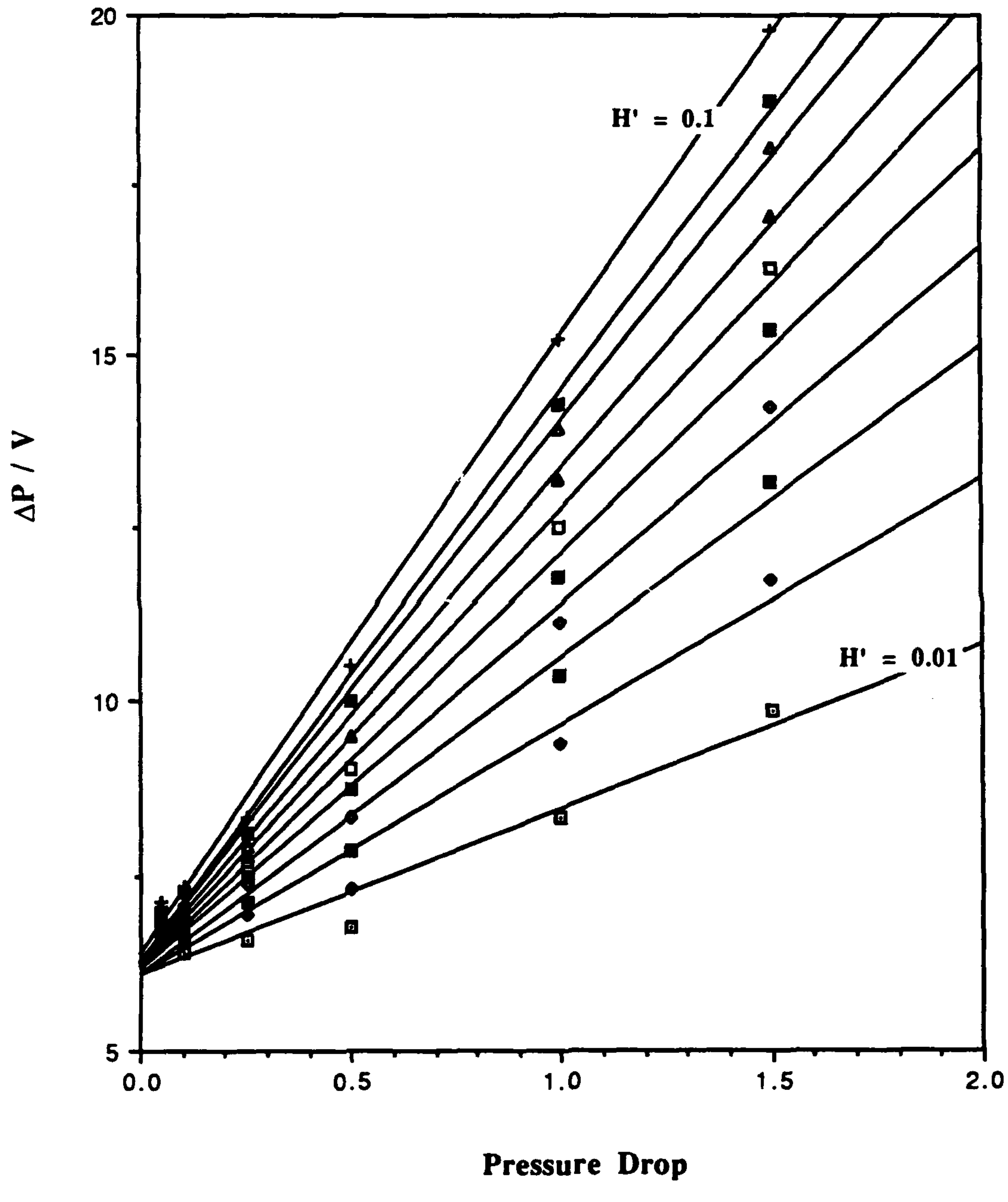


Figure 4. ΔP/V vs. ΔP (for H' = 0.01-0.1); Prahl Linearization

[4] The lines for the individual H' values were expressed by equations of the type.

$$\Delta P/V = m\Delta P + n \qquad (16)$$

Values of m and n for different H' were taken from Figure 4.

[5] The m and n values for the individual H' lines were plotted versus H', and a straight line (with slope = p and y-intercept = q) was fitted to the points. The same was done for the n values (slope = r and y-intercept = s). These lines, shown in Figure 5, may be expressed as

$$m = pH' + q \qquad (17)$$

$$n = rH' + s \qquad (18)$$

[6] Rearrangement of Equation (16) gives the final equations implemented in the ASDC program

$$\Delta P = \frac{Vn}{1 - Vm} \qquad (19)$$

$$V = \frac{\Delta P}{m\,\Delta P + n} \qquad (20)$$

where m and n are defined as in Equations (17) and (18).

In the process of applying above procedures, it was found that no single set of p, q, r, and s values could be used to represent accurately the generalized pressure drop curves for the entire range of flow parameter H'. Therefore, fitting was performed for three different ranges of the flow parameter for accurate fitting of the data. The three different ranges for H' were from 0.004 to 0.2, 0.2 to 2, and 2 to 8. The first two ranges were fitted according to the procedures described above, and two sets of p, q r, and s values were obtained. For H' less than 0.2, the best fit values were p = 68.64, q = 2.21, r = 3.04, and s = 6.03; for H' between 0.2 and 2 the best fit values were p = 40.74, q = 5.63, r = 10.08, and s = 4.80. At higher flow parameter values, i.e., H' greater than 2, the relationship between H' and V for particular ΔP values is approximately linear on a log-log scale. Therefore, a linear regression equation was obtained to describe the generalized pressure drop curve at higher H' values:

$$\log V = -\ 1.74 + 0.398 \log \Delta P - 1.22 \log H' \qquad (21)$$

Figure 6 shows a comparison of calculated V versus H' curves with the actual curves from the Eckert generalized pressure drop correlation. The fitting relationships used to generate

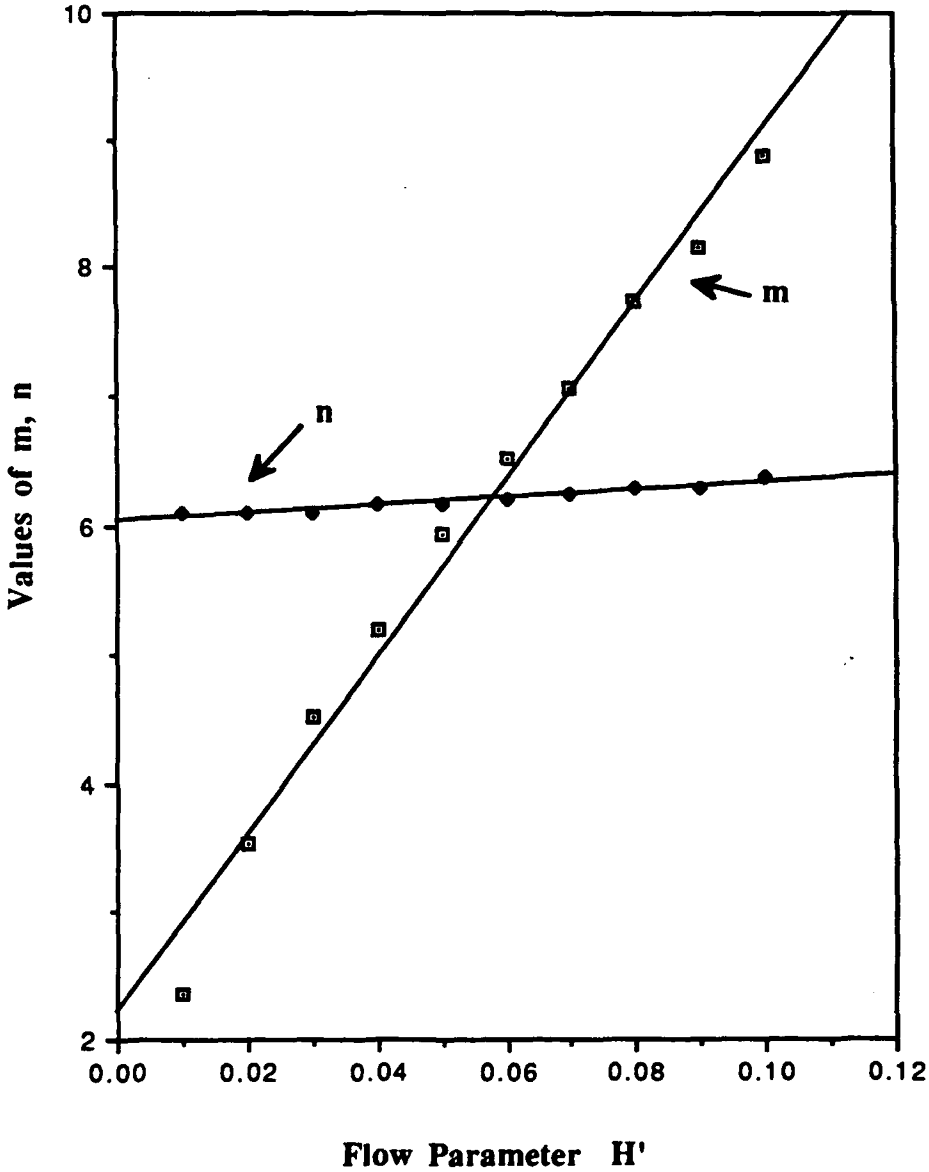


Figure 5. m, n vs. Flow Parameter H'; Prahl Linearization

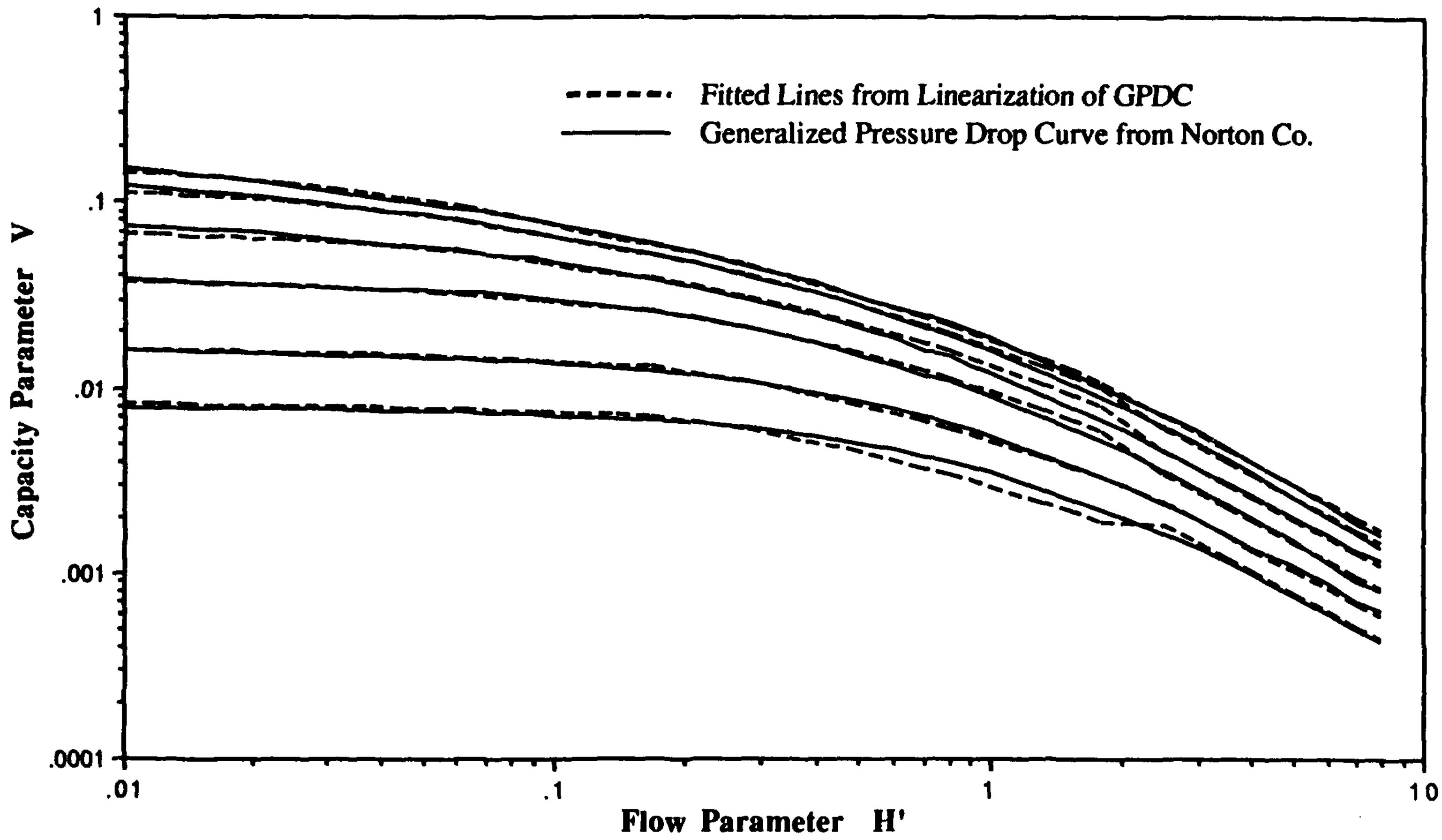


Figure 6. Linearization Fits of the Generalized Pressure Drop Curves

the fitted curves enable prediction of V given H' for any value of ΔP in the range covered; thus, they serve as an interpolation device as well as a fitting device.

Kister et al. (Reference 32) used about 2,800 processed pressure drop data to evaluate the Eckert relationship. Overall, they found that the Eckert correlation yields good pressure drop predictions for the air/water system at atmospheric pressure throughout the entire flow parameter range. Some shortcomings related to use of the Eckert relationship were noted, however. First is the inaccuracy inherent in any graphical method. Second is the large distance between the ΔP lines, which can make graphical interpolation difficult. The fitting and interpolation algorithm for the generalized pressure drop curves that is incorporated in the ASDC program avoids these problems.

The generalized pressure drop curves are empirical and extrapolation is not reliable. Thus, in ASDC the specified pressure drop must be within the ΔP data range on the Eckert plot, i.e., from 0.05 to 1.5 inch of water/ft (41 to 1225 $N/m^2 \cdot m$).

A generic flooding curve is indicated on the Eckert plot for ΔP in the range of 2 to 4 inches of water per foot of packing. However, Kister et al. (Reference 32) examined about 200 flood conditions and found that, while the flood point is independent of the flow parameter, it varies within a packing family and among packing types. Similar observations have been reported by Zenz (Reference 33) and Strigle and Rukovena (Reference 34). Kister et al. developed the following empirical equation for estimating the flood point for a particular packing material:

$$\Delta P_{flood} = 0.115\, F^{0.7} \tag{22}$$

where ΔP_{flood} is the pressure drop at the flood point and F is the packing factor for the packing material in ft^{-1}. This equation is implemented in the ASDC program for providing the upper limit of the pressure drop that can be specified.

D. TEMPERATURE DEPENDENCY OF HENRY'S LAW CONSTANT

In the overview of air stripper design methodology presented in Section II.A, it is shown that the value of the Henry's Law constant has a significant influence on the calculated design. It affects NTU directly and HTU indirectly through $K_L a$. Thus, accurate values for Henry's Law constants are critical for useful design calculations. The ASDC program includes a compound property data base which contains H values at 20°C and 25°C. Since Henry's Law constants can vary significantly with temperature, it is important to use H values for the relevant water temperature in performing design calculations. ASDC includes an algorithm to adjust H values in the data base to the water temperature of interest. The basis for this algorithm is described below.

For a compound i, the equilibrium air:water partition constant (the Henry's Law constant) is given by:

$$H = \frac{P_{i,a}}{C_{i,w}} \quad (23)$$

where $P_{i,a}$ is the partial pressure of compound i in the gas phase and $C_{i,w}$ is the molar concentration of the compound in water. For the relatively low aqueous phase concentrations of most VOCs,

$$H = H^{sat} = \frac{P^o_{i,L}}{C^{sat}_{i,w}} \quad (24)$$

where $P^o_{i,L}$ is the vapor pressure over the pure organic (liquid) compound at the temperature of interest, and $C^{sat}_{i,w}$ is the aqueous phase solubility. The close correlation of H with vapor pressure and aqueous solubility enables evaluation of the temperature dependency of H. With use of the Clausius-Clapeyron equation, and consideration of temperature effects on aqueous solubility, it may be shown that

$$ln\, H = -\left(\frac{\Delta H_v + \Delta H^e_s}{R}\right)\frac{1}{T} + A' \quad (25)$$

where ΔH_v is the molar hear of vaporization, ΔH^e_s is the excess molar heat of solution, R is the molar gas constant, and A' is a constant. For most small and/or polar compounds, ΔH^e_s is close to zero or slightly negative, and is usually much smaller than ΔH_v. The influence of temperature on H is, at maximum, similar in magnitude to the influence of temperature on vapor pressure, approximately doubling for a 20°F increase. Thus, knowledge of H at a particular temperature (e.g., 20°C) may be used for estimation of H at another temperature by the following equations if ΔH_v is known for each compound at different temperatures.

$$ln\, H\,(T_1) = \frac{\Delta H_v(T_1)}{R}\frac{1}{T_1} + A' \quad (26a)$$

$$ln\, H\,(T_2) = \frac{\Delta H_v(T_2)}{R}\frac{1}{T_2} + A' \quad (26b)$$

Subtraction of Equation (26a) from (26b) yields:

$$ln\frac{H\,(T_2)}{H\,(T_1)} = \frac{-\Delta H_v(T_1)}{R}\frac{1}{T_1} + \frac{\Delta H_v(T_2)}{R}\frac{1}{T_2} \quad (27)$$

In the ASDC program, Equation (27) is used to estimate H at any specified temperature using H (T_1 = 20°C or 25°C) as the reference value. All ΔH_v values required for this calculation are estimated using the method of Haggenmacher (described below) which estimates ΔH_v from vapor pressure and requires knowledge of critical pressure (P_c), critical temperature (T_c), and the Antoine constants for each compound. These data, together with H (T = 20°C or 25°C), have been incorporated in the compound property data base that accompanies the program.

1. Estimation of ΔH_v

The vapor pressure curve for any compound as a function of the temperature can be described by the Clapeyron Equation.

$$\frac{dP}{dT} = \frac{\Delta H_v}{T(V_G - V_L)} \qquad (28)$$

where dP/dT is derivative of vapor pressure with respect to temperature, ΔH_v is the molar heat of vaporization at temperature T, V_G is the saturated molar volume of the vapor phase, and V_L is the saturated molar volume of the liquid phase. The quantity (V_G - V_L) can be obtained from the compressibility equation of state:

$$V_G - V_L = \frac{RT}{P}(Z_G - Z_L) \qquad (29)$$

where R is the universal gas constant and Z_G and Z_L are the compressibility factors for the vapor and the liquid phases, respectively. Substitution of Equation (29) into the Clapeyron equation and rearrangement yields:

$$\frac{d(lnP)}{d(\frac{1}{T})} = \frac{-\Delta H_v}{R\,(Z_G - Z_L)} \qquad (30)$$

This equation can be employed for estimating the heat of vaporization of a compound or predicting the shape of its vapor pressure curve.

Vapor pressure versus temperature data for a compound may also be described by the Antoine relationship :

$$\log P = A - \frac{B}{t + C} \qquad (31)$$

where A, B, and C are constants and t is temperature, all expressed in °C except A, which is dimensionless. The Antoine relationship is a widely used empirical tool for describing and estimating vapor pressure as a function of temperature. Antoine constants A, B, and C have been compiled for many compounds.

The Haggenmacher method (Reference 28, Chapter 13) for estimating ΔH_v is derived from combination of Equation (31) with Equation (30) and the following:

$$Z_G - Z_L = [1 - \frac{(P/P_c)}{(T/T_c)^3}]^{0.5} \tag{32}$$

which expresses the compressibility difference in terms of two pressures and two temperatures. Equation (32) provides a good approximation at temperatures near or below the boiling point, T_b. The resulting expression for ΔH_v is:

$$\Delta H_v = \frac{2.303\, BRT^2 \, [1 - \frac{(P/P_c)}{(T/T_c)^3}]^{0.5}}{(t + C)^2} \tag{33}$$

where T and T_c are in °K, P and P_c are in atmospheres, and B, C and t are in °C. The constant 2.303 is the natural logarithm of 10, and R is the gas constant equal to 1.9872 cal/mol·K. Equation (33) is employed in the ASDC program to estimate the heat of vaporization at different temperatures. To enable use of this equation, values of P_c and T_c are included in the compound property data base.

2. Validation of Temperature Dependency Algorithm

Munz and Roberts (Reference 35) reported the temperature dependency of the Henry's Law constant in the range of 10 to 30°C for bromoform, chloroform, trichloroethylene, tetrachloroethylene, and carbon tetrachloride. The values from Munz's experiments and results from other experiments compiled by Munz were used for the validation of the method used in ASDC to describe the temperature dependency of H. The H value for each compound at 25°C was used as the basis for estimation of H at other temperatures. In Figures 7A-7D, H values for the four compounds are compared to the values measured at various temperatures. The Henry's Law constants predicted with the model incorporated in ASDC generally agree closely with the measurements of Munz and Roberts (Reference 35) and others cited by them.

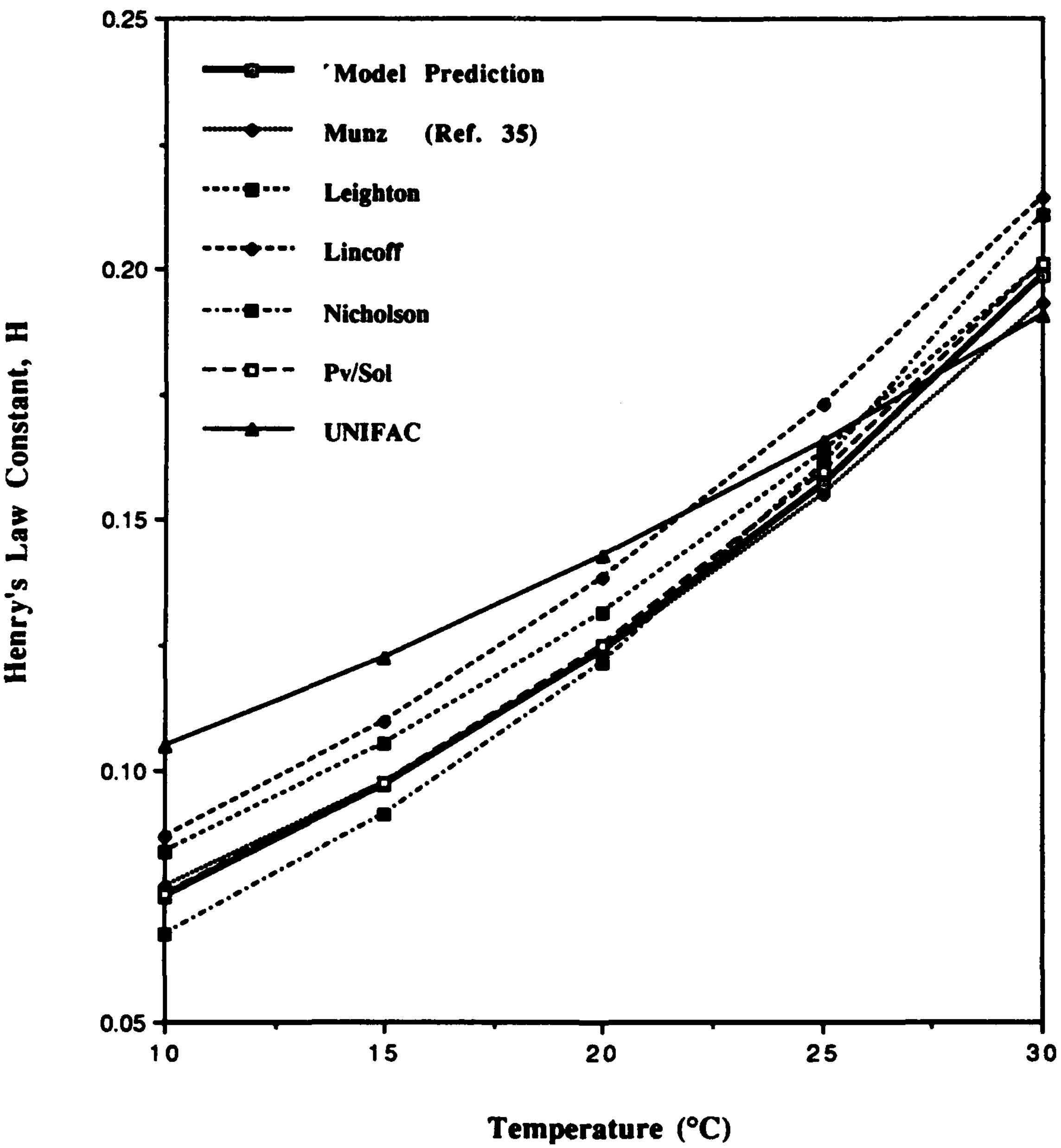


Figure 7A. Temperature-Dependency of H for Chloroform

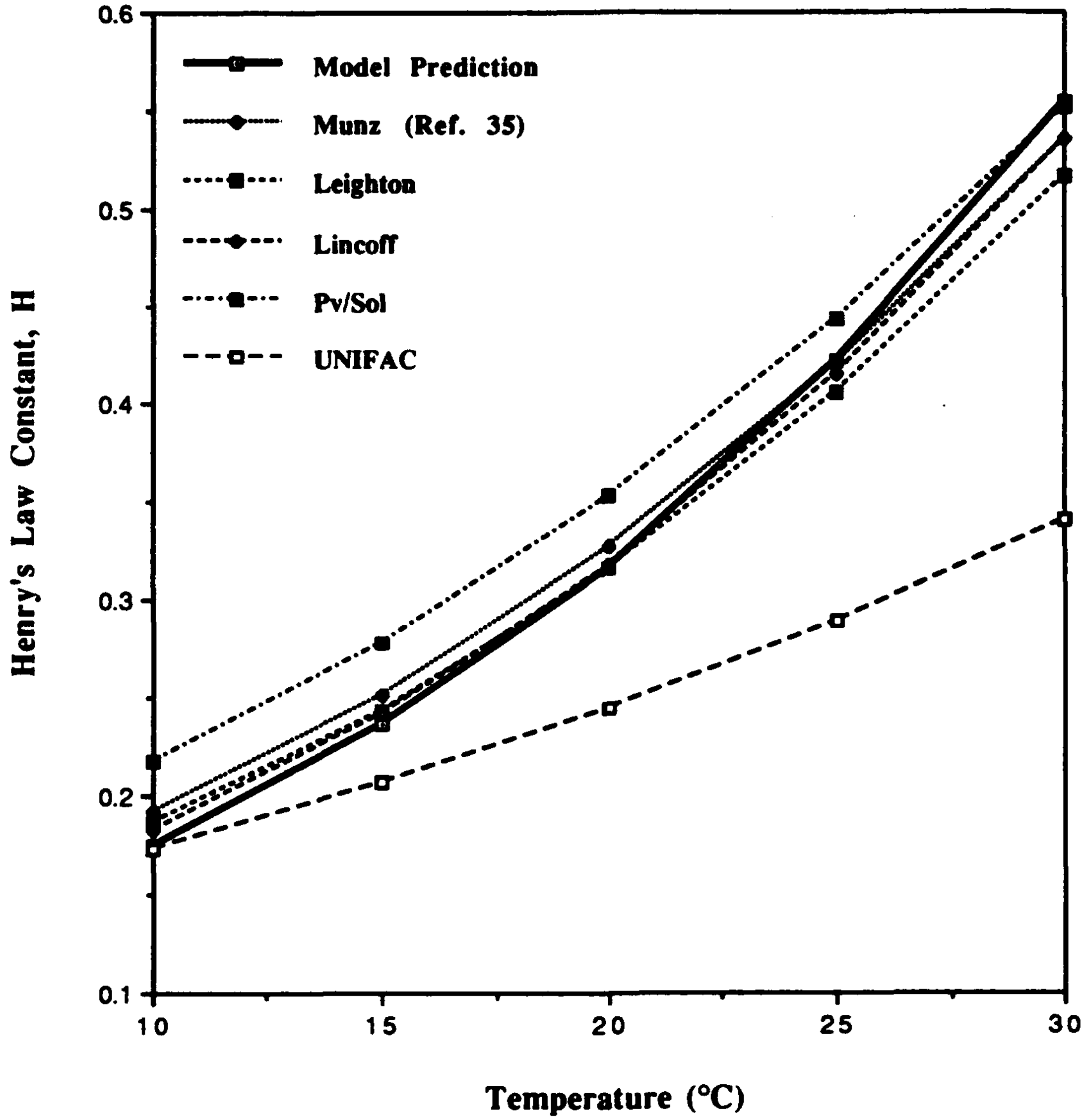


Figure 7B. Temperature-Dependency of H for Trichloroethylene

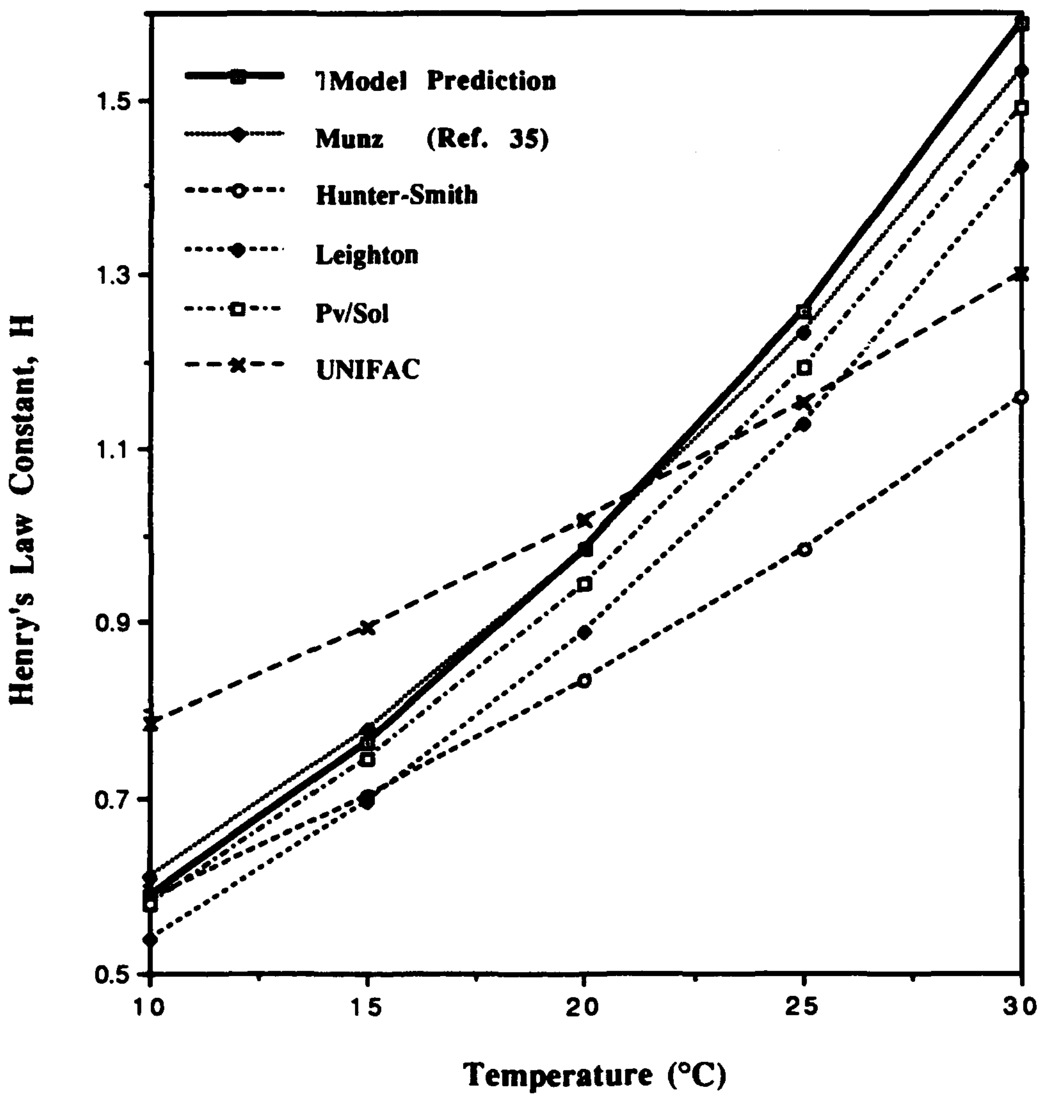


Figure 7C. Temperature-Dependency of H for Carbon Tetrachloride

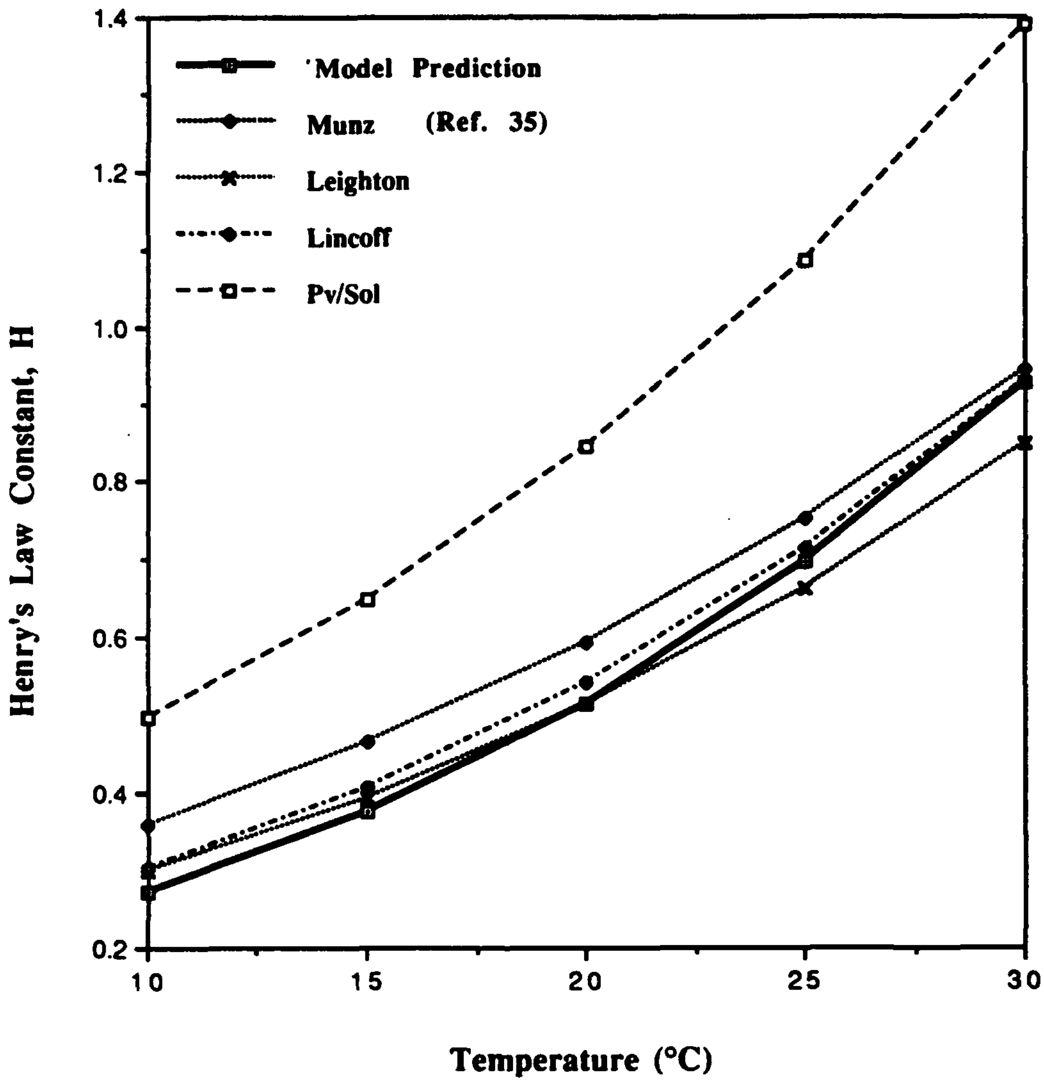


Figure 7D. Temperature-Dependency of H for Tetrachloroethylene

E. DESIGN AIR AND WATER TEMPERATURES

Water temperature affects a number of parameters involved in air stripper design and operation, most importantly the Henry's Law constant and the mass transfer coefficient for the target VOC contaminants. The higher the water temperature, the greater the Henry's Law constant and the mass transfer coefficient. At higher water temperatures, lower air:water ratios may thus be employed. Effects of water temperature on H and $K_L a$ are taken into account in ASDC, as discussed previously.

The temperature of influent air has been found to have little affect on the performance of air stripping units. Gross and Termaath (Reference 2) evaluated air temperature effects in a full-scale system in which the inlet air temperature was varied systematically from 15 to 50°F. During these tests, no change in water temperature was detected along the packed column. In similar experiments with a pilot-scale column, Cummins (Reference 36) took water and air temperature measurements along the column and determined that the water temperature remained essentially constant and that air temperature adjusted rapidly to that of the water. These observations are consistent with basic thermodynamics. Straudinger (Reference 37) performed a heat balance calculation for a hypothetical air stripping system with an inlet air temperature of 0°F, an inlet water temperature of 55°F, and an air:water ratio of 20, and estimated that the water temperature would not change by more than 1°F.

In the ASDC program, the inlet water temperature is used as the design temperature upon which all the air, water, and contaminant property values are calculated. This approach is employed commonly in air stripper design.

F. DESIGN AIR AND WATER PROPERTIES

The basic properties of air and water used in the design of an air-stripping system, especially in estimation of $K_L a$, are density and viscosity and, for water, surface tension. All these property values vary with temperature, though water viscosity exhibits the greatest sensitivity to temperature. It increases by approximately a factor of two from 10°C to 30°C. The ASDC program contains functions that can estimate the values for the air and water properties at different temperatures.

Extensive data for water density as a function of temperature are available. In Perry's Chemical Engineers' Handbook (Reference 29), such data are given for 0 to 100°C. The following polynomial equation can fit these data well:

$$\rho_L = 999.85 + 6.1474 \times 10^{-2}(T) - 8.3633 \times 10^{-3}(T^2) + 6.6805 \times 10^{-5}(T^3) - 4.3869 \times 10^{-7}(T^4) + 1.3095 \times 10^{-9}(T^5) \quad (34)$$

where ρ_L is water density in kg/m^3 and T is the temperature in °C. Equation (34) is incorporated in ASDC for estimation of ρ_L.

Estimation of water viscosity as a function of temperature is performed in ASDC using data fitting equations from the CRC Handbook of Ch. mistry and Physics (Reference 38):

$$\log \mu_L = \frac{1301}{998.333 + 8.1855\,(T-20) + 5.85 \times 10^{-3}\,(T-20)^2} - 1.30233 \qquad 0<T<20^oC \qquad (35)$$

$$\log \frac{\mu_L}{\mu_{20}} = \frac{1.3272\,(20-T) - 1.053 \times 10^{-3}\,(T-20)^2}{T + 105} \qquad 20<T<100^oC \qquad (36)$$

where μ_{20} is the water viscosity in centipoise at 20 °C and T is the temperature of interest in °C. To convert centipoise to kg/m·sec, multiply by 0.001.

The dependence of water surface tension on temperature is also described using an equation for data in the CRC Handbook (Reference 38):

$$\sigma_L = 75.712 - 0.14475T - 2.352 \times 10^{-4}T^2 \qquad (37)$$

where σ_L is water surface tension in dyne/cm and T is the temperature of interest in °C. Equation (37) is valid for 0 to 100°C. To convert dyne/cm to kg/sec^2, multiply by 0.001.

Air density and viscosity values for temperatures in the range of 0 to 100° C are given in the CRC Handbook (Reference 38) and Roberson and Crowe (Reference 39). The following equations describe these data accurately and are incorporated in ASDC:

$$\rho_G = 1.2926 - 4.6769 \times 10^{-3}T + 1.3986 \times 10^{-5}T^2 \qquad (38)$$

$$\mu_G = 1.71 \times 10^{-5} + 5.0 \times 10^{-8}T \qquad (39)$$

where ρ_o is air density in g/L or kg/m^3, μ_o is air viscosity in N·sec/m^2, and T is the temperature of interest in °C.

SECTION III

COST MODEL

A. INTRODUCTION

A cost model is incorporated in the ASDC program to give an approximate indication of the costs associated with a particular design. In many cases, capital and operating costs will not be the only considerations involved in the selection of an optimal design. Designs less than optimal with respect to total costs may be needed to provide flexibility for possible changes in influent characteristics or flow rate, to provide operational simplicity, or to fulfill any of a number of design goals other than the minimum cost. However, capital and operating costs will almost always be design considerations, if for no other reason than to quantify the price of meeting noneconomic design criteria.

The cost model incorporated in ASDC is not intended to provide a highly accurate estimate of the cost of a particular system, but rather to enable comparison of approximate costs for different designs on a consistent basis. Major capital and operating costs are evaluated using cost data and estimation methods obtained from manufacturers and from engineering literature. System costs are evaluated by summing up the component capital and operating costs. An alternative approach is to estimate whole system cost by empirical correlation with total costs for existing systems of similar size (e.g. References 40-43). The component-by-component approach was selected because (1) system costs exhibit variability due to site-specific factors, (2) the component approach enables identification of key cost factors, and (3) single component cost information is easier to update.

An outline of the capital and operating costs considered in the cost model is provided in Figures 8 and 9. Estimation of direct capital costs (excluding electrical equipment and control system costs) depends on equipment sizes and material quantities and is performed for a given design on the basis of unit prices in the cost data base. For indirect capital costs and electrical/control equipment, coarse but generally accepted estimation methods are employed. The chief operating costs for an air stripping unit are the energy costs for the water pump and the air blower. Power cost estimation is performed using the operating characteristics for the particular pump and blower selected by the program for a particular design. Key assumptions necessary for estimation of labor and maintenance costs are requested from the user. Costs included in the cost data bases are referenced to 1990 and can be adjusted in the program for inflation through use of the Engineering News Record (ENR) Construction Index. Detailed descriptions of the components of the cost model are provided below.

B. STANDARD AIR STRIPPER CONFIGURATION

Construction considerations vary from site to site and, therefore, an assumed standard configuration of the air stripping system is employed in the cost model. This is done to

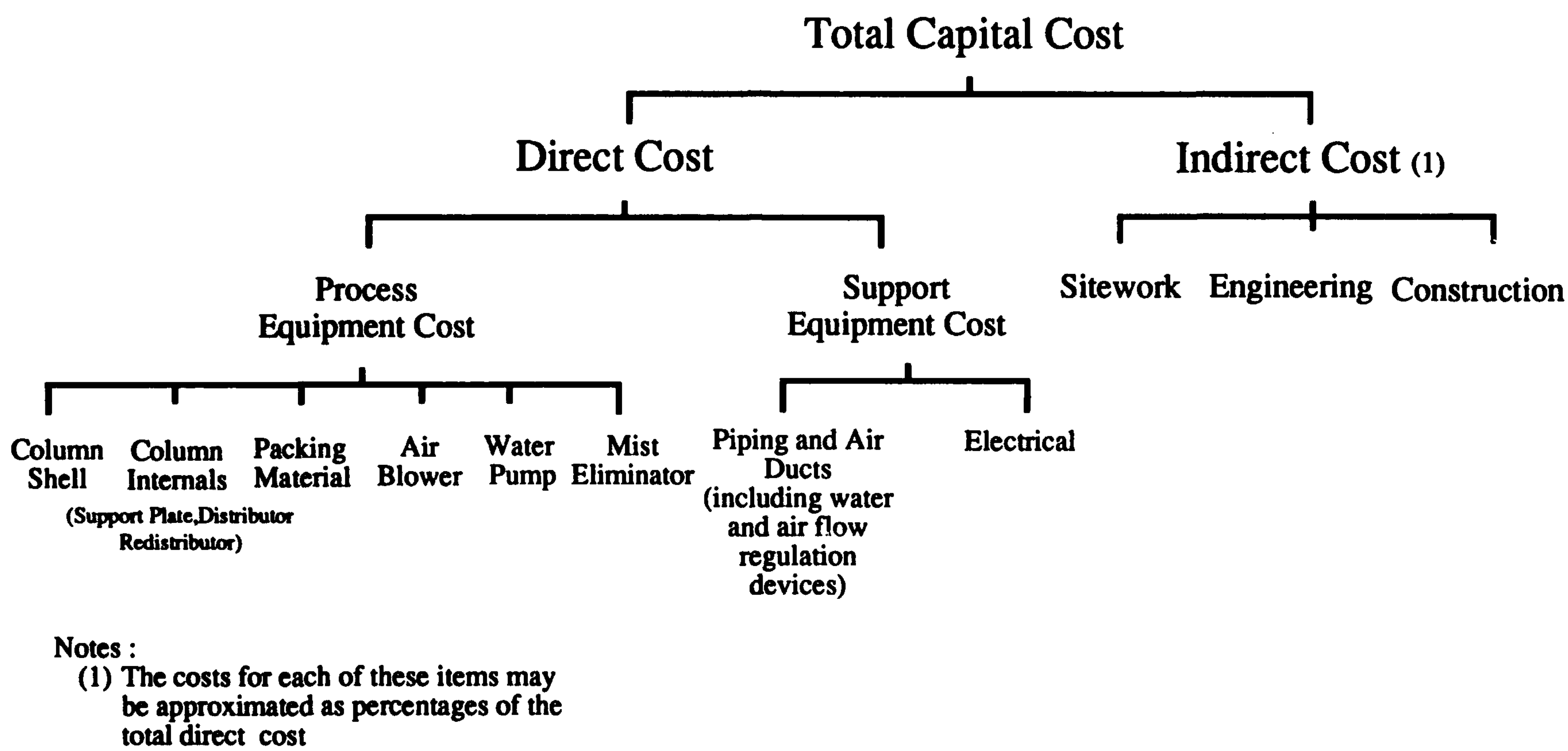
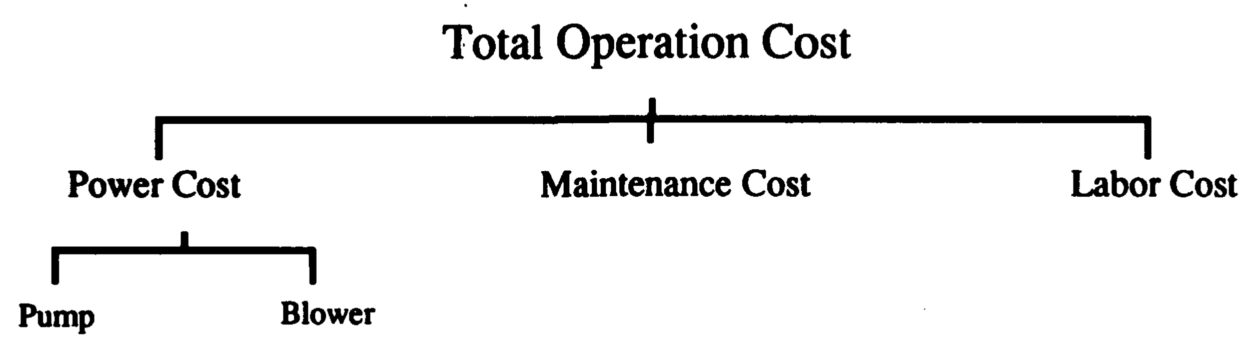


Figure 8. Major Capital Costs for an Air-Stripping Unit



Notes :

The pump cost is based on :

1. projected volume of water treated per year
2. head loss through the column
3. head loss through the piping
4. pump efficiency
5. motor efficiency

The blower cost is based on :

1. volume of air used per year
2. air pressure drop through the column
3. pressure drop through the ducts
4. fan efficiency
5. motor efficiency

Figure 9. Major Operation Costs for an Air-Stripping Unit

provide internal consistency in the cost estimates for alternative designs. The assumed configuration, shown in Figure 10, contains the basic process and support equipment required for a single tower system. It includes the column shell, column internals (i.e., liquid distributor, liquid redistributor(s), and packing support plate), random packing material, mist eliminator, one centrifugal pump, and one centrifugal fan. A constant suction head loss to the water pump of 5 feet is assumed. Support equipment considered includes a 15 feet x 15 feet x 4 feet concrete foundation, steel piping (with a valve and flow meter) from the pump discharge to the top of tower, 100 feet of field piping to the pump, 10 feet of stainless steel air duct (with a damper and a flow meter) from the blower discharge directly to the base of the tower, a gas pressure measurement device at the air inlet and outlet locations in the tower, and a simple manual switch-on electrical power and control system.

C. DIRECT CAPITAL COSTS

The direct capital cost includes all the physical items required for installation of an air stripping tower, that is, process and support equipment costs. The process equipment cost is the key component of the cost model. Process equipment includes the column shell, column internals (i.e., liquid distributor, liquid redistributor, and packing support plate), packing material, air blower, water pump, and mist eliminator. Equipment size requirements calculated in the design procedure are used to determine the quantity of material involved with a particular design.

1. Column Shell

The cost of the column shell is one of the key components of the tower direct cost. Column shells typically are constructed using aluminum or corrosion-resistant steel, predominantly the former. Generic cost data for air stripper column shells are difficult to obtain since they are often custom fabricated. Some very approximate prices for aluminum column shells were provided by one leading manufacturer of air stripper systems. These prices were compared to prices for standard pressure vessels in Richardson Process Plant Construction Estimating Standards (Reference 44, Sections 100-341 to 100-362) and it was found that the approximate column prices were similar to those for pressure vessels constructed with A-285 and A-515 pressure-vessel-quality steel plate. As is the case for an air stripping column shell, the cost of a pressure vessel depends on its height and diameter. A general expression is given in the Richardson Standards for the cost of the pressure vessels cited above:

$$C_{\text{column}} = (45.2 + 3.5D_i - 7.7 \times 10^{-3} D_i^2) \times H_{\text{tower}} \qquad (40)$$

where D_i is the column diameter in inches and H_{tower} is the column total height in feet. This expression is used in the ASDC program to estimate the base cost of an aluminum column shell.

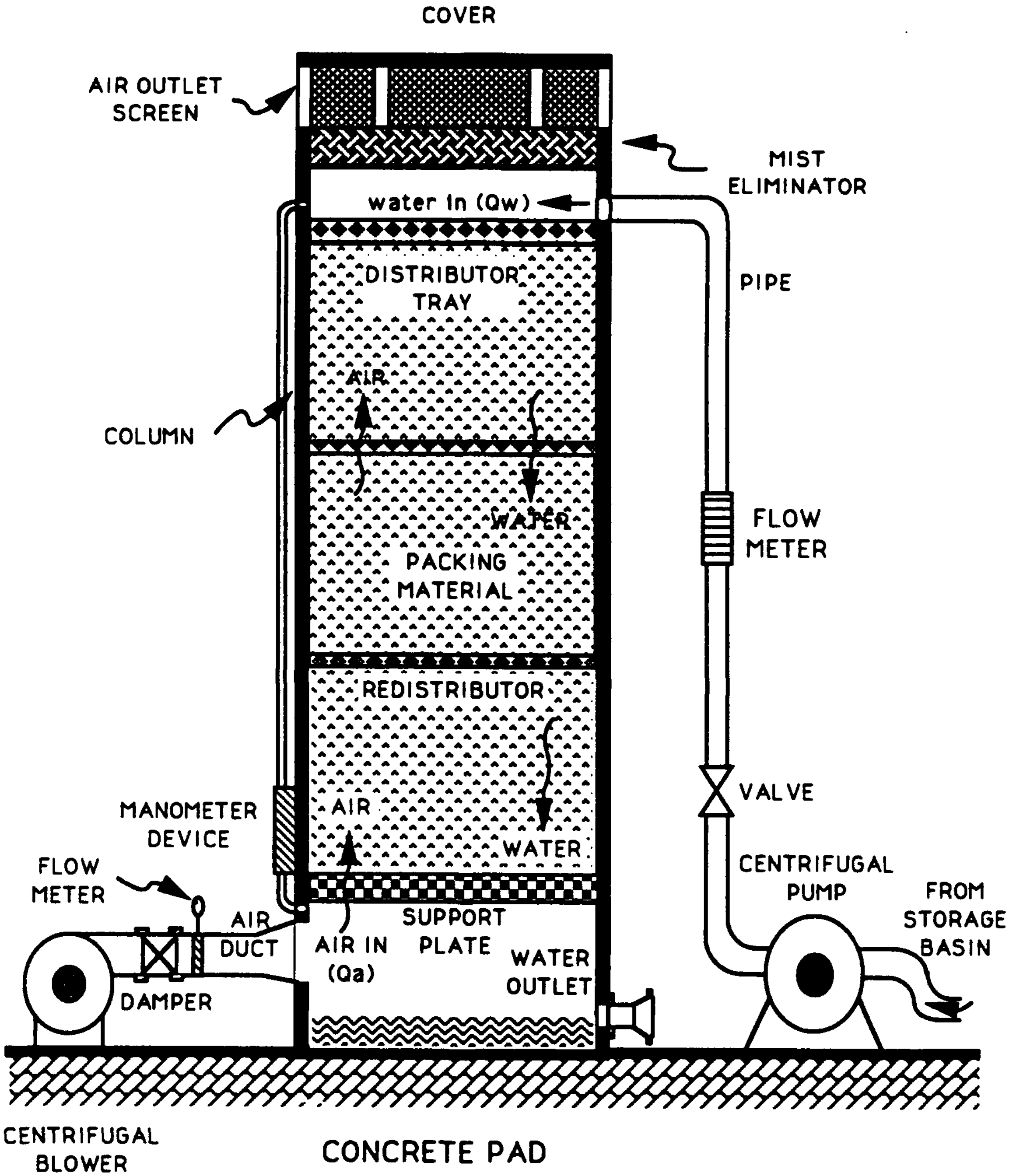


Figure 10. Standard Air Stripping Configuration

The cost for the column shell itself is related with the total height of the column. The total height of the column is the sum of the packing material height, the height of the column skirt which accommodates the air duct inlet and treated water outlet, and the height of the column top for the water pipe inlet, liquid distributor, mist eliminator, and some other devices (e.g., connection to off-gas treatment). As the sizes of these accessories vary, determination of the total height of the air stripping tower requires some assumptions. The ASDC program assumes that the total height is given by the packing height plus some fraction of the packing height. From careful examination of several air stripper designs, it was determined that the multiplication factor is a function of the water flow rate. The multiplication factors employed in ASDC for determining total column height are given in Table 1.

To estimate the total cost of the column shell, the cost of shell accessories must be considered along with the cost of the shell itself. As shown in Figure 10, the assumed configuration of the column shell includes two access ports for maintenance, one pipe inlet, one air duct inlet, one water outlet, and some open nozzles for instrument devices. The costs for all of these items depend on size and quantity.

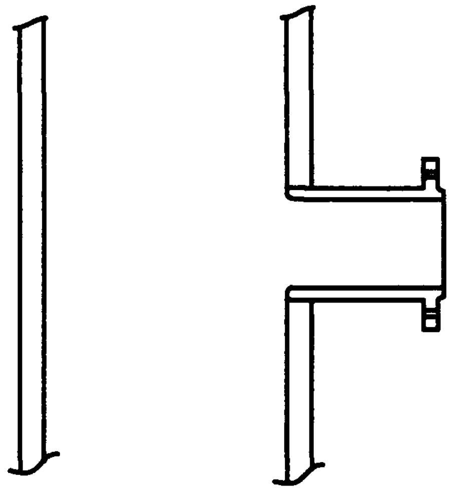
TABLE 1. PACKING HEIGHT MULTIPLIERS FOR ESTIMATING TOTAL COLUMN HEIGHT

Water Flow Rate (gpm)	Packing Height Multiplier
<500	1.30
500-1000	1.40
1000-1400	1.45
1400-1800	1.50
>1800	1.60

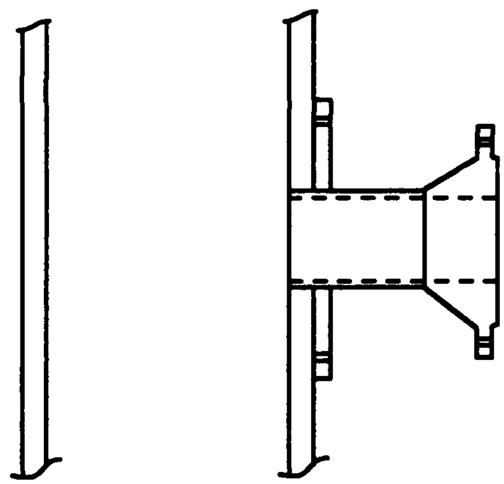
The access ports are assumed to be of the same material as the column shell. The assumed access port type, a long weld neck-type radial nozzle, is illustrated in Figure 11. In ASDC, access ports ranging in size from 2 to 24 inches in diameter are considered and the following equation from the Richardson Standards (Reference 44, Section 100-348) is used to estimate access port cost:

$$C_{\text{port}} = -31.6 + 72.8D_m - 2.8D_m^2 + 0.11D_m^3 \qquad (41)$$

where D_m is the diameter of the access port in inches. The size for the port is determined in



Typical Long-Weld Neck Type Nozzles



Typical Buttweld Flange Type Nozzles

Figure 11. Column Shell Accessories Assumed in Standard Configuration

relation to the diameter of the column. The ASDC program chooses the largest available size that does not exceed two-thirds of the column diameter up to a maximum 24 inches.

Costs for the water pipe inlet and treated water outlets are also estimated in ASDC using a correlation equation from the Richardson Standards (Reference 44, Sections 100-347 and 100-349) for buttweld flange-type nozzles:

$$C_{\text{outlet}} = 133.8 + 42D_p + 4.8D_p^2 \tag{42}$$

where D_p is the pipe diameter in inches. In ASDC the water inlet pipe size is the optimal pump discharge pipe size, discussed later in the section on water pump selection. The treated water outlet pipe size is determined by the same rules for choosing access port size. Estimation of cost for the instrument device nozzles also is performed using the above equation by considering six 2-inch or smaller nozzle openings. The cost for the air duct inlet is estimated using the cost equation for the access port and an additional five percent is added for the tangential shape of the air duct inlet.

TABLE 2. DESIGN-CONTINGENCY-OVERHEAD MULTIPLIERS FOR TOTAL COLUMN COST

Total Colum Cost ($)	Design-Contingency-Overhead Multiplier(1)
≤ 6,000	1.25
6,000-8,000	1.24
8,000-10,000	1.23
10,000-15,000	1.22
15,000-20,000	1.21
20,000-25,000	1.20
25,000-35,000	1.19
35,000-50,000	1.18
50,000-75,000	1.17
≥ 75,000	1.16

Note: 1. From Richardson (Reference 44), Section 100-358.

In the assumed tower configuration, tray rings are used to support the liquid distributor and fiberglass-reinforced plastic (FRP) support plate. The number of tray rings used is discussed in the next subsection on column internals. Ring cost estimation is performed using a correlation equation from the Richardson Standards (Reference 44, Section 100-352):

$$C_{\text{ring}} = 70.4 + 4.45D_i + 1.73 \times 10^{-2} D_i^2 \tag{43}$$

where D_i is the column diameter in inches.

The total cost of the column shell is estimated by adding the shell accessory costs to the cost of the shell itself. A cost multiplier of approximately 1.2 (see Table 2) is added to the total column shell cost to account for engineering design, contingency, and overhead.

2. Column Internals

The column internals include one plate-type liquid distributor, wall-wiper liquid redistributors (for every 5 to 6 feet), and one (FRP) packing support plate. For packing height greater than 30 feet or the ratio of packing height to tower diameter greater than 10, another liquid distributor is included. The costs of these items are functions of diameter. Costs of FRP grid support plates were obtained from equipment vendors, while costs for orifice plate-type liquid distributor trays were taken from the Richardson Standards (Reference 44, Sections 100-353 and 100-359). Correlations of cost versus diameter were developed as follows:

$$C_{tray} = 658.1 - 6.5\,D_i + 0.22\,D_i^2 \tag{44}$$

$$C_{plate} = 20.6 + 1.1\,D_i + 1.1\,D_i + 9.7 \times 10^{-2}\,D_i^2 \tag{45}$$

where C_{tray} is the cost for the liquid distributor, C_{plate} is the cost for the FRP packing support plate, and D_i is the column diameter in inches. The wall-wiper liquid redistributors are assumed to be 5 percent of the liquid distributor cost. The total cost for internals is obtained by summing these components and applying a factor of 1.2 for contingency and overhead.

To illustrate calculation of the costs of internals, consider a column with diameter of 5 feet (1.52 m) and packing height of 32 feet (9.75 m). The cost for the two liquid distributors required would be \$1060 x 2, or \$2120. The cost for four wall-wiper redistributors would be 1060 x 0.05 x 4, or \$212. The number of wall wipers is determined by the rule that if more than one distributor is used, consider one redistributor every 6 feet over half of the packing height. If only one liquid distributor is used, a redistributor is placed every 5 feet over the entire packing height. The cost of FRP support plate would be \$436. Therefore, the total cost for the column internals, including the contingency factor, would be (\$2120 + 212 + 436) x 1.2 or \$3322.

3. Packing Material

The cost for packing material is also one of the key components of the tower direct cost. This cost can be calculated readily with knowledge of the unit prices for different types of packing material. From contacts with several packing material manufacturers, cost data for some common polypropylene packing materials were obtained. The average unit costs incorporated in the program are listed in Table 3. Packing costs for materials other than polypropylene were determined using the polypropylene packing cost data in Table 3 and cost multiplying factors ascertained from manufacturers. For ceramic and metal (i.e., stainless steel) packing, cost-multiplying factors of 5.0 and 2.5 are employed in ASDC. The program provides users the flexibility to input cost information for specific packing material for more accurate estimation of packing materials cost.

TABLE 3. AVERAGE UNIT COSTS FOR POLYPROPYLENE PACKING MATERIAL

Packing Volume	Unit Packing Cost ($/ft^3)
0-99	20
100-499	18
500-999	16
1000-1999	15
> 2000	14

4. Water Pump

An algorithm is included in the ASDC program to determine the pump type and size required for a particular design. This level of design detail is necessary for process capital and operating cost estimation. For pump sizing, the total head loss to be overcome and system flow rate must be known. Determination of the total system head requires knowledge of the pump discharge head loss which is related to the pump discharge pipe size. Therefore, pipe sizing is the first step in the algorithm.

Generally, the aim in designing a piping system is to transmit the desired flow rate at the lowest overall cost. The cost of the pipe and associated fittings is directly proportional to the pipe diameter. The energy cost of pumping is, however, inversely proportional to the diameter. Thus, an economic balance is needed such that the pipe diameter gives the minimum sum for capital and operating cost. To determine the optimum pump discharge pipe diameter, the ASDC program employs the methodology developed by Genereaux (Reference 45) and by Sarchet and Colburn (Reference 46); the approach is summarized in Reference 47. In this approach, the annual cost of pumping and the annual (amortized) cost of a unit length of pipe are combined and the pipe diameter that gives the minimum sum is selected. The power required in a year for pumping liquids is given by the product of flow rate (Q), pressure drop (ΔP), and duration of operation (Y):

$$\text{power} = Q\,\Delta P\,Y = Q\left(\frac{4fLV^2}{2gD}\right) Y \tag{46}$$

where	Y	= duration of operation per year
	f	= friction factor = $0.04 / N_{Re}^{0.16}$ for turbulent flow
	N_{Re}	= Reynold number = $DV\rho/\mu$
	D	= pipe diameter
	ρ	= fluid density
	μ	= fluid viscosity
	V	= fluid velocity
	L	= pipe length
	g	= gravitational constant

Over the course of a year, the cost of pumping may be obtained by considering the cost of electricity and the pump efficiency.

$$C_{\text{pump}} = Q\left(\frac{4fLV^2}{2gD}\right) Y \frac{K}{E} \tag{47}$$

where	K	= electricity cost (cost per KW · hr)
	E	= efficiency of motor and pump
	C_{pump}	= pumping cost per linear foot of pipe per year

For pipe sizing calculations, a combined efficiency of 0.5 is assumed in the program ($E = E_{\text{pump}} \times E_{\text{motor}} = 0.8 \times 0.6 = 0.5$).

Capital pipe cost must be considered as well as the associated operating cost. For most types of pipe, a plot of logarithm of the pipe diameter versus the logarithm of the purchase cost per foot is essentially a straight line. Therefore, the purchase cost for pipe may be represented by the following equation:

$$C_{\text{pipe}} = X D^n \tag{48}$$

where	C_{pipe}	= purchase cost of new pipe per foot of pipe length
	X	= purchase cost of new pipe per foot for unit diameter
	n	= constant with value dependent on type of pipe

The annual cost for the installed piping system may be expressed as follows:

$$C_{\text{pipe}} = (1 + F) X D^n K_F \tag{49}$$

where K_F is the amortized annual fixed cost, expressed as a fraction of initial cost, for installed pipe and F is the ratio of cost for fitting and installation to purchase cost of pipe.

Combining the annual operating cost (C_{pump}) and amortized capital cost (C_{pipe}) yields the total annual cost, C_T. The differential of C_T with respect to D may then be taken, set equal to 0, and the resulting expression solved from $D_{optimum}$, the economic pipe size. Various expressions for $D_{optimum}$ are summarized in Reference 47, Chapter 10; one of these (Equation 39) is implemented in ASDC for determination of the discharge pipe size.

Once the pump discharge pipe size is selected, the optimum pump size can be determined for different flow rates. In ASDC, the total system head is set at the pump discharge head loss plus the assumed 5 feet suction head loss and the static discharge head (the tower height). Determination of the optimum pump size is accomplished by the following procedure:

[1] Determine the pump system head, h_{sys}.

[2] For pumps (included in a database) that can handle the desired flow rate, Q_w, and system head, h_{sys}, scan the pump characteristic curve data for each pump to determine the pump efficiency at the specified operation point (Q_w, h_{sys}).

[3] Choose the most efficient pump.

Characteristic curves for a number of variable speed centrifugal water pumps, with capacities from 150 gpm to 4000 gpm (for h_{sys} < 100 feet) have been obtained from several leading pump manufacturers. These characteristic curves have been described using polynomial fitting equations and included in a data base (see Appendix A). Pump selection is performed using this data base and the procedures discussed above.

Once a pump is selected, its capital cost is determined directly from cost information incorporated in the cost data base (see Table A-1 in Appendix A). When the flow rate is outside of the 150 gpm to 4000 gpm range, pump capital cost is estimated via a simple extrapolation procedure that utilizes the available pump cost data. Pump capital cost is estimated by applying a multiplier to the capital cost for either the 150 gpm or the 4000 gpm pump that reflects the proportional flow below 150 gpm or above 4000 gpm. For a flow Q_1 less than 150 gpm, the pump capital cost is estimated as $C_{pump,\ Q_1} = C_{pump,\ 150} \times (Q_1/150$ gpm). At a flow Q_2 above 4000 gpm, $C_{pump,\ 4000}$ is multiplied by the factor Q_2/4000 gpm.

Pump operating cost (discussed later) is calculated using the efficiency for the operating condition and determined in the pump selection routine, except when the flow rate is outside the range of available data. For water flow rates less than 150 gpm and greater than 4000 gpm, a pump efficiency of 70 percent is assumed.

5. Air Blower

An algorithm is included in ASDC for determination of air blower type and size for a particular design. As in the case of the water pump, detailed blower design is necessary for capital and operating cost estimation.

Air blower size is determined by the system static pressure drop and the air flow required which depends on the air/water ratio. The system air pressure drop is the sum of the pressure drop over the tower plus the pressure drop over the equipment (e.g., air duct, support plate, liquid distributor, and mist eliminator). A value of 1.5 in-H_2O is assumed in the program for the pressure drop over the equipment; pressure drop over the packing is specified by the user (i.e., ΔP). Fan capacity tables for a number of variable speed centrifugal air blowers, with capacity ranging from 200 cfm up to approximately 40,000 cfm (for ΔP up to 10 in-H_2O), have been obtained from a leading blower manufacturer. These tables are included in a data base in ASDC which is scanned for determination of the appropriate fan size. The tables are given in Appendix B. Blower selection is accomplished in ASDC by the following procedure:

[1] Determine the system static pressure drop, ΔP.

[2] Calculate the required air volume from air loading rate, tower area, and the density of air.

[3] For blowers (included in a database) that can handle the desired air volume, Q_a, and ΔP, scan the fan capacity tables for each blower to determine the blower efficiency at the specified operation point (Q_a, ΔP).

[4] Choose the most efficient blower.

Once a blower is selected, its capital cost is determined directly from cost information incorporated in the cost data base (see Table B-1 in Appendix B). When the blower flow rate is outside the range of available data (200 cfm to 40,000 cfm), blower capital cost is estimated using the same extrapolation procedure described for estimation of pump capital costs at high and low flow rates. For an air flow Q_1 less than 200 cfm, $C_{blower,\ Q_1}$ is estimated by multiplying $C_{blower,\ 200}$ by Q_1/200 cfm. At a flow Q_2 greater than 40,000 cfm, $C_{blower,\ 40,000}$ is multiplied by Q_2/40,000 cfm.

Blower operating cost (discussed later) is calculated using the efficiency for the operating condition and particular blower determined in the blower selection routine, except when the flow rate is outside the range of available data. For air flow rates less than 200 cfm or greater than 40,000 cfm, a blower efficiency of 70 percent is assumed.

6. Mist Eliminator

The mist eliminator is assumed to be stainless steel mesh type, 4 inches in thickness. Its cost is estimated using data given in the Richardson Standards (Reference 44, Section 100-360). The correlation developed for the demisting pad and associated bottom grid is:

$$C_{mist} = 1.2\, x\, (46.4 + 9.3\, D_i + 0.14\, D_i^2) \qquad (50)$$

where D_i is the tower diameter in inches and the constant 1.2 is the multiplier assumed for contingency and overhead. The correlation is based upon data for mist eliminators with diameters varying from 36 to 144 inches.

To examine the accuracy of the above equation for mist eliminators having diameters near and below 36 inches, estimated costs were compared against some data obtained from a vendor. The results of this comparison are shown in Table 4, where it may be seen that the accuracy of the estimation equation degrades when it is applied outside the range of the calculation data, but for the purpose of the approximate cost estimation, accuracy below 36 inches diameter appears to be acceptable.

TABLE 4. COMPARISON OF MIST ELIMINATOR[1] COST ESTIMATES WITH DATA

Diameter (inches)	Vendor Cost ($)	Estimated Cost ($)
23	345	401
46	925	927
90	2425	2431

Note: 1. No. 304 stainless steel, mesh type, 4 inches thick

7. Support Equipment

Ancillary equipment needed for connection of the major process equipment components includes piping and air ducts, and electrical control equipment. In ASDC, costs for these support equipment items are basically estimated as percentages of the total process equipment cost. Pipe and air duct costs are estimated as 20 percent of the total process equipment cost plus the cost of piping from the water pump discharge to the top of the column. For the discharge piping cost, the optimum pipe diameter is estimated as described in subsection C.3 above; the pipe length is given by the column height, and unit prices for steel pipe are taken from Richardson Standards (Reference 48, Section 15). Electrical system cost is estimated as 10 percent of total process equipment cost. This fraction is representative of basic electrical control system costs (References 47, 48, 49); it is not intended to include the cost of elaborate instrumentation.

D. INDIRECT CAPITAL COSTS

Indirect capital cost includes all nonphysical items required for an air stripping system. The indirect capital costs considered in the ASDC program include sitework, engineering design, construction, and contingency and profit. The cost estimates for each of these items are based on percentages of the total direct cost, the approach most commonly used for estimation of indirect costs. Percentages used in the program for sitework, design, and construction are 15 percent, 27 percent, and 20 percent, respectively. These percentages include contractor profit and overhead, and were selected after review of cost estimating procedures for various water treatment technologies (e.g., References 49, 50). Actual percentages will be site specific, but use of a single set of percentages in the program provides internal consistency in cost estimates for alternative designs.

E. OPERATING COSTS

The main operating cost associated with operation of an air stripper is the energy cost for electrical power to drive the water pump and the air blower. Power costs are based on the projected volume of water to be treated in a year and the electrical power consumed therewith. Energy requirements for treatment in a packed tower depend on the liquid and gas flow rates and associated friction losses. Once these have been calculated and a particular blower and pump have been selected, estimation of power consumption is straightforward.

Other operating costs include maintenance costs (cleaning of the tower, pump and blower maintenance, etc.), labor costs, and administrative costs. Labor cost may be included with maintenance cost or estimated separately. These costs are usually calculated on the basis of water volume treated. Administrative cost may be estimated as the sum of fractions of labor and maintenance costs, but it is usually not significant and hence is not considered explicitly in the ASDC program.

1. Power Cost

The power cost is based on the projected volume of water to be treated per year and the electrical power consumed by the pump and the blower associated with the air stripping system. The pump power cost is based on the volume of water pumped per year, head loss through the pipes, pump efficiency, and motor efficiency. It can be expressed as:

$$C_{pump} = 0.746 \frac{Q\, h_{sys}\, Y}{3960\, E_{pump}\, E_{motor}} \tag{51}$$

where C_{pump} = pump operating power cost (\$/yr)
Q = average water flow rate (gallon/min)
h_{sys} = total system head loss (ft)
Y = electricity cost (\$/KW·hr)
E_{pump} = pump efficiency (%)
E_{motor} = motor efficiency (%)

In ASDC, pump efficiency is determined in the pump selection algorithm, as discussed above. The motor efficiency is assumed to be 60 percent.

The blower power cost can also be calculated using Equation (51) and is based on volume of air used per year, air pressure drop through the column and through the ducts, fan efficiency, and motor efficiency. The air pressure drop is that through the packing plus that through the other column equipment and ducts. For the column internals other than packing, a pressure drop equal to 1 inch of water is assumed. The air volume is calculated from the design air:water ratio; the blower efficiency is determined in the blower selection algorithm. The cost of electricity is fixed by the user in the ASDC program.

2. Maintenance and Labor

The maintenance cost for an air stripping system will vary a lot from site to site. It depends significantly upon the chemistry of the inlet water which determines the likelihood of potential problems such as scaling or biofouling. Some existing full-scale systems have been operated without any serious problems, while other systems have experienced problems with clogged packing material after just a few months (e.g., References 2, 14). For internal consistency among cost estimates for alternative designs, 10 percent of the direct capital cost is assumed in ASDC for the maintenance cost. This method of estimating maintenance cost is common and the percentage employed is typical (References 14, 43). The labor cost is based on a flat rate of 0.5 cent per 1000 gallon treated plus an add-on for the total volume of liquid treated per year.

F. TOTAL ANNUAL COST

The total annual cost is estimated by summing the amortized capital cost and annual operating cost. The amortized cost is the total capital cost amortized over a particular time period at a interest rate. Both the time period and interest rate can be specified by the user in the ASDC program.

G. ADJUSTMENT OF COSTS FOR INFLATION

Costs in the ASDC cost data bases and calculated by ASDC are referenced to 1990. However, cost calculations including adjustment for inflation may be performed for any year with the program through use of the ENR Construction Cost Index. All costs estimated by ASDC are adjusted for inflation using this index. Table 5 lists average values of the ENR Construction Cost Index for the years 1971-1991; the index value of interest is specified by the user in ASDC, with the default value being that for 1990.

TABLE 5. AVERAGE ENR CONSTRUCTION COST INDEX VALUES FOR 1971-1991

Year	Average ENR CCI Value (1)
1971	1581
1972	1753
1973	1895
1974	2020
1975	2212
1976	2401
1977	2576
1978	2776
1979	3003
1980	3237
1981	3535
1982	3825
1983	4066
1984	4146
1985	4195
1986	4295
1987	4406
1988	4519
1989	4606
1990	4732
1991(2)	4795

Notes: 1. Base Year = 1913; ENR CCI = 100.
2. Average for January - July, 1991.

SECTION IV

PROGRAM OPERATION

A. INTRODUCTION

The Air Stripper Design and Cost (ASDC) program is intended to serve as an aid in designing an air-stripping unit for removal of VOCs from water and wastewater. It is an interactive, menu-driven program written in C language that can be run on IBM or IBM-compatible microcomputers. ASDC is based upon well-established procedures for design of countercurrent air stripping units (Section II) and includes a cost model (Section III). For a specified treatment scenario, ASDC can generate up to 144 alternative designs simultaneously and approximate costs for each of these designs. A flow chart for ASDC is given in Figure 12. Consideration of costs enables evaluation of optimum designs with respect to cost. The cost model included in the program is fairly detailed but not intended to provide highly accurate cost estimates for specific situations. Rather, the purpose of the cost model is to provide a means of assessing relative costs among different designs.

While the ASDC program has been constructed with care, it is furnished "as is" and with absolutely no warranty, expressed or implied. The entire risk associated with use of ASDC is with the user. All information generated by the program should be evaluated independently by the user as to its accuracy, completeness, reliability, and suitability for any particular purpose.

B. HARDWARE REQUIREMENTS

ASDC is designed to run on IBM and IBM-compatible microcomputers. Microsoft DOS (Version 2.0 or higher) and a minimum of 640 Kb of random access memory (RAM) are required. A math coprocessor chip is not required but is recommended. The use of systems based on 80286, 80386, or 80486 processor chips will speed program execution.

Although the ASDC program can be run on a 1.2 Mb high-density diskette drive, a hard disk is highly recommended. The program occupies approximately 0.4 Mb of diskspace, and about 0.2 Mb is used for the database files.

For use of the graphical analysis tools, a CGA, EGA, or VGA color graphics card and monitor are required. The graphics routines cannot be run on systems with a monochrome display adapter (MDA). The system will crash if the graphical analysis tools are invoked with MDA systems.

C. INSTALLATION

The ASDC program is provided on one 1.2 Mb high-density diskette or on two double-density diskettes (5.25-in., 360 Kb). All files must be loaded into the same directory on the hard disk. For the high-density diskette, the DOS "COPY" command can be used to transfer

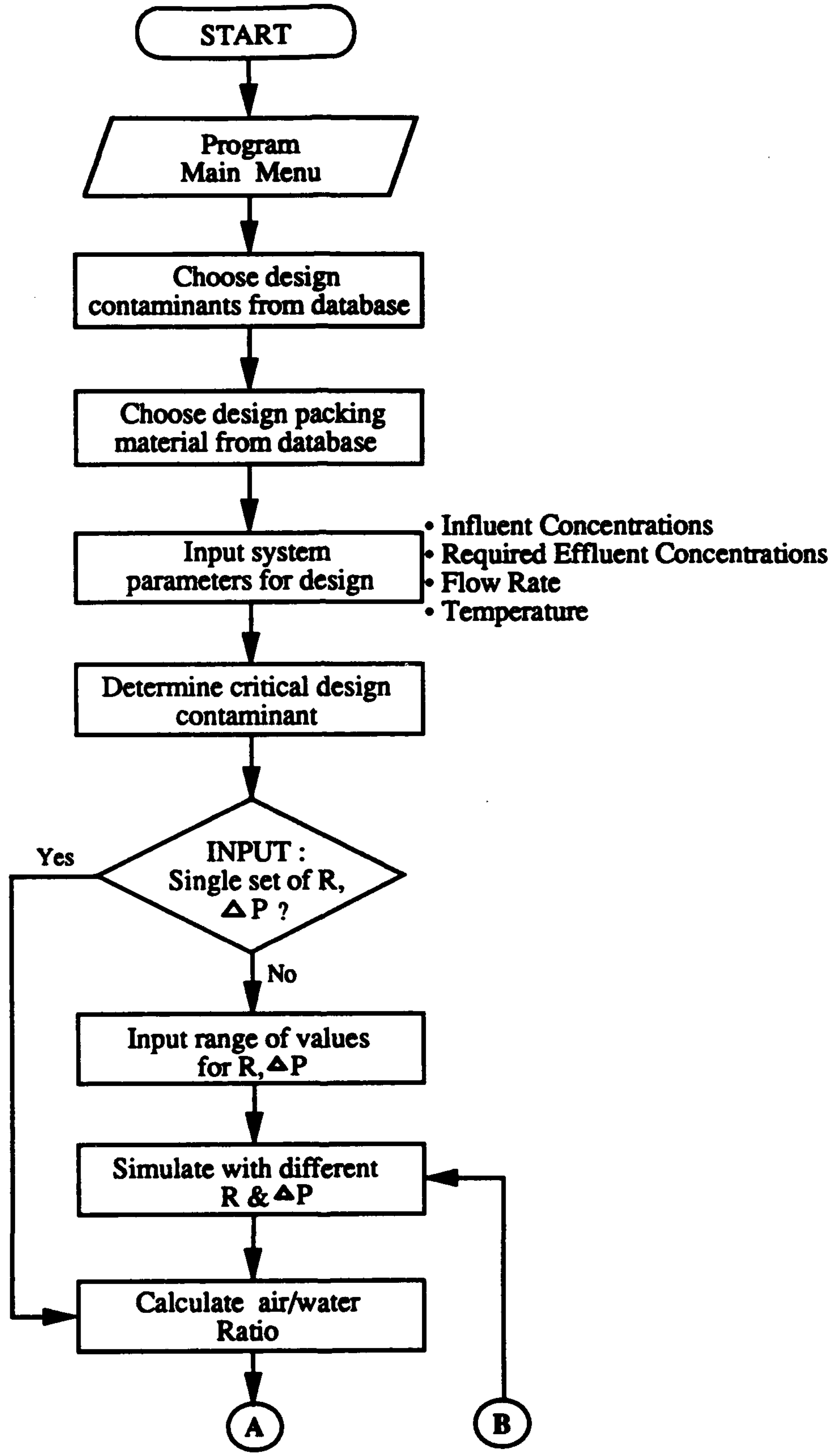


Figure 12. Flowchart for the ASDC Program

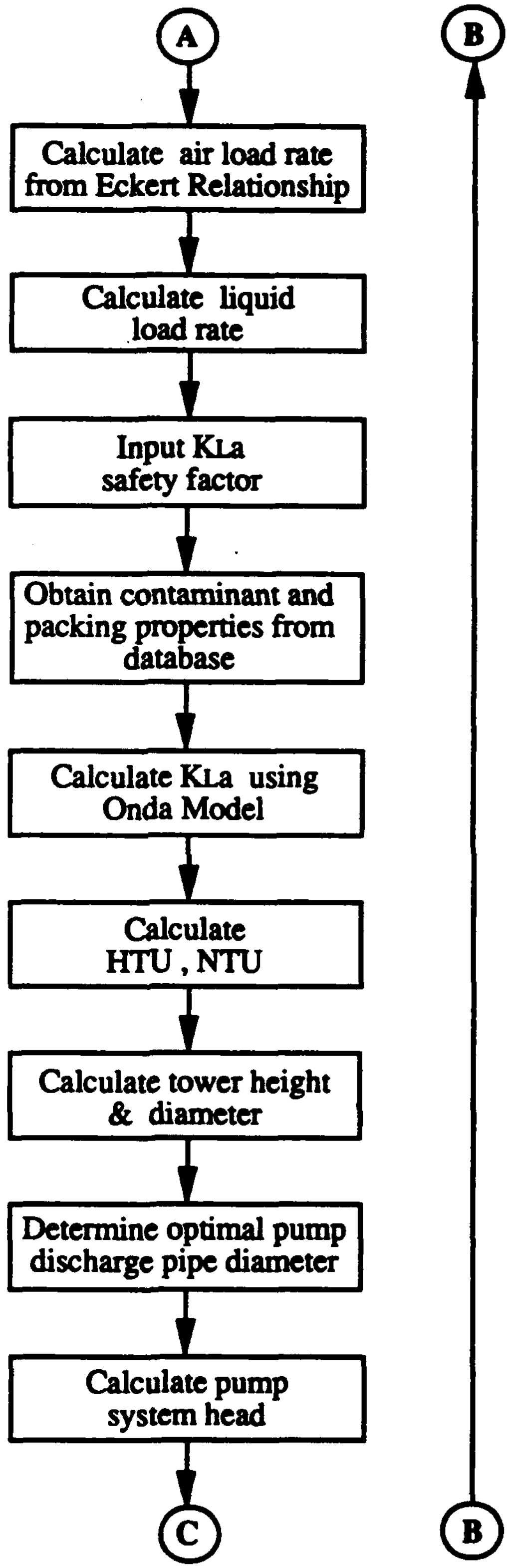


Figure 12. Flowchart for the ASDC Program (continued)

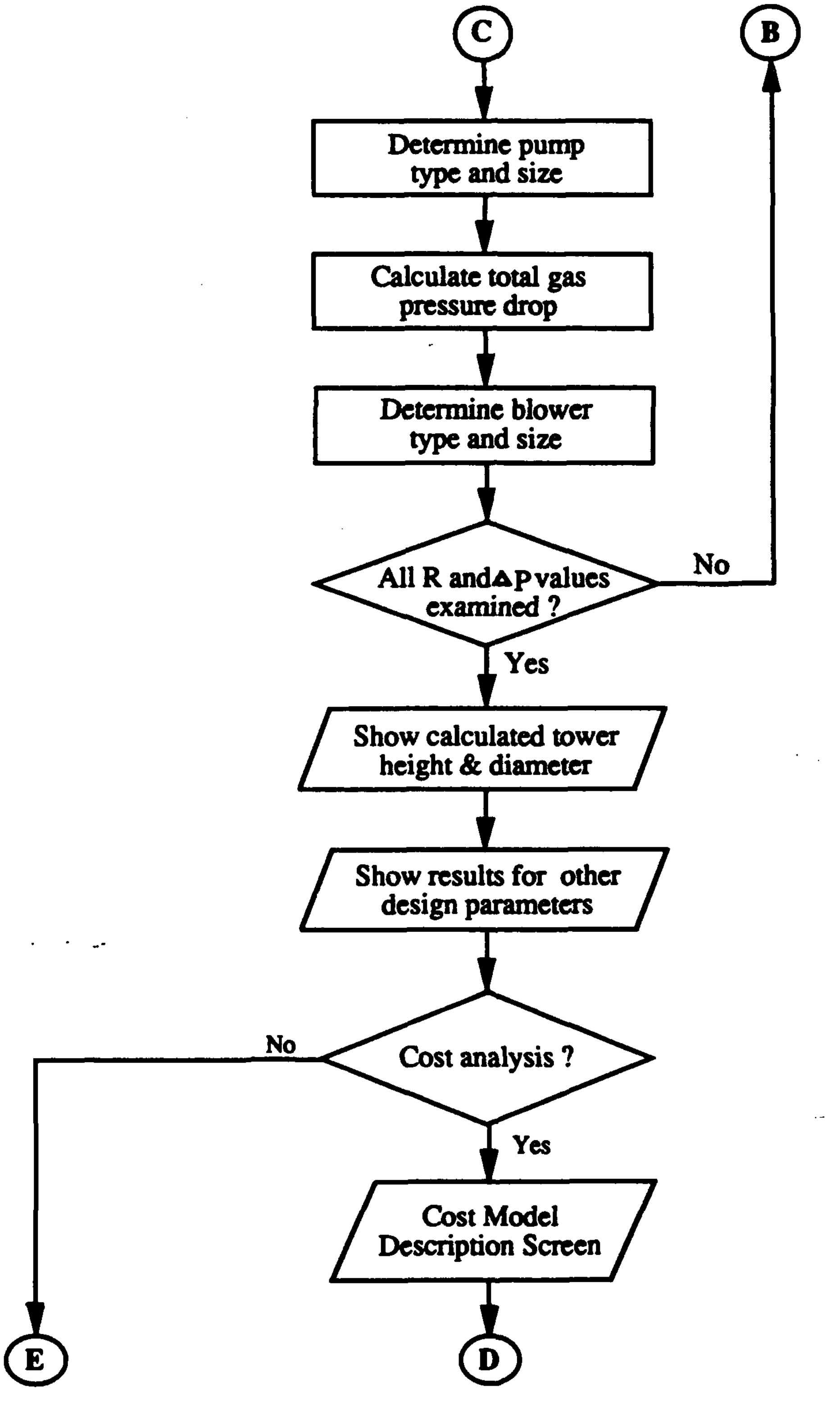


Figure 12. Flowchart for the ASDC Program (continued)

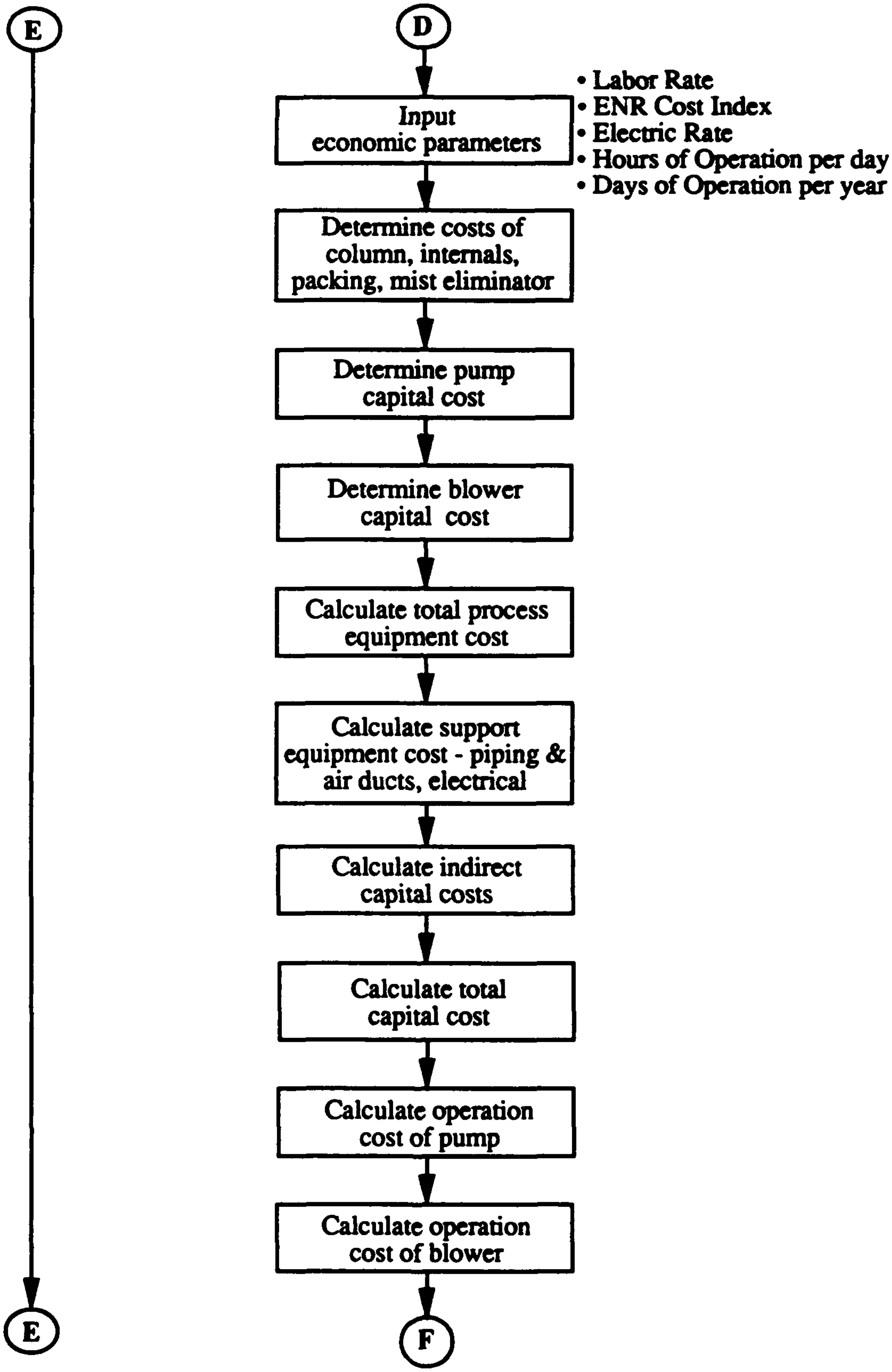


Figure 12. Flowchart for the ASDC Program (continued)

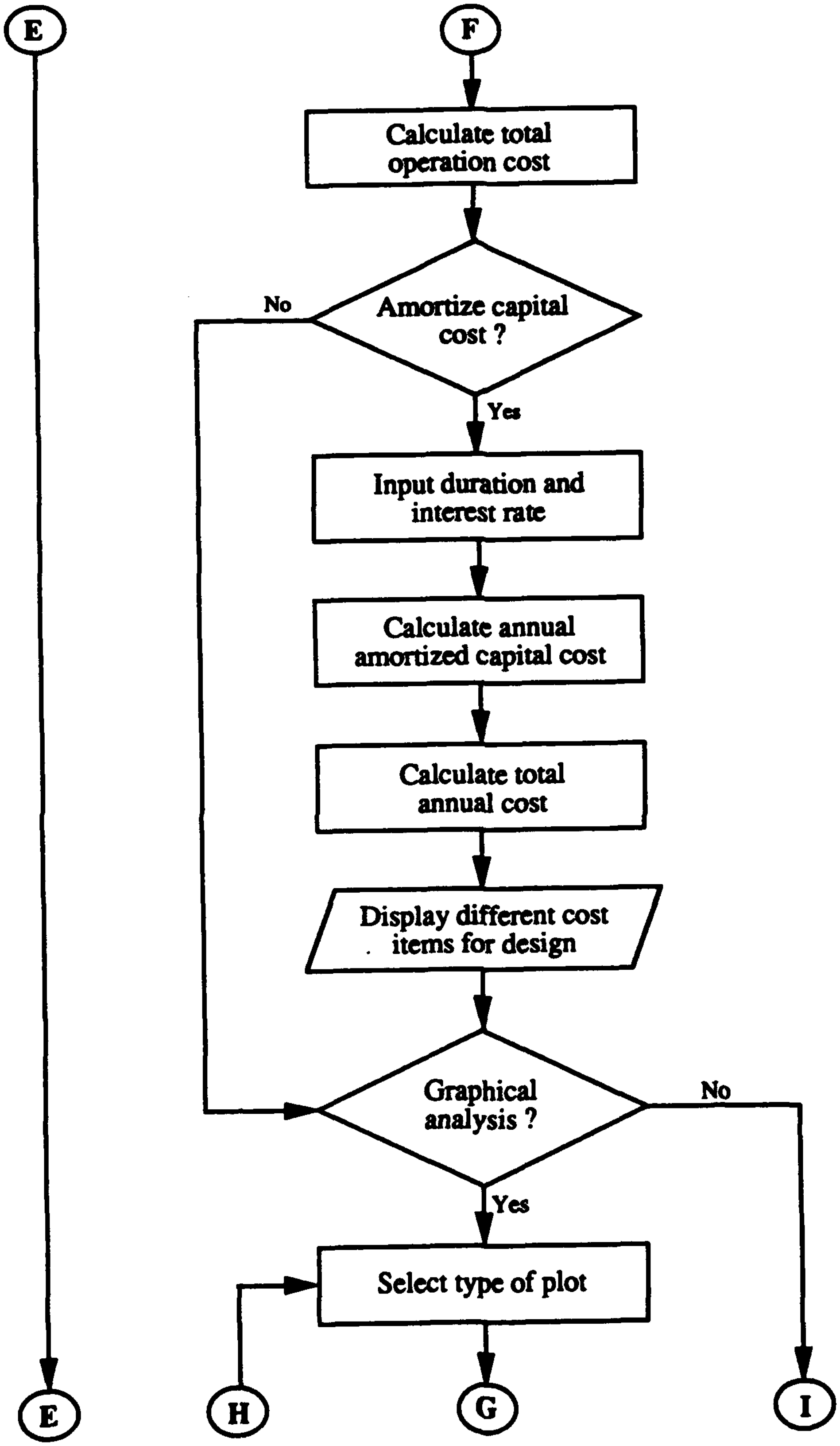


Figure 12. Flowchart for the ASDC Program (continued)

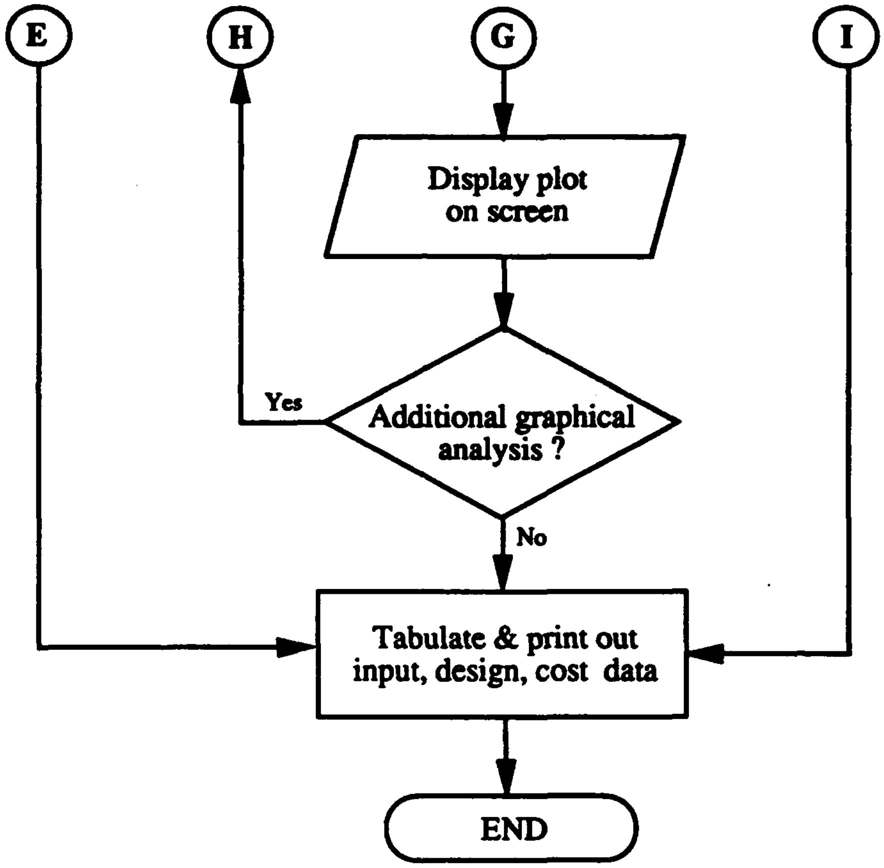


Figure 12. Flowchart for the ASDC Program (concluded)

the files to the hard disk. For the double-density diskettes, the DOS "RESTORE" command must be used to transfer the files, starting with the diskette labelled No. 1. The following files are supplied on the diskettes:

ASDC1.EXE	Main program
SORT.EXE	Utility for sorting compound database
CONTAM.AIR	Contaminant database
PUMPDATA.AIR	Pump database
FAN-DATA.AIR	Blower database
PACKING.AIR	Packing database
REFER.AIR	Contaminant property reference database
MAINMENU.HLP	ASDC help files
DESIGN.HLP	ASDC help files
ASDC.HLP	ASDC help files

D. PROGRAM FUNCTIONS

Program execution is initiated by typing ASDC1 at the DOS prompt for the drive where the program is resident (e.g., C:\ASDC1>). The first screen to appear will be a title screen followed by a screen with the conditions of software use and a screen describing the hardware requirements.. After these screens, the main menu is displayed (Figure 13). Each menu item is highlighted when it is selected with the Up/Down arrow keys (i.e., ↑/↓ on keyboard) or item hot keys (e.g., "E" for exit program). As the items shown in Figure 13 indicate, all of the primary functions of ASDC are accessed from the main menu. Each of the primary functions is described below.

The ASDC program has interactive menus and on-screen help and instructions, making most operations self-explanatory. When guidance is needed, on-line help can be accessed by pressing the F1 function key which will result in a popup help screen. Exit from the help screen is accomplished by pressing the ESC key.

It becomes evident through use of the program but is worth noting here that the "Air Stripping Tower Design" menu item is the most actively used function of the main menu. Not only are design calculations performed through this function, but system design/cost files generated by the user are saved and reloaded through this function. Thus, the section below describing the "Air Stripping Tower Design" function is especially important for understanding operation of ASDC.

1. Contaminant Selection and Properties

This function enables specification of the contaminants upon which air stripper design is to be based. Compounds are selected from an on-screen menu (Figure 14) which contains approximately 110 volatile organic compounds from the U.S. EPA priority pollutant list, hazardous substance list, and drinking water primary contaminant list. Specification of compounds is performed by moving the highlight bar up and down through the menu and

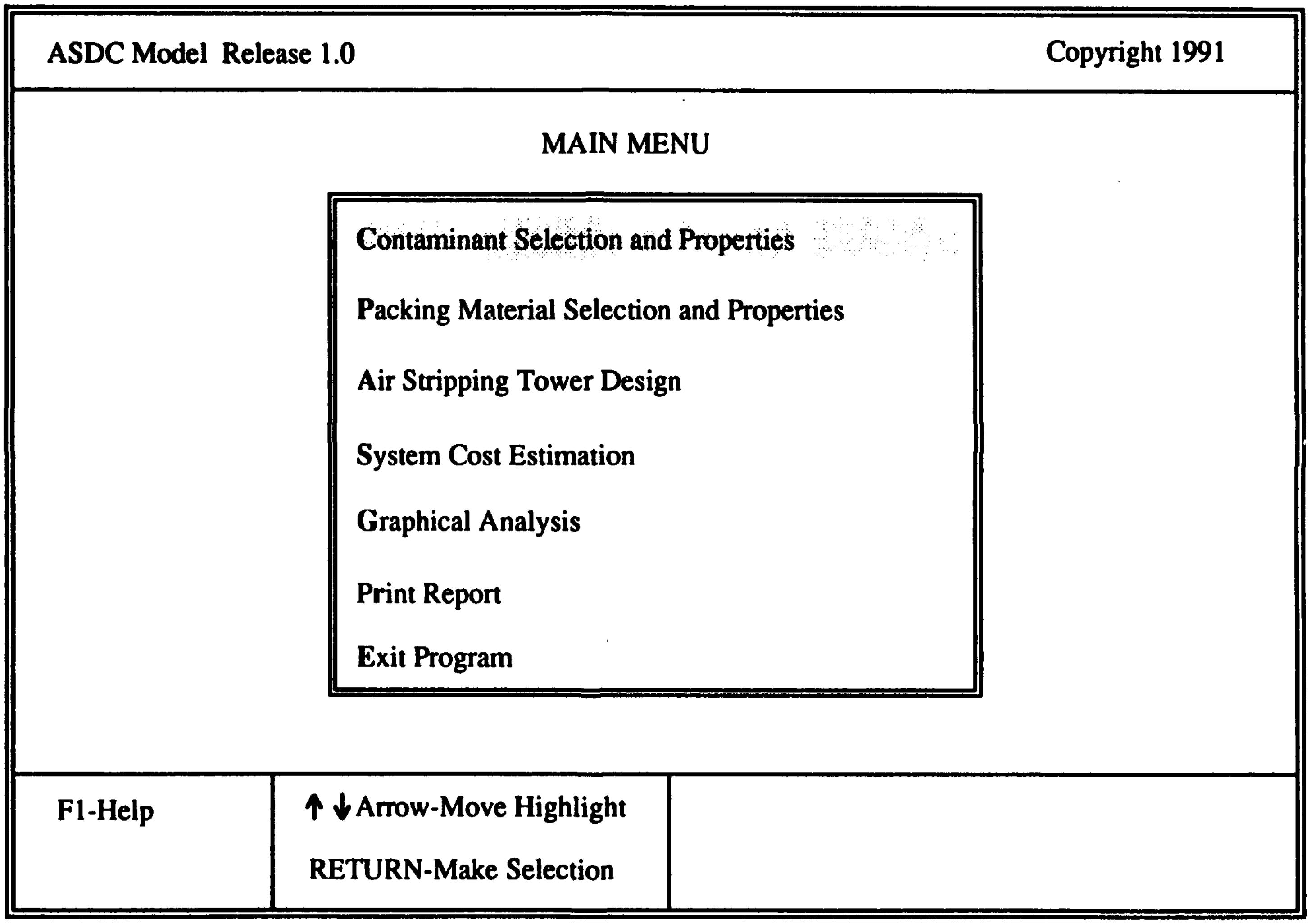


Figure 13. ASDC Main Menu Screen

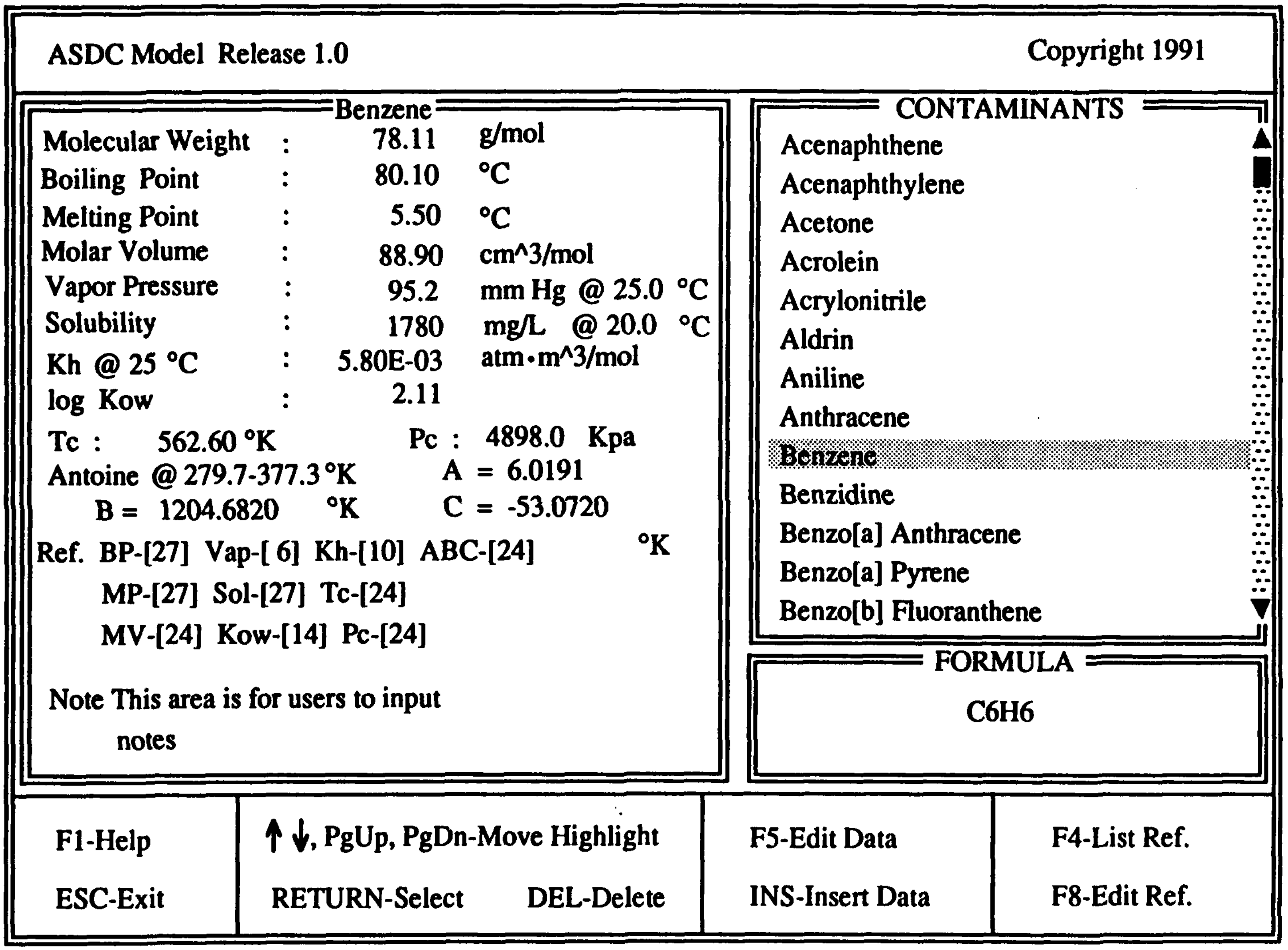


Figure 14. ASDC Contaminant Selection and Properties Screen

pressing the RETURN key to make a selection. The user can use Up/Down arrows (i.e., ↑/↓) on the keyboard or PAGEUP/PAGEDOWN to move the highlight bar. When a selection is made, a check mark (√) will be shown in front of the highlighted compound. A selection may be canceled by pressing RETURN again at the highlighted compound; the check mark will disappear. Up to 10 contaminants may be specified. Once all contaminants of interest have been selected, the user exits to the main menu to continue the design analysis by pressing ESC. A summary of key functions for the contaminant selection and properties screen is given in Table 6.

TABLE 6. KEY FUNCTIONS FOR CONTAMINANT SELECTION AND PROPERTIES SCREEN

F1	Help
F4	List contaminant property references
F5	Edit contaminant properties
F8	Edit contaminant property references
RETURN	Enter selection or inut
ESC	Back to previous screen or no change of input
DELETE	Delete compound from database
INSERT	Input new compounds
END	Move cursor to the end of string
HOME	Move cursor to the beginning of string
↑/↓	Move highlight bar up/down
←/→	Move cursor or highlight to the left/right
PAGEUP	Scroll window one page up
PAGEDOWN	Scroll window one page down

Properties relevant to prediction of air-water exchange have been compiled in a data base for each of the compounds in the menu. Table 7 lists the properties included in the data base. The property values for individual compounds and their corresponding literature sources are presented on-screen for each compound selected with the highlight bar, as shown on Figure 14. Most of the properties are for use in the Onda correlation for prediction of mass transfer coefficients. The Antoine constants, critical temperature, and critical pressure are used to estimate the variation of Henry's Law constant with temperature. Some additional properties relevant to the environmental fate and transport of the compound are also included for the user's information. For some compounds in the database, values for certain properties (most commonly, molar volume, critical temperature, and critical pressure) were not found in the literature examined. It is up to the user to locate or provide estimates for these property values. When missing property values are required for execution of the program (e.g., for calculation of K_La via the Onda Model), a message is displayed on screen informing the user of the property value that is needed for the particular contaminant selected by the user.

The user can edit, insert, and delete compounds and their properties in the database. To edit the compound properties, press the *F5* function key and the cursor will appear at the first character of the compound's name. The Left/Right arrow (i.e., $\leftarrow / \rightarrow$) on the keyboard or HOME/END key can then be used to move the cursor and make corrections. New characters can be typed to overwrite those displayed. When editing of an item is completed, press the RETURN key to move to the next item. Pressing the ESC key will leave the edit for this item unchanged.

TABLE 7. VOC COMPOUND PROPERTIES IN ASDC DATA BASE

Molecular Weight
Boiling Point
Melting Point
Molar Volume
Vapor Pressure
Aqueous Solubility
Henry's Law Constant
log K_{ow}
Critical Temperature
Critical Pressure
Antoine Constants

To input a new compound, press the INSERT key on the keyboard and an input screen will popup. The input screen format is just like that on the contaminant properties screen (Figure 14). The compound name and values for compound properties may be typed in the spaces provided. A highlight bar is present on the screen for indication of the property awaiting input; press the RETURN key after an appropriate value is entered. Exit from the compound insertion screen is accomplished by pressing ESC; upon doing this, all of the information entered will be saved. New compounds will be added to the end of the data base. The revised data base can be sorted alphabetically, according to the first capital letter in the compound name (e.g., Chloroform), using the utility called "SORT.EXE" that is provided with the program. To perform this, exit the program and under the DOS prompt (e.g. C:\ASDC>) type SORT. The utility will automatically sort the compounds.

To delete a compound from the database, move the highlight bar to the compound of interest and then press the DELETE key on the keyboard. A screen will popup to reconfirm the request. If a "YES" response is given, the compound will be removed from the database.

References for the compound property data are listed by index number on the property screen and can be reviewed by pressing the *F4* function key. All references cited in the original compound property database are listed in detail in Appendix C. Existing references can be edited or more references can be added to the database by pressing the *F8* function key. After pressing *F8*, an input screen will popup and a request for input of a reference index number will be displayed. If the reference index number entered is currently in use for another reference, a popup screen will request user confirmation for modification of the existing reference. To edit the existing reference, the user can move the highlight bar or press "E" (for "Edit") and the cursor will appear at the first character of the reference. To input a new reference, a new index number should be entered after pressing *F8*. Once a new index number is entered, a screen with spaces for input of reference information will be displayed (Figure 15).

2. Packing Material Selection and Properties

This function enables selection of a particular random packing material and its properties for subsequent air stripper design calculations. Approximately 60 different packing materials available from several manufacturers (Ceilcote, Glitsch, Jaeger, Koch, Lantec, and Norton) are listed in an on-screen menu (Figure 16). Selection of a packing material is performed by moving the highlight bar to the packing of interest and pressing the RETURN key. A check mark (√) will be displayed in front of the packing selected. Only one kind of packing material can be specified. A selection may be canceled by moving the highlight bar to the packing with the check mark and pressing RETURN whereupon the check mark will disappear and another selection can be made. Once a packing material has been chosen, the user exits to the main menu to continue design analysis by pressing *ESC*. A summary of key functions for the packing material selection screen is given in Table 8.

TABLE 8. KEY FUNCTIONS FOR PACKING MATERIAL SELECTION AND PROPERTIES SCREEN

F1	Help
F5	Edit packing material properties
RETURN	Enter selection or input
ESC	Back to previous screen or no change of input
DELETE	Delete packing material from database
INSERT	Input new packing material
END	Move cursor to the end of string
HOME	Move cursor to the beginning of string
↑/↓	Move highlight bar up/down
←/→	Move cursor or highlight to the left/right
PAGEUP	Scroll window one page up
PAGEDOWN	Scroll window one page down

Properties reported by the manufacturers of the various packing materials have been compiled in a data base. Table 9 lists the assembled properties. Properties are displayed on-screen (Figure 16) for the packing material under the highlight bar.

The user can edit, insert, or delete packing materials and their property values. To edit the packing material name and/or properties, press the *F5* function key and the cursor will appear at the first character of the packing material name. The Left/Right arrow keys (i.e., ←/→ on keyboard) or the HOME/END key can then be used to move the cursor and make the desired correction. Characters entered will overwrite the existing characters. When

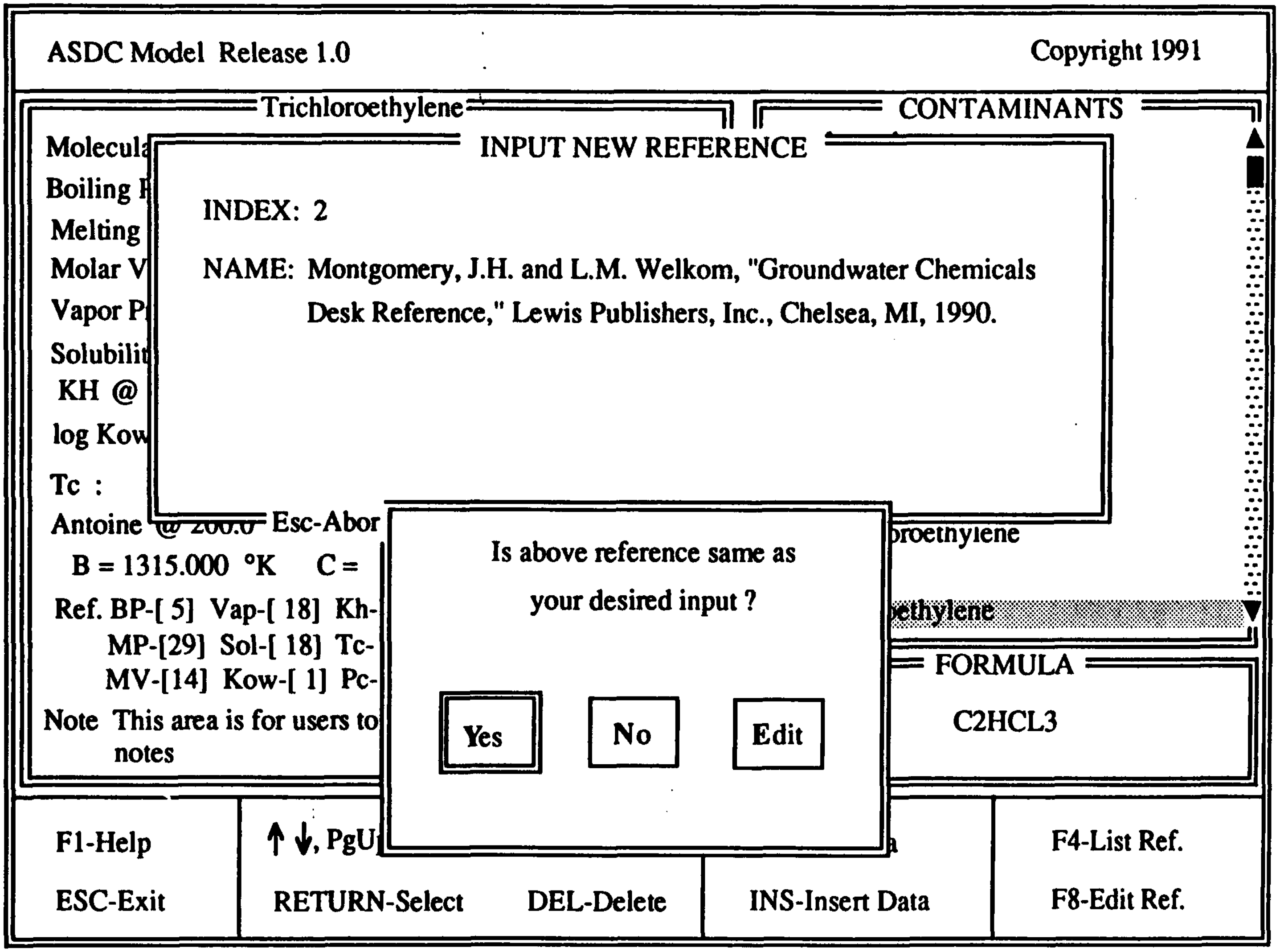


Figure 15. ASDC Reference Input and Edit Screen

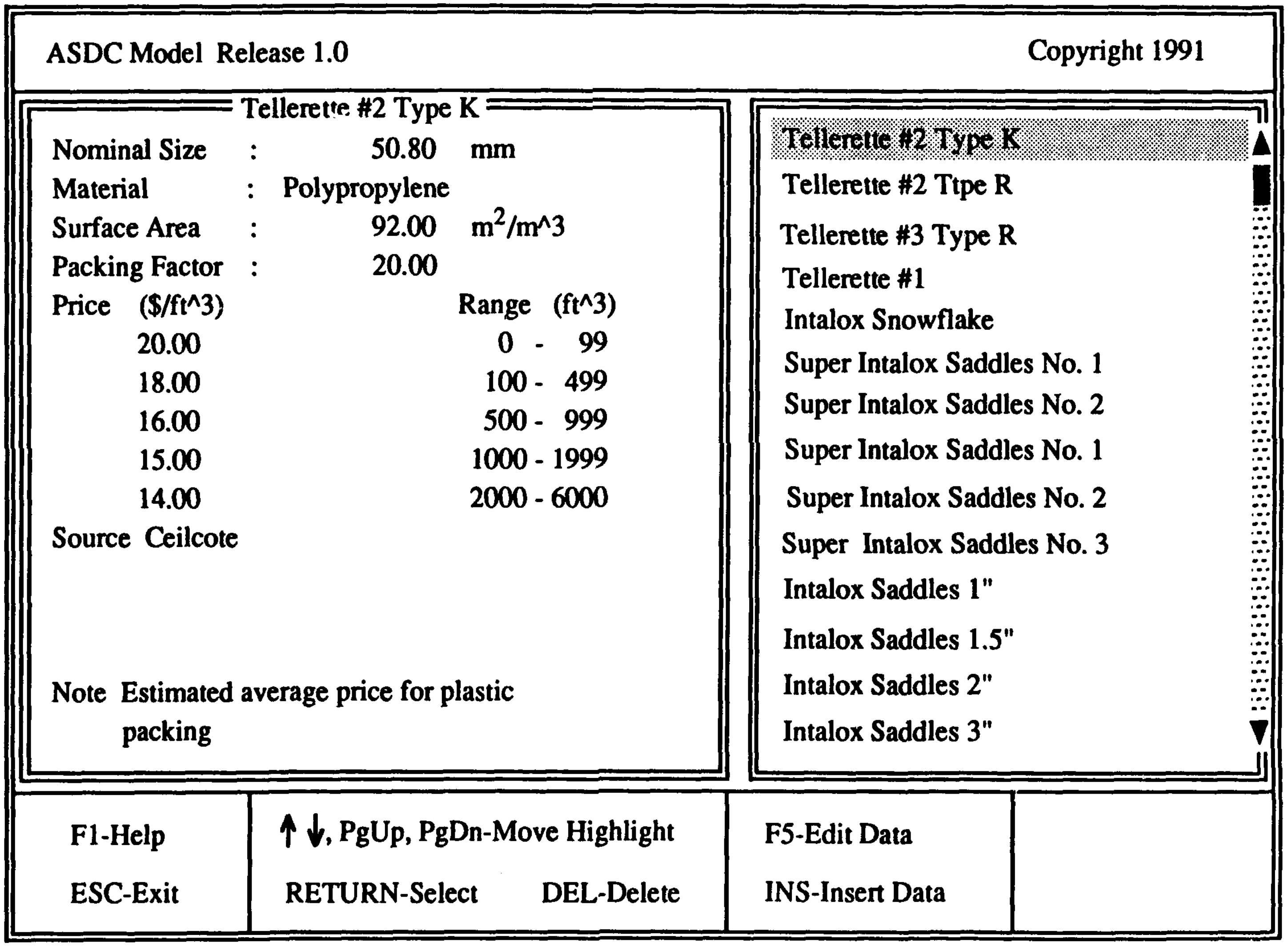


Figure 16. ASDC Packing Material Selection and Properties Screen

editing of a particular item on the screen is completed, press the RETURN key to move to the next item. The ESC key will leave the edit unchanged.

To input a new packing material, press the INSERT key on the keyboard and a blank line will be inserted right after the highlighted packing material. Type the name of the packing material on this line and then enter its properties by pressing RETURN and following the procedures outlined above. If the ESC key is pressed prior to completing the input of data for the packing, ASDC will exit from the insert routine and the data base will be unchanged.

To delete a packing material from the database, press the DELETE key on the keyboard. A screen will popup to confirm the request. If a "YES" answer is provided, the packing material will be removed from the database.

TABLE 9. PACKING MATERIAL PROPERTIES INCLUDED IN ASDC DATA BASE

Material type (propylene, ceramic, or stainless steel)
Nominal size
Total specific surface area
Packing factor

3. Air Stripping Tower Design

This function performs the air stripping tower design calculations for removal of the specified contaminants using the selected packing material. Before the design calculations can be performed, however, values for the important design parameters must be specified. Once this is done, alternative designs are generated simultaneously by the program for the design parameter ranges specified.

Upon selection of the "Air Stripping Tower Design" function, a popup screen is displayed requesting designation of the file to be used for the design calculations. This screen provides the options listed in Table 10. If a user has just initiated a new design analysis by selecting contaminants and a packing material, the "New File" option is appropriate. The "Same File" option is useful when repeated sets of design calculations are desired in which only one or two of the design parameters are being altered. This option keeps the design parameters currently in memory resident.

TABLE 10. DESIGN FILE DESIGNATION OPTIONS

Option	Function
New File	Create a new design file (in RAM), i.e., a new set of design parameter values
Same File	Use the design file that is currently in memory (RAM)
Load File	Load a design file previously saved on the hard disk.
Save File	Save a particular design file (set of design parameter values) and the associated designs on the hard disk in a named file. If this option is invoked after design calculations <u>and</u> cost calculations have been completed, the costs associated with the various designs will also be saved.

The "New File" and "Load File" options will erase design parameter values entered previously. To save a particular set of design parameter values and associated designs on the hard disk, the "Save File" option should be selected. The user will be prompted for a file name. Saved design files can be reloaded for additional analysis at a later time via the "Load File" command.

Once a design file designation option has been selected, the design parameter selection screen shown in Figure 17 will be displayed. As indicated on Figure 17, this screen is divided into two windows: one for specification of water flow rate, water temperature, ambient air pressure, and ranges of the variable design parameters R (stripping factor) and ΔP (gas pressure drop); and one for specification of influent and desired effluent concentrations for the specified compounds. The PAGEUP and PAGEDOWN keys are used to switch between these windows. The Up/Down and Left/Right arrow keys (i.e., $\uparrow/\downarrow$ and $\leftarrow/\rightarrow$ on keyboard) or HOME/END keys are used to move the highlight bar from item to item. In order to input a value for a design parameter, the RETURN key must first be pressed after the highlight bar is moved to the item of interest. A summary of key functions for the air stripping design screen is given in Table 11.

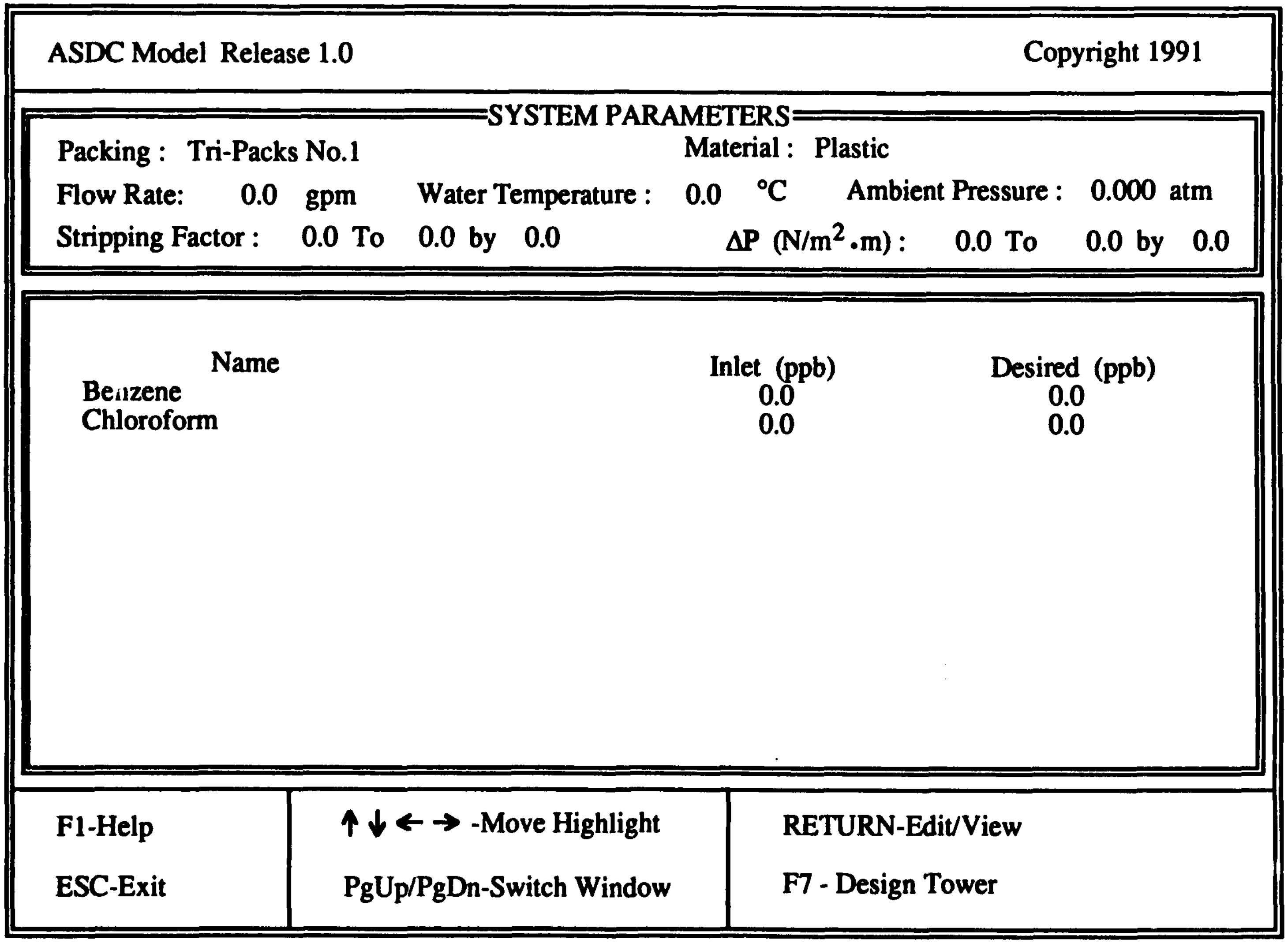


Figure 17. ASDC Air Stripping Tower Design Screen

TABLE 11. KEY FUNCTIONS FOR THE AIR STRIPPING TOWER DESIGN SCREEN

F1	Help
F3	View the specified and calculated effluent concentrations
F7	Design air stripping tower
RETURN	Enter selection or input
ESC	Back to previous screen or no change of input
END	Move cursor or highlight to the end
HOME	Move cursor or highlight to the beginning
↑/↓	Move highlight bar up/down
←/→	Move cursor or highlight to the left/right
PAGEUP	Switch to the design parameter window
PAGEDOWN	Switch to specified contaminant window

For a set of specified contaminants, design calculations are performed for the compound having the highest NTU (number of transfer units) and *R* (stripping factor) greater than 1. Preliminary NTU estimates are made by applying the Onda model, with an assumed air:water ratio of 30 (which fixes *R*), to each contaminant specified by the user. The NTU and *R* criteria are then applied to these results. The compound selected as the basis for air stripper design using this procedure is effectively the least volatile compound for which air stripping is feasible. In ASDC, an option is provided for the user to override the program's choice of design contaminant. A popup screen requesting user confirmation of the design contaminant appears before initiation of design calculations. After all design parameters indicated on Figure 17 are entered, the tower design calculations are initiated by pressing *F7* function key. A popup screen will be displayed before calculations begin requesting confirmation of the program-selected design compound. Another popup screen is displayed which allows the user to input a safety factor for the estimated mass transfer factor, K_La. A default value of 1.2 is provided for the K_La safety factor. The user can press RETURN to accept the value or type in a new value. ASDC then computes the alternative designs for the specified *R* and ΔP ranges.

Once a compound acceptable to the user is in place and calculation options have been specified, design calculations are performed. The output configurations (tower diameter and packing height), i.e., the alternative designs, are displayed on-screen after the calculations are completed. As shown in Figure 18, the calculated configurations corresponding to each pair of *R* and ΔP values is displayed. (In the example shown, benzene removal from 100 ppb to 5 ppb and chloroform removal from 800 ppb to 5 ppb were specified. Design was based on chloroform removal.) The user can examine values of the other design parameters associated with a particular configuration by moving the highlight bar (see Figure 18) to the configuration of interest and pressing the RETURN key. A popup screen is displayed which contains values of all design parameters for that design configuration (Figure 19). The user can also examine the predicted effluent concentrations for the specified contaminants by pressing the *F3* key. A popup screen is displayed which contains the specified influent and desired effluent concentrations, along with the predicted effluent concentrations.

4. System Cost Estimation

Once design calculations have been completed for a particular design file (set of design parameter values), approximate capital and operating costs associated with the various alternative designs can be estimated. This is done by selecting the "System Cost Estimation" item on the main menu (see Figure 13).

The first screen to be displayed after selection of the cost estimation function contains a menu of economic parameter values, primarily related to operating costs, that the user can modify for a particular design scenario. A reproduction of this screen is given in Figure 20. In addition to operating cost parameters, it also includes the Engineering News Record (ENR) Construction Cost Index which is used for inflation adjustment of cost data in the ASDC data base. To change any of the default values on the screen, the user can move the highlight bar to the item of interest and press RETURN to edit.

Cost calculations are performed by pressing the *F10* function key. After the calculations are completed, a tree-diagram containing the components of the cost model is displayed on screen (Figure 21). The user can move the highlight bar from component to component using the directional arrow keys or the HOME/END keys on the keyboard. Calculated costs for the highlighted component are displayed by pressing the RETURN key. An example detailed cost screen is shown in Figure 22. Return to the main menu is achieved by pressing ESC. A set of cost calculations can be saved (together with the associated design calculations) by selecting the "Save File" option in the "Air Stripping Tower Design" function at the main menu after exiting "System Cost Estimation."

In order that cost variations across the ranges of values for the design variables can be examined, the program is not constructed to identify a single design associated with the minimum cost. Rather, costs associated with all possible designs within the ranges specified for design variables are displayed. Flexibility is usually required in air stripping design to account for changes in operating conditions, so cost is not the only factor that determines the final design. However, knowledge of cost is important in the design process in that the price of different levels of flexibility can be taken into account. The need for the simultaneous consideration of cost and the range of operating conditions is the reason why all possible designs are output rather than just the single design associated with the minimum total cost.

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SYSTEM PARAMETERS

Packing : Tri-Packs No.1 Material : Plastic

Flow Rate: 200.0 gpm Water Temperature : 20.0 °C Ambient Pressure : 1.000 atm

Stripping Factor : 2.0 To 5.0 by 1.0 ΔP ($N/m^2.m$): 50.0 To 100.0 by 10.0

DESIGN TOWER OUTPUT

Flow Rate: 400.0 gpm Stripping Factor

ΔP	2.00		3.0		4.00		5.00	
($N/m^2 \cdot m$)	H (m)	D (m)	H (m)	D (m)	H (m)	D (m)	H (m)	D (m)
50.0	15.24	0.55	10.82	0.60	8.82	0.69	7.85	0.74
60.0	15.36	0.54	10.91	0.59	8.96	0.66	7.98	0.71
70.0	15.47	0.54	10.98	0.58	9.08	0.64	8.09	0.69
80.0	15.55	0.53	11.05	0.57	9.18	0.63	8.18	0.67
90.0	15.63	0.52	11.10	0.56	9.27	0.61	8.26	0.66
100.0	15.71	0.52	11.16	0.56	9.35	0.60	8.33	0.64

F1-Help	↑ ↓ ← → -Move Highlight	RETURN-Edit/View
ESC-Exit	PgUp/PgDn-Switch Window	F7 - Design Tower

Figure 18. ASDC Tower Design Output Screen

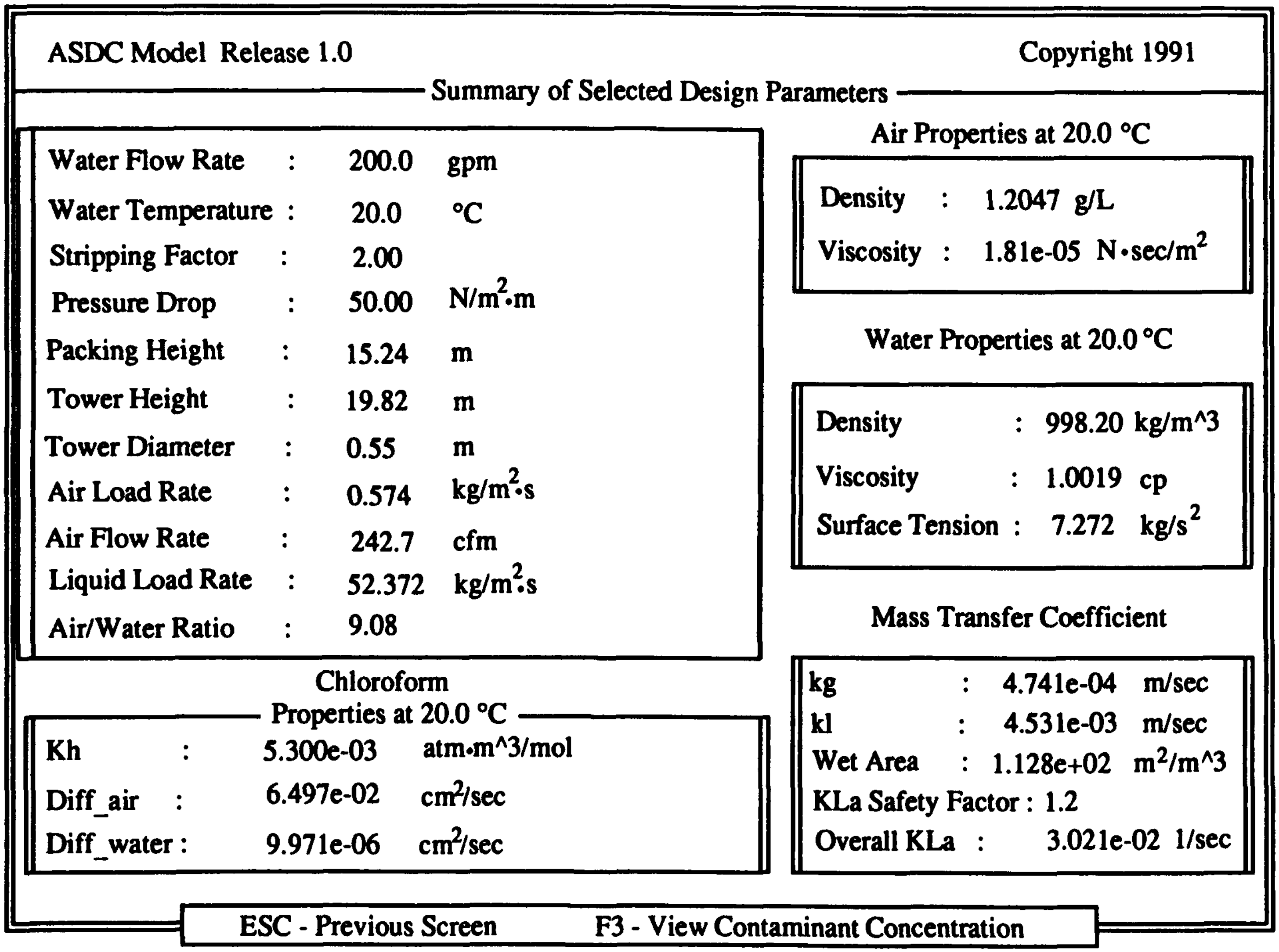

Figure 19. ASDC Detailed Design Parameters Output Screen

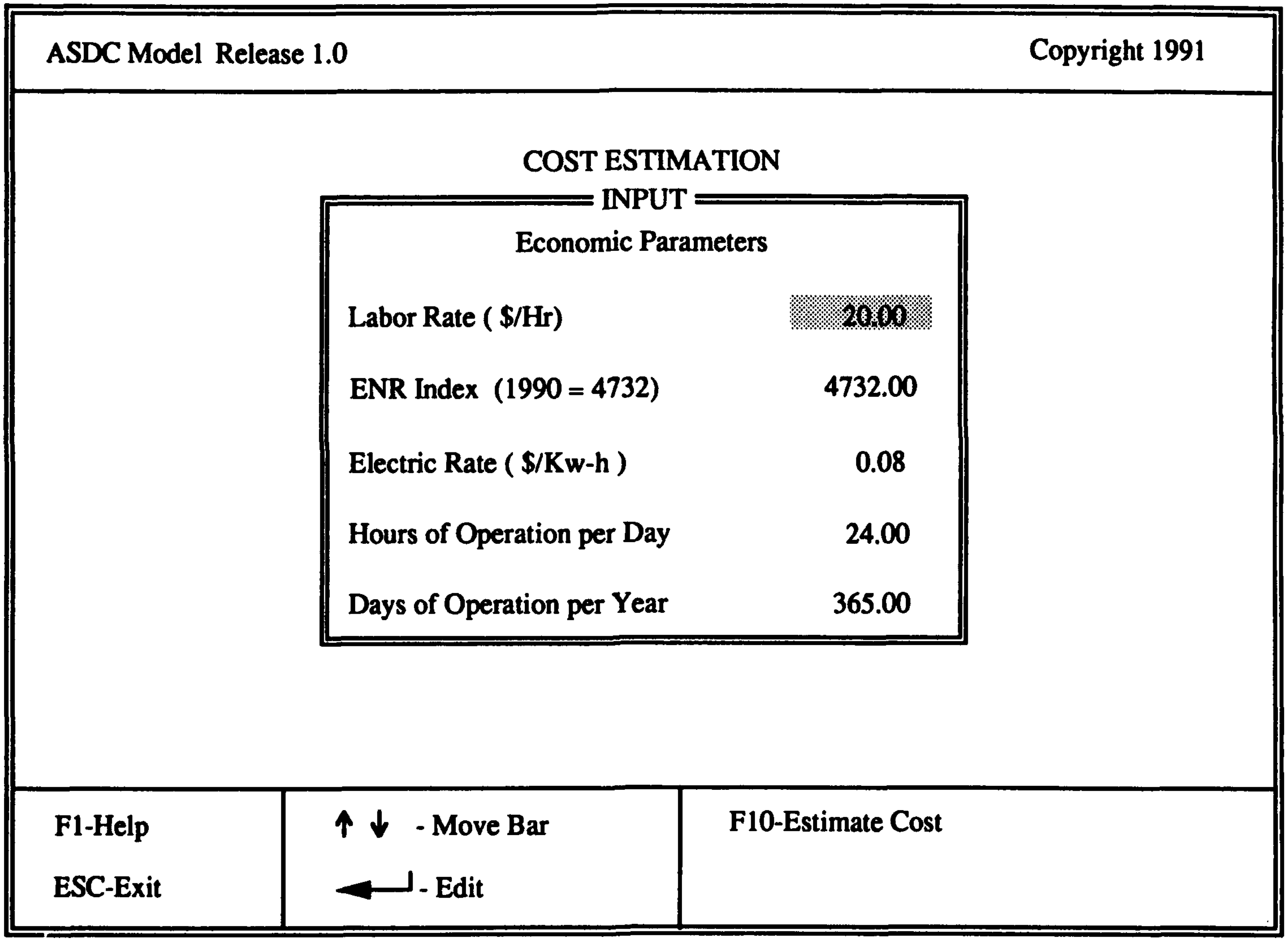

Figure 20. ASDC Economic Parameters Input Screen

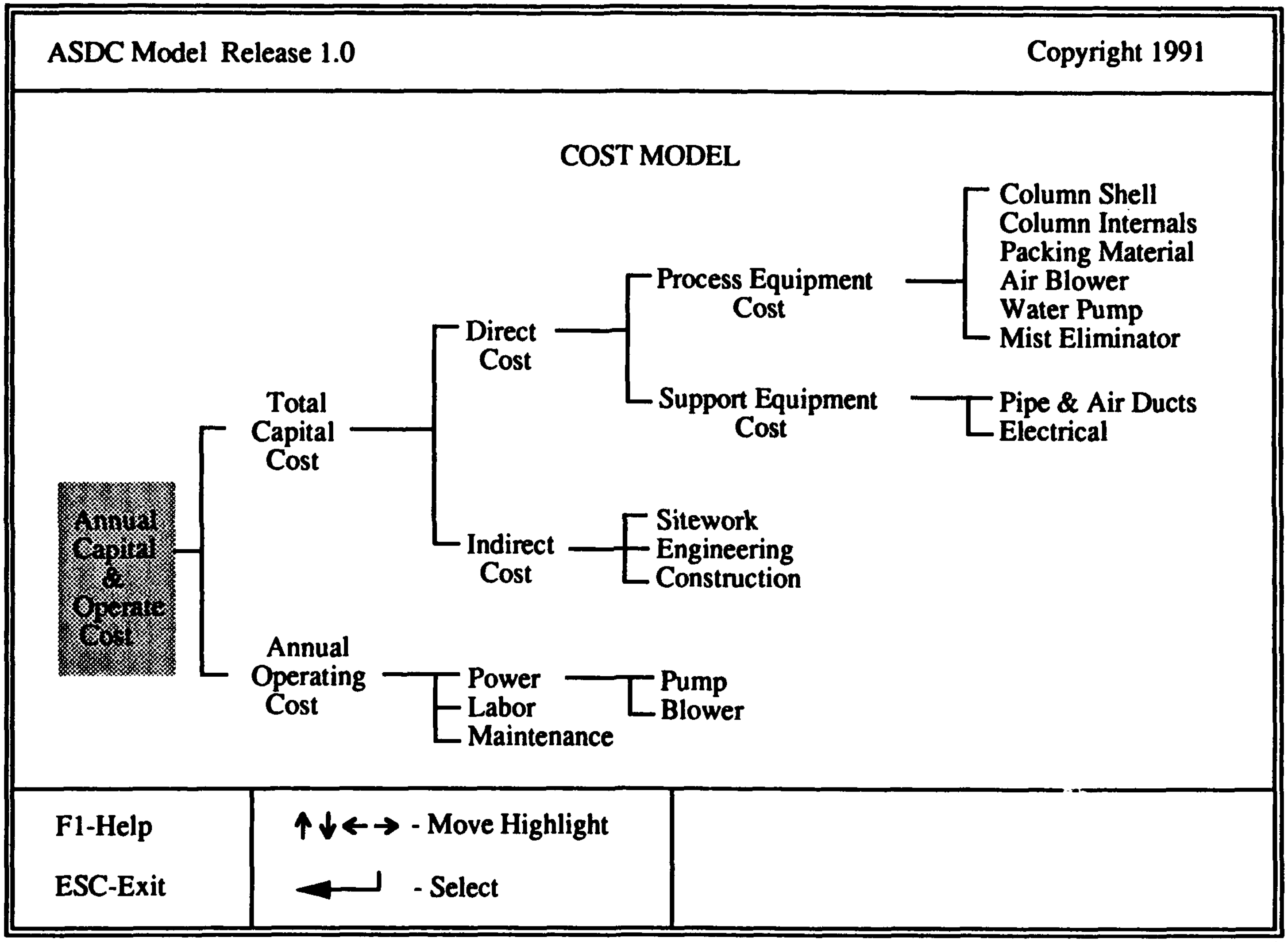

Figure 21. ASDC Cost Model Output Screen

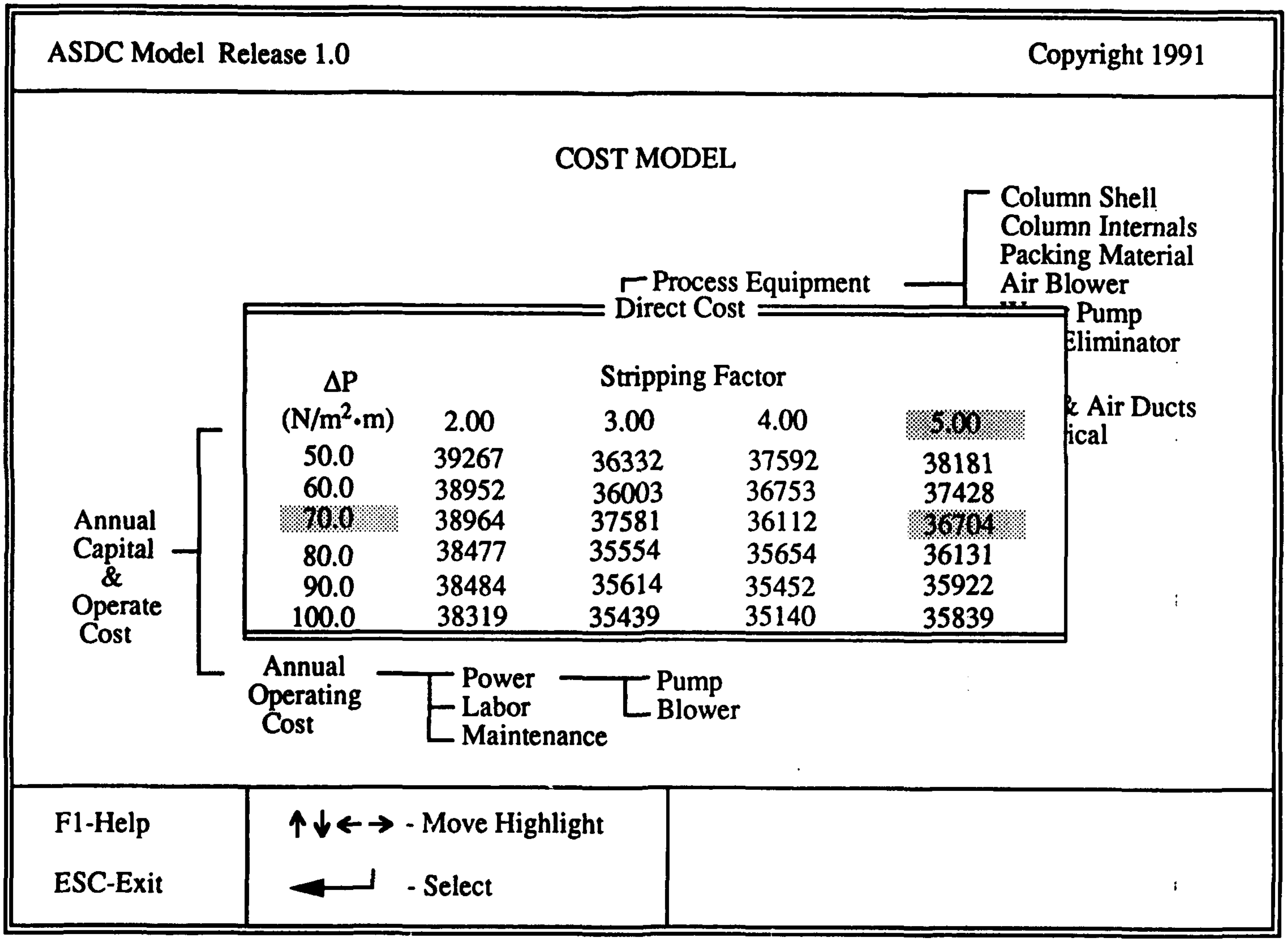

Figure 22. ASDC Detailed Direct Cost Output Screen

5. Graphical Analysis

This function enables the user to view results of the cost calculations on two- or three-dimensional graphs of cost (any cost component) versus R or ΔP or both. To run the graphical analysis routines, a minimum of 640 Kb RAM and a CGA, EGA, or VGA color monitor is required. These routines cannot be run with a monochrome display adapter. With on-screen display of such graphs, the user can assess quickly the sensitivity of any individual cost or the total cost to variation in R and ΔP and to identify the ranges of these variables associated with minimum cost. The plots can be "dumped" to a graphics printer directly linked to the microcomputer using the SHIFT-PRINT SCREEN keyboard command.

Upon selelction of graphical analysis from the main menu, the user is asked to identify the data file from which data are to be plotted. A screen presenting the plotting options is then displayed as shown on the right side of Figure 23. The two-dimensional graphing options for cost-data are x-y scatter plot, x-y line plot (scatter plot with points connected by lines), and piechart. The scatter plot and line plot options produce x-y plots with one or more user-specified cost components as the y-axis and either R or ΔP on the x-axis. If R is selected as the abscissa, then ΔP must be fixed, and vice versa (see center windows of Figure 23). The user is prompted for the x-axis design variable, fixed value for the second design variable, and desired y-axis cost components. Selection of the cost components for the y-axis is performed using the cost model tree-diagram (Figure 21). To select a cost component, move the highlight bar to the item of interest and press RETURN; a check mark (√) will be generated in front of the item. A selection may be canceled by moving to the selected item and pressing RETURN again. When the graph items have been selected, the graph is generated by pressing ESC. Up to four different cost components can be plotted simultaneously.

For generation of a piechart plot, the procedures are close to those described for the x-y plots. The user selects up to 10 cost components from the cost model tree diagram, and upon pressing ESC is asked to specify the R and ΔP combination of interest. ASDC calculates the total cost represented by all the items selected and the percentage of the total cost for each of the individual items. A piechart reflecting these calculated percentages is then produced on screen. It is up to the user to select reasonable groups of cost items.

A three dimensional plot of a cost component versus R and ΔP can also be generated. The z-axis is used for the cost component which is selected by the user via the cost model tree diagram. Three dimensional cost versus R and ΔP plots are perhaps the most useful for identifying ranges of R and ΔP associated with minimum cost.

6. Print Report

Results of design and cost calculations performed by ASDC can be saved in files on the hard disk and/or printed directly if an on-line printer is available. Upon selection of the "Print Report" function, the user will be asked to specify the design/cost file saved on the hard disk and the design parameter values of interest (e.g., $R = 5$, $\Delta P = 80$ N/m^2.m). Once

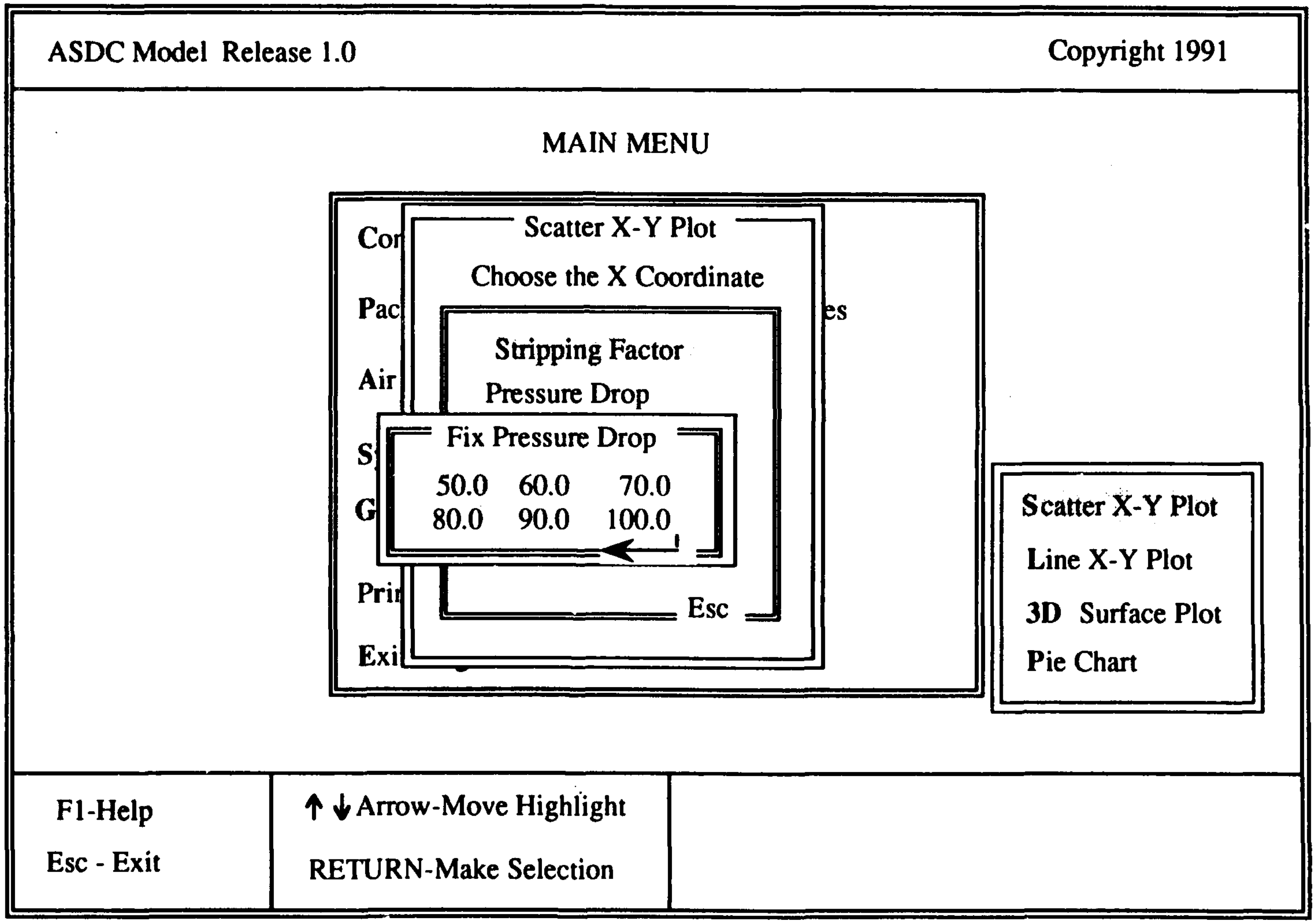

Figure 23. Graphical Analysis Selection Screen

the design parameters are specified, the user is given the option to name and save the report in a file for later use. All saved reports are given the name extension "*.RPT".

A typical report from the ASDC program, as shown in Table 12, consists of three pages. The first page contains the system design parameters and their specified values, the design contaminant properties, the packing material properties, and the mass transfer parameters and their values. Also presented on the first page is the tower configuration calculated for the specified design conditions.

The second page lists the physical properties of water and air at the system design temperature (i.e., influent water temperature) and the calculated influent and effluent concentrations for all specified contaminants in the aqueous phase. If cost estimation is performed, this page also contains specified values for the cost parameters (i.e., electrical rate, interest rate, amortization period, operating days per year, etc.). The third page lists all the cost items in the cost model under the general categories of capital cost and annual cost. Calculated values for all the cost items are presented.

TABLE 12. ASDC PRINTED REPORT

FINAL REPORT OF ASDC DESIGN

Page : 1/3

SYSTEM DESIGN PARAMETERS

Water Temperature	:	20.0	C
Water Flow Rate	:	200.0	gpm
Ambient Pressure	:	1.000	atm
Stripping Factor	:	2.00	
Pressure Drop Gradient	:	50.00	N/m^2.m
Tower Diameter	:	0.55	m
Packing Height	:	15.24	m
Tower Height	:	19.82	m
Volumetric Air/Water Ratio	:	9.08	
Water Mass Loading Rate	:	5.237e+01	kg/m^2 sec
Air Mass Loading Rate	:	5.737e-01	kg/m^2 sec
Air Flow Rate	:	242.7	cfm

DESIGN CONTAMINANT PROPERTIES

Name	:	Chloroform	
Formula	:	CHCl3	
Molecular Weight	:	119.38	g/mol
Boiling Point	:	61.70	C
Molar Volume	:	80.60	cm^3/mol
Vapor Pressure @ 25.0 C	:	198	mmHg
Solubility @ 25.0 C	:	9300.0	mg/L
Henry's Constant @ 20.0 C	:	5.300E-03	atm m^3/mol
Henry's Constant @ 20.0 C	:	2.203E-01	atm m^3/mol
Diffusivity in Air	:	6.497E-02	cm^2/sec
Diffusivity in Water	:	1.000E-05	cm^2/sec

PACKING MATERIAL PROPERTIES

Name	:	Tri-Packs No.1	
Material	:	Plastic	
Nominal Size	:	50.80	mm
Specific Area	:	157.50	m^2/m^3
Packing Factor	:	16.0	

MASS TRANSFER PARAMETERS

Packing Material Wetted Area	:	112.755	m^2/m^3
Mass Transfer Rate in Water	:	4.741e-04	m/sec
Mass Transfer Rate in Air	:	4.531e-03	m/sec
Overall Mass Transfer Rate	:	3.215e-04	m/sec
Overall Mass Transfer Coefficient	:	3.021e-02	1/sec
Overall KLa Safety Factor	:	1.20	
Height of Transfer Unit (HTU)	:	1.737	m

TABLE 12. ASDC PRINTED REPORT (CONTINUED)

FINAL REPORT OF ASDC DESIGN

==

PHYSICAL PROPERTIES OF WATER/AIR

Density of Water	:	9.982e+02	kg/m^3
Viscosity of Water	:	1.002e+00	Centipose
Surface Tension of Water	:	7.272e-02	Kg/sec^2
Density of Air	:	1.205e+00	g/L
Viscosity of Air	:	1.800e-05	N sec/m^2

CONTAMINANT REMOVAL

Name	Influent Conc. (ppb)	Effluent Conc.(ppb)	Removal Efficiency(%)
Benzene	100.00	0.81	99.19
Chloroform	800.00	5.00	99.38

COST PARAMETERS

Labor Rate	:	20.00	$/Hr
Electric Rate	:	0.08	$/Kw Hr
ENR Index (1990 = 4732)	:	4732.00	
Operating Hours per Day	:	24.00	Hr/Day
Operating Days per Year	:	365.00	Day/Year
Interest Rate	:	10.00	%
Amortization Period	:	20.00	Year

==

TABLE 12. ASDC PRINTED REPORT (CONCLUDED)

FINAL REPORT OF ASDC DESIGN

Page : 3/3

COST ESTIMATE

Capital Cost

Column Shell	:	18596
Column Internals	:	1897
Packing Material	:	2331
Air Blower	:	1930
Water Pump	:	4860
Mist Eliminator	:	379
Process Equipment Cost	:	29992
Pipe & Air Ducts	:	6276
Electrical	:	2999
Support Equipment Cost	:	9275
Total Direct Cost	:	39267
Sitework	:	5890
Engineering	:	10602
Construction	:	7853
Total Indirect Cost	:	24346
Total Capital Cost	:	63613

ANNUAL COST ($/Year)

Blower Operating Cost	:	392
Pump Operating Cost	:	4788
Labor Cost	:	5256
Maintenance Cost	:	3927
Annual Operating Cost	:	14362
Amortized Capital Cost	:	7472
Total Annual Cost	:	21834

SECTION V

CASE STUDIES

A. INTRODUCTION

In this section, predictions of air stripper performance and cost by ASDC are compared to performance and cost data for some actual air stripping units. One purpose of these simulations was for verification of the ASDC program as a whole. During construction of ASDC, its various components were verified individually as they were incorporated in the program. Comparison of ASDC predictions against system data was conducted to verify the overall performance of the program. Another purpose of these simulations was to examine how ASDC can be applied to analyze the performance and costs of an existing system.

Operating and/or cost data for six air stripper units representing a variety of designs were obtained. These systems and the corresponding ASDC simulations are described below.

B. HYDRO GROUP STANDARD UNITS

1. System Data

Hydro Group, Inc. (Bridgewater, New Jersey) manufactures four standard air-stripping units for water treatment applications. The sizes and approximate 1990 prices for these units are summarized in Table 13. Each standard unit includes a structural grade aluminum self-supporting tower, tower internals, (distributor tray, redistributors, polypropylene mesh-type mist eliminator, plastic packing material, FRP gridded support plate, etc.), and a blower. The distributor tray is constructed of structural grade aluminum and includes an influent velocity breaker, air exhaust stacks, and distributor orifices. Tri-Pack® No. 2 plastic packing is standard in these units. The prices listed in Table 13 do not include costs for the water pump and associated piping, or for tower installation.

2. ASDC Simulation

The data for the Hydro Group standard units were used for verification of process equipment capital cost estimation (minus the water pump) in ASDC. ASDC simulations were performed for a range of R, ΔP, and $K_L a$ safety factor values to identify operating conditions corresponding to the tower configurations listed in Table 13. The design VOC compound was assumed to be benzene ($C_{influent}$ = 100 ppb), and a 95 percent removal efficiency was specified. The maximum water flow rates were assumed. The operating conditions associated with the given tower configurations are summarized in Table 14.

TABLE 13. SIZES AND COSTS FOR HYDRO GROUP STANDARD UNITS

Model No.	Water Flow Capacity (gpm)	Tower Diameter (inches)	Packing Height (feet)	Tower Height (feet)	Approx. 1990 Price ($)
1	20	10	15	20	10,000
2	100	23	25	33	23,000
3	400	46	25	33	36,000
4	1600	90	25	37	65,000

The calculated tower configurations and process equipment costs (excluding the water pump) for the design conditions specified above and in Table 14 are presented in Table 15. As indicated in Table 15, ASDC estimates for process equipment cost are close to the approximate costs provided by Hydro Group. For towers having water flow capacities greater than 100 gpm, ASDC appears to underestimate system capital costs slightly. Contributing to this are the generic packing material cost data considered in the program and the small differences between the actual and simulated total tower height. Both of these cost factors influence the capital cost for an air stripping unit significantly.

TABLE 14. OPERATING CONDITIONS USED FOR SIMULATION OF HYDRO GROUP STANDARD UNITS[1]

Model No.	Water Temp. (°C)	Ambient Pressure (atm)	R	ΔP ($N/m^2 \cdot m$)	S.F. for $K_L a$
1	20	1.00	9.0	95	1.2
2	20	1.00	8.5	70	2.0
3	20	1.00	7.5	50	1.95
4	20	1.00	7.0	50	1.9

Note: 1. Tri-Pack® No. 2 plastic packing in each unit.

TABLE 15. COMPARISON OF DATA FOR HYDRO GROUP STANDARD UNITS WITH ASDC SIMULATION RESULTS

Model No.	Diameter (m) Actual	Diameter (m) ASDC	Packing Ht.(m) Actual	Packing Ht.(m) ASDC	Tower Ht.(m) Actual	Tower Ht.(m) ASDC	Approximate Process Equipment Cost[1] (1990) Actual	Approximate Process Equipment Cost[1] (1990) ASDC
1	0.25	0.25	4.57	4.56	6.10	5.93	10,000	10,828
2	0.58	0.57	7.62	7.62	10.06	9.91	22,000	19,533
3	1.17	1.17	7.62	7.68	10.06	9.98	36,000	36,139
4	2.29	2.29	7.62	7.74	11.08	11.60	65,000	63,799

Note: 1. Does not include costs for the water pump.

C. UNITS AT WRIGHT-PATTERSON AFB

1. System Data

A well field used for water supply at Wright-Patterson Air Force Base in Dayton, Ohio draws upon an aquifer that is contaminated with VOCs. Four of the major wells in this field (Area C), identified as Wells 1, 2, 3 and 7, are pumped at average flows of 500, 700, 1200, and 1100 gpm, respectively. These wells were, in the late 1980s, found to be contaminated by trichloroethylene, cis-1-2-dichloroethylene, 1,1,1-trichloroethane, and tetrachloroethylene. Trichloroethylene was detected in all wells at levels ranging from 1.0 to 8.7 ppb, and tetrachloroethylene concentrations ranged from 8.0 to 21.2 ppb. The daily flow rate from these four wells varies from 1.0 to 2.0 million gallons.

An air-stripping system manufactured by Hydro Group was installed in 1989 to treat the combined flows from the four wells. According to information provided by Mr. C.J. Vehorne of Wright-Patterson AFB, this system consists of two air-stripping units, each of which was designed to handle 1,750 gpm of influent water. Each tower is 8.5 feet (2.59 m) in diameter, has 17.5 feet (5.33 m) of packing, and has a total column height of 36 feet (10.97 m). One orifice plate liquid distributor, three redistributors, and an FRP packing support plate is included in each tower. Both towers are packed with 2-inch Norpac® polypropylene packing material. A single fan with a capacity of 17,500 cfm and a 20 hp motor operating at 1,750 rpm and 4.5 in-H_2O static pressure drop is attached to each tower.

The direct capital cost (in 1991 dollars) for each air stripping unit was approximately $74,950. This price does not include the water pump and yard piping. Field piping requirements at this site to incorporate the air stripping units in the existing water supply and treatment system were extensive, involving capital costs of $43,410 (1991 dollars). Costs for electrical system modification and for electrical control of the air stripping units were also significant, amounting to $63,710 (1991 dollars).

2. ASDC Simulation

First, design simulations were performed to establish a set of operating conditions that, when input to ASDC, reproduce the Wright-Patterson configurations. Ranges of R, ΔP, and $K_L a$ safety factor values were investigated to identify the combination that most closely refleccts the existing tower configurations. Parameter values used in the analysis were a water temperature of 10°C, a water flow of 1,750 gpm, a trichlorethylene concentration of 10 ppb in the water, a removal efficiency of 95 percent, and a safety factor of 1.2 for $K_L a$. Design calculations with ASDC revealed that that R = 13 and ΔP = 70 $N/m^2 \cdot m$ yields a column with a diameter of 2.62 m, a packing height of 6.22 m, and a total column height of 9.33 m. For a stripping factor of 13 and trichloroethylene as the design contaminant, the corresponding air:water ratio is 58, with an air flow of 13,450 cfm.

The process equipment costs (in 1991 dollars) estimated by ASDC for the specified operating conditions are $86,996 which includes $17,930 for the cost of the water pump, $8,900 for the fan cost, and the cost of the column shell, column internals, packing, and mist eliminator. The ASDC estimate for pipe and air duct cost is $18,075, while the estimate for the electrical system cost is $8,700. If the water pump cost is excluded, the estimate for the total cost of the other process equipment is $69,066 which is close to the $74,950 (in 1991 dollars) reported for the Wright-Patterson units. The piping and electrical system costs deviate significantly from the yard piping and electrical connection costs noted earlier, but the latter reflect complex site specific requirements.

D. UNITS AT BREWSTER WELL FIELD

1. System Data

The Brewster Well Field Area No. 1 is composed of nine wells and supplies drinking water to the Village of Brewster in Putnam County, New York. The contaminants detected at Brewster Well Field No. 1 are primarily tetrachloroethylene, trichloroethylene, cis- and trans-1,2-dichloroethylene, and vinyl chloride. A full-scale air stripping system was placed in operation in October 1984 to remove these VOC contaminants (Reference 51).

The Brewster air-stripping system operates at a water flow rate of 300 gpm and is designed for an air:water ratio of 50:1. Tables 16 and 17 summarize the contaminant design concentrations, stripper design tower configuration, and other design parameter values. Data for the performance of this system have been reported (Reference 51) and may be used for comparison with ASDC performance predictions.

2. ASDC Simulation

The design input parameters in Tables 16 and 17 were incorporated in ASDC and, by examining ranges of R and ΔP values, a design close to that of the Brewster system was generated.

TABLE 16. SUMMARY OF DESIGN CONTAMINANT LEVELS FOR BREWSTER AIR STRIPPER

VOC Contaminant	Measured Conc. (ppb)	Design Influent Conc. (ppb)	Design Effluent Conc. (ppb)
Tetrachloroethylene	200	215	5
Trichloroethylene	30	77	5
1,2-Dichloroethylene	38	68	5
Vinyl Chloride	ND(1)	2	< 1(ND)

Note: 1. "ND" means not detectable.

TABLE 17. SUMMARY OF DESIGN FOR BREWSTER AIR STRIPPER

Water Flow	300 gpm
Air Flow	2000 cfm
Tower Height	27 ft (8.23 m)
Tower Diameter	4.75 ft (1.45 m)
Packing Height	17.75 ft (5.41 m)
Packing Type	1" Plastic Saddles
Air:Water Ratio	50:1
Air Loading Rate	0.68 $kg/m^2 \cdot sec$
Water Loading Rate	11.41 $kg/m^2 \cdot sec$

The Brewster tower configuration was simulated by assuming 10°C for the water temperature, 1 atm for the ambient pressure, and 1.25 for the K_La safety factor. The packing material used in the calculations was 1-inch Novalox® plastic saddles. Design calculations with ASDC indicated that R = 12.0 and ΔP = 50 $N/m^2 \cdot m$ yielded a tower with a diameter (1.43 m) and packing height (5.38 m) close to that of the actual system. The total column height estimated by ASDC was 6.99 m and the calculated air:water ratio was 50:1 with tetrachloroethylene as the design contaminant.

For the tower configuration matching that of the Brewster system, ASDC predicted removals of the four target compounds that closely matched the observed removals. Removal efficiencies predicted by ASDC are compared to observed removal efficiencies in

Table 18. Predictions made with the air stripping design module in ASPEN, a large process plant design program, are shown in Table 18 for comparison.

TABLE 18. COMPARISON OF PERFORMANCE PREDICTIONS WITH ACTUAL PERFORMANCE DATA FOR BREWSTER AIR STRIPPER

VOC Contaminant	Design Influent Conc. (ppb)	Observed Removal Efficiency (%)	ASPEN Predicted Efficiency (%)	ASDC Predicted Efficiency (%)
Tetrachloroethylene	215	98.5	99.4	97.7
Trichloroethylene	77	93.3	98.7	98.0
trans-1,2-Dichloroethene	68	95.6	99.7	98.6

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APPENDIX A

WATER PUMP PRICE LIST AND CHARACTERISTIC CURVES

TABLE A-1. WATER PUMP PRICE LIST

Pump Type	Water Volume (gpm)	MOTOR HORSE POWER											
		3 HP	5 HP	7.5 HP	10 HP	15 HP	20 HP	25 HP	30 HP	40 HP	50 HP	60 HP	75 HP
1	275 - 750	$3376	$3402	$3449									
2	150 - 600	$3566	$3660	$3842	$3957								
3	250 - 800		$3838	$4020	$4135								
4	400 -1400			$4331	$4392	$4497	$4606						
5	300 -1200			$4750	$4865	$5055							
6	400 -1200				$5150	$5404	$5561						
7	450 -1500				$5560	$5750	$5907						
8	800 -2400							$4926	$5060	$5299			
9	400 -2200			$6177	$6292	$6482	$6639	$6858					
10	700 -2500						$8082	$8300	$8535	$8856			
11	750 -2000			$8891	$9006	$9291							
12	750 -2100				$10226	$10416	$10573	$10793	$11028				
13	1250-3000					$10828	$10985	$11205	$11440	$11761			
14	600 -1700				$15167	$15357	$15514						
15	900 -2700					$19785	$19942	$20130	$20365				
16	1500-4000									$13576	$13988	$14762	$15199

Note : Prices are 1990 based

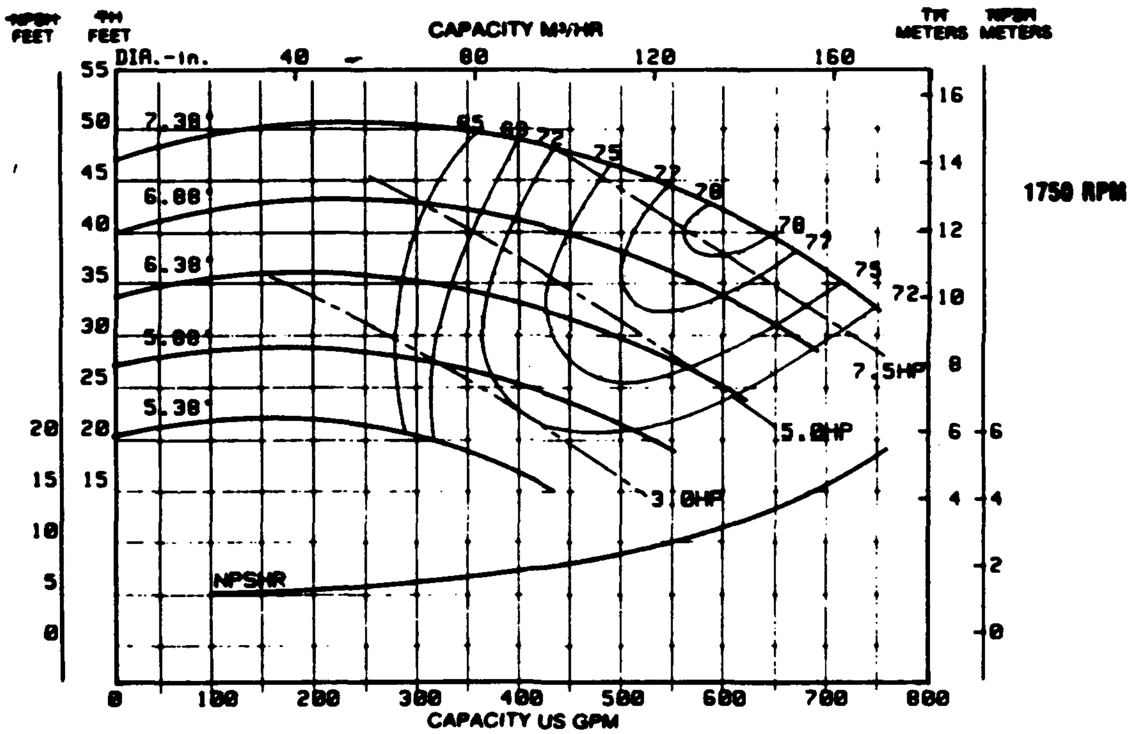

Figure A-1. Type 1 Pump Characteristic Curves

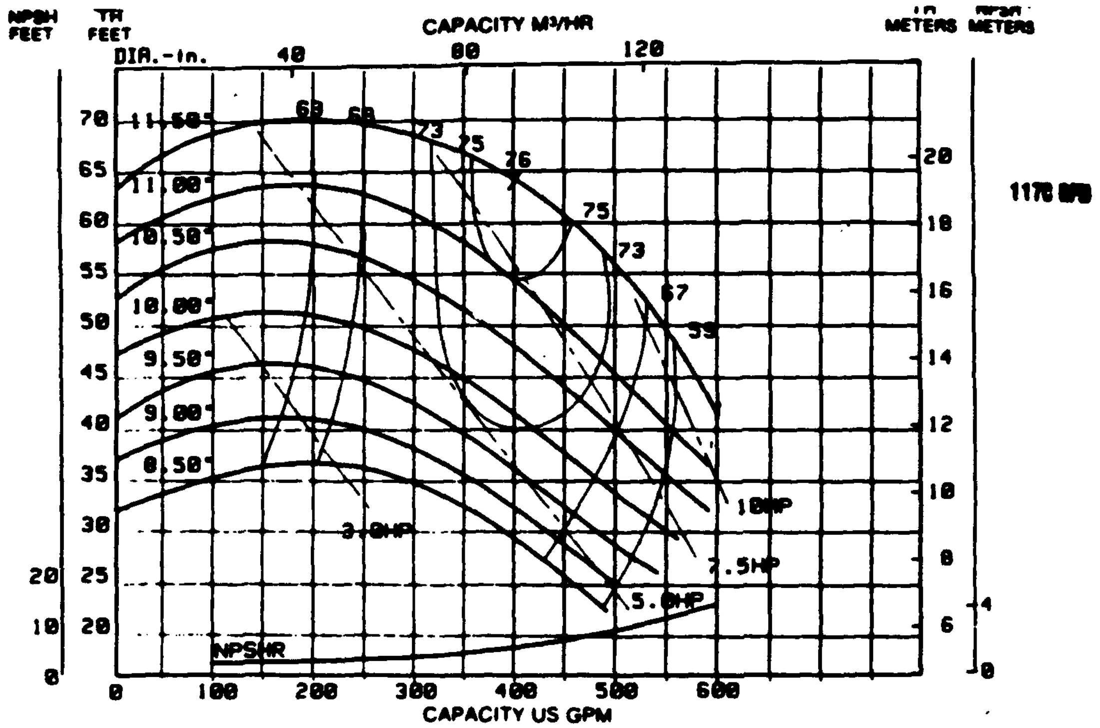

Figure A-2. Type 2 Pump Characteristic Curves

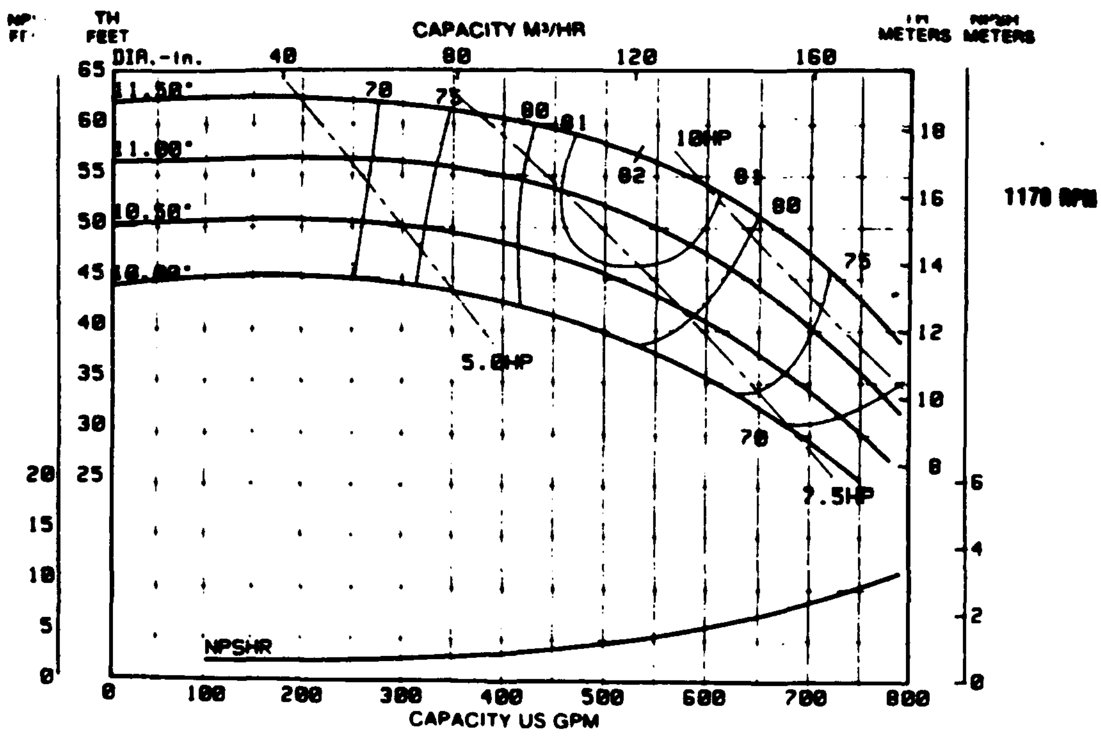

Figure A-3. Type 3 Pump Characteristic Curves

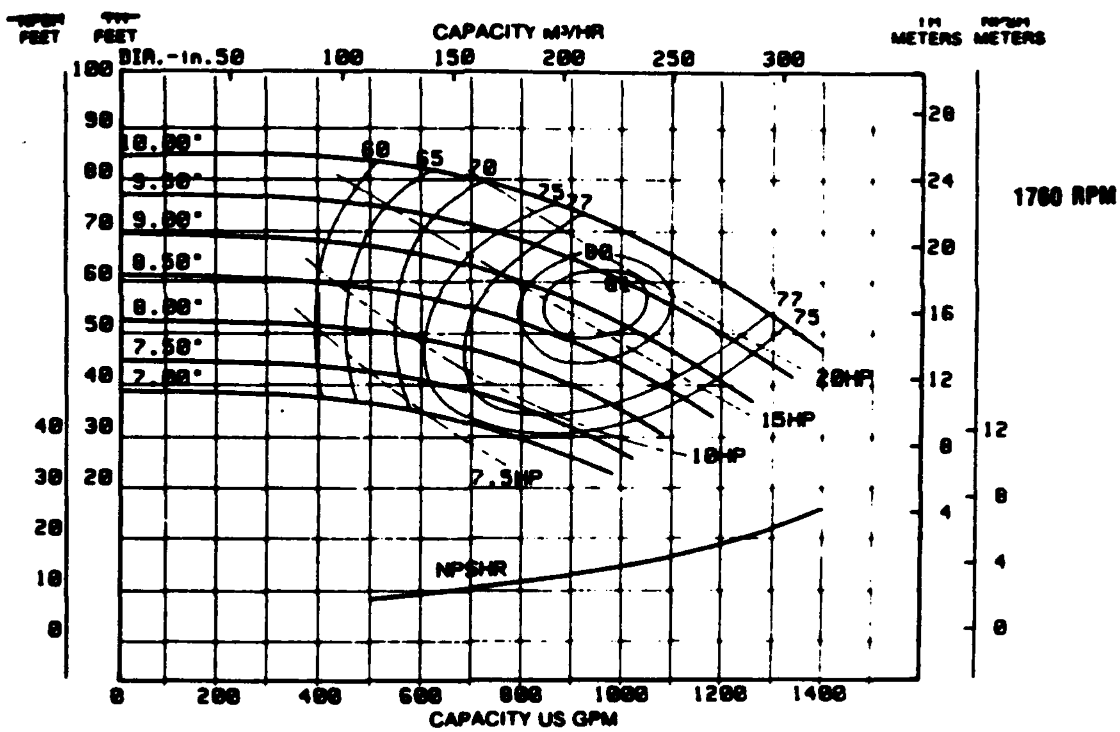

Figure A-4. Type 4 Pump Characteristic Curves

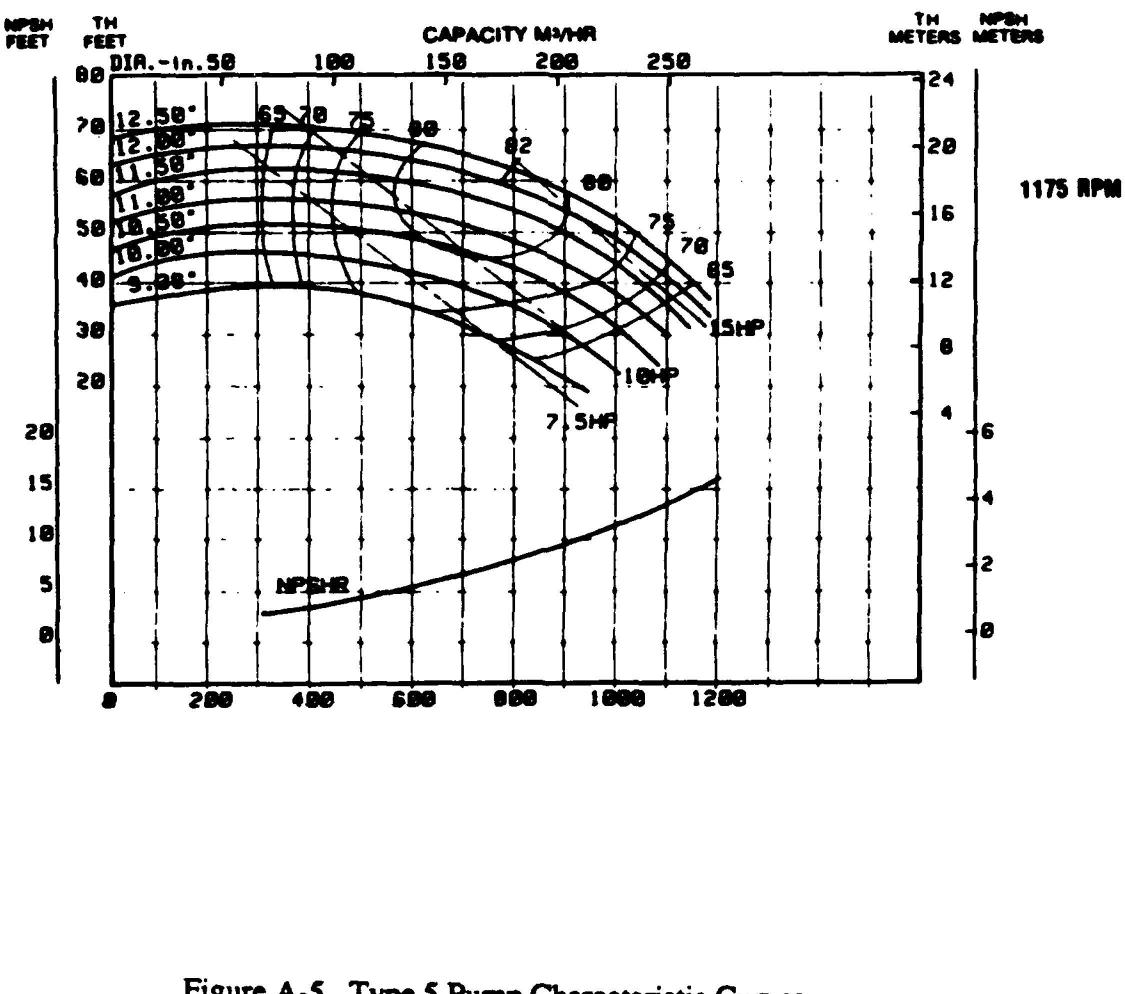

Figure A-5. Type 5 Pump Characteristic Curves

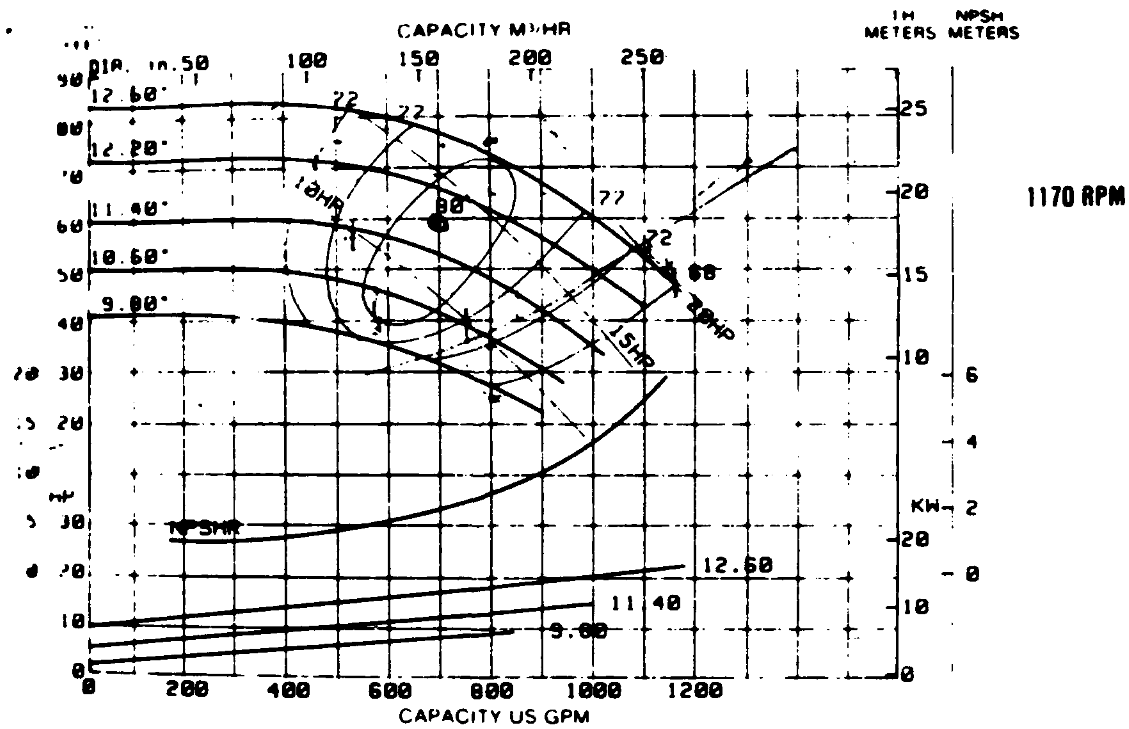

Figure A-6. Type 6 Pump Characteristic Curves

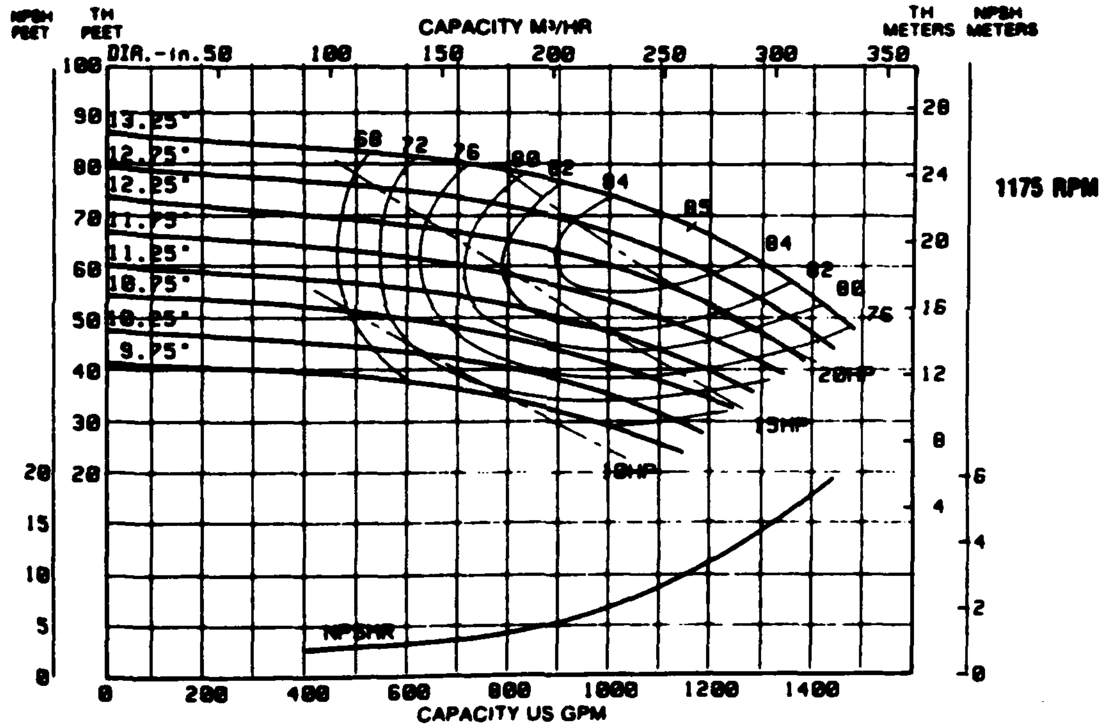

Figure A-7. Type 7 Pump Characteristic Curves

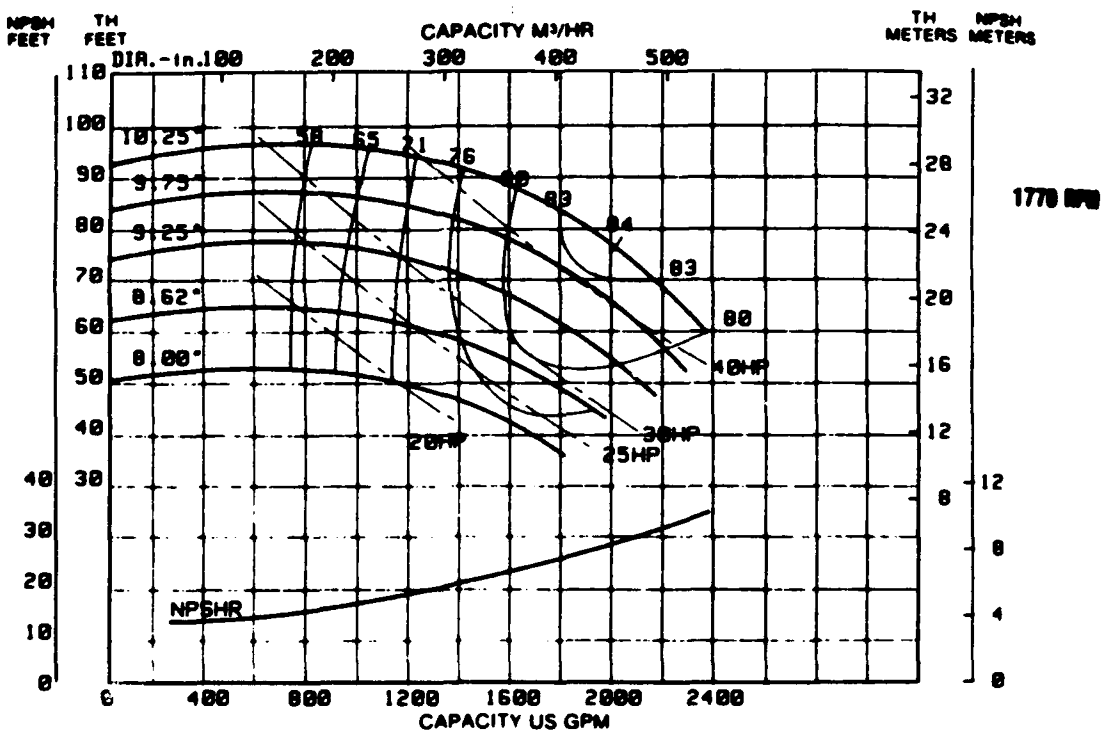

Figure A-8. Type 8 Pump Characteristic Curves

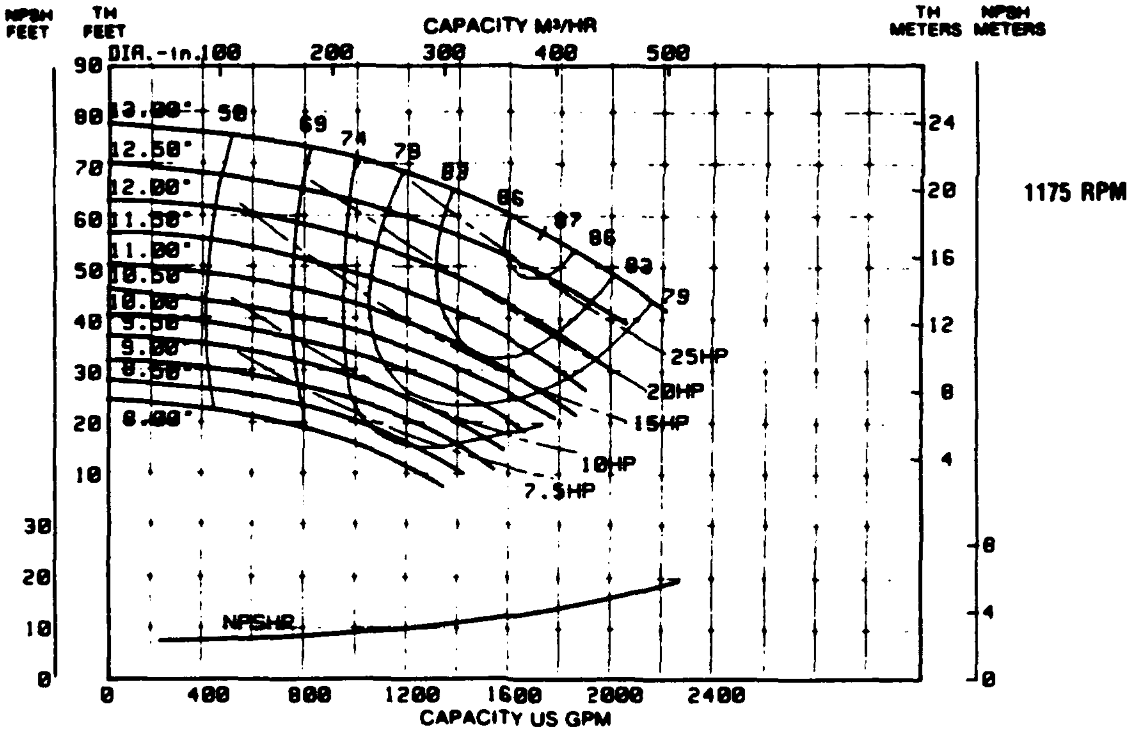

Figure A-9. Type 9 Pump Characteristic Curves

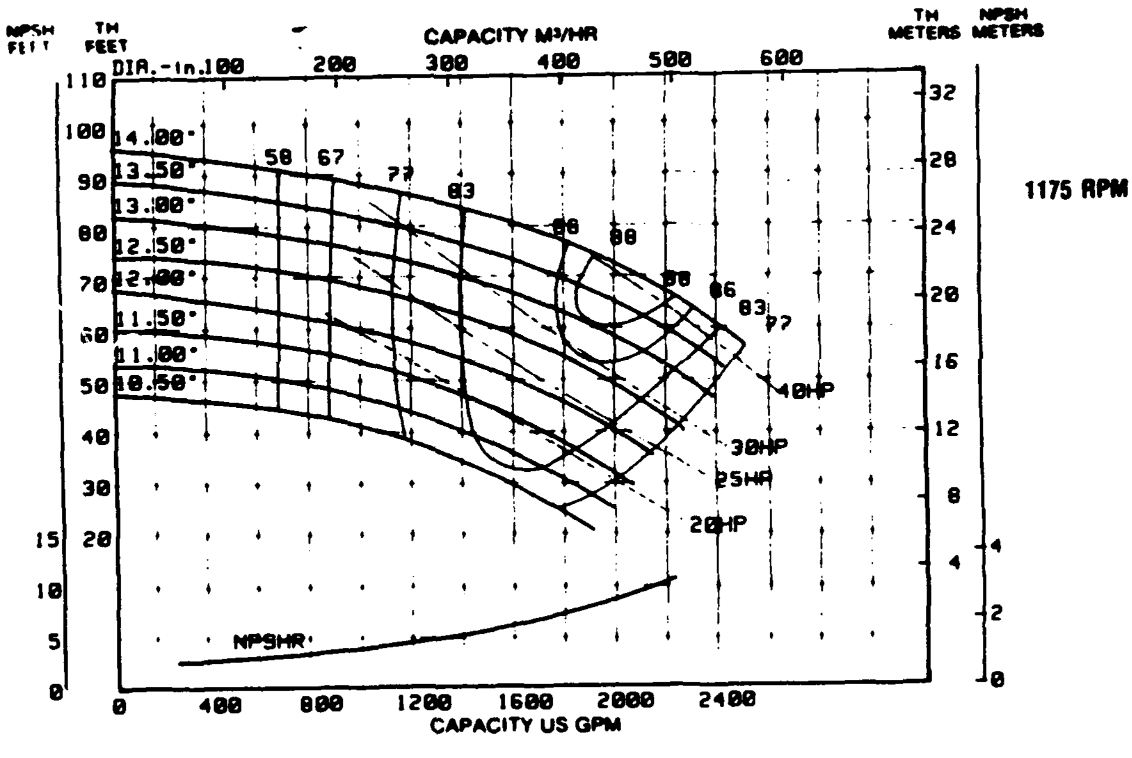

Figure A-10. Type 10 Pump Characteristic Curves

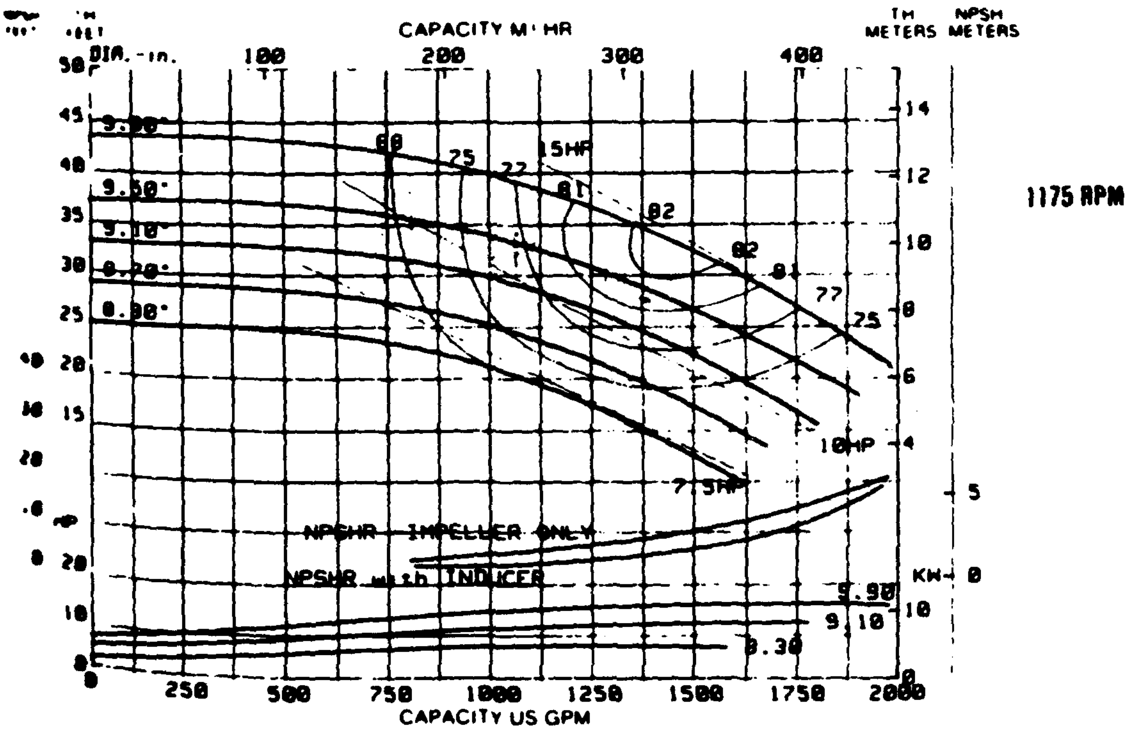

Figure A-11. Type 11 Pump Characteristic Curves

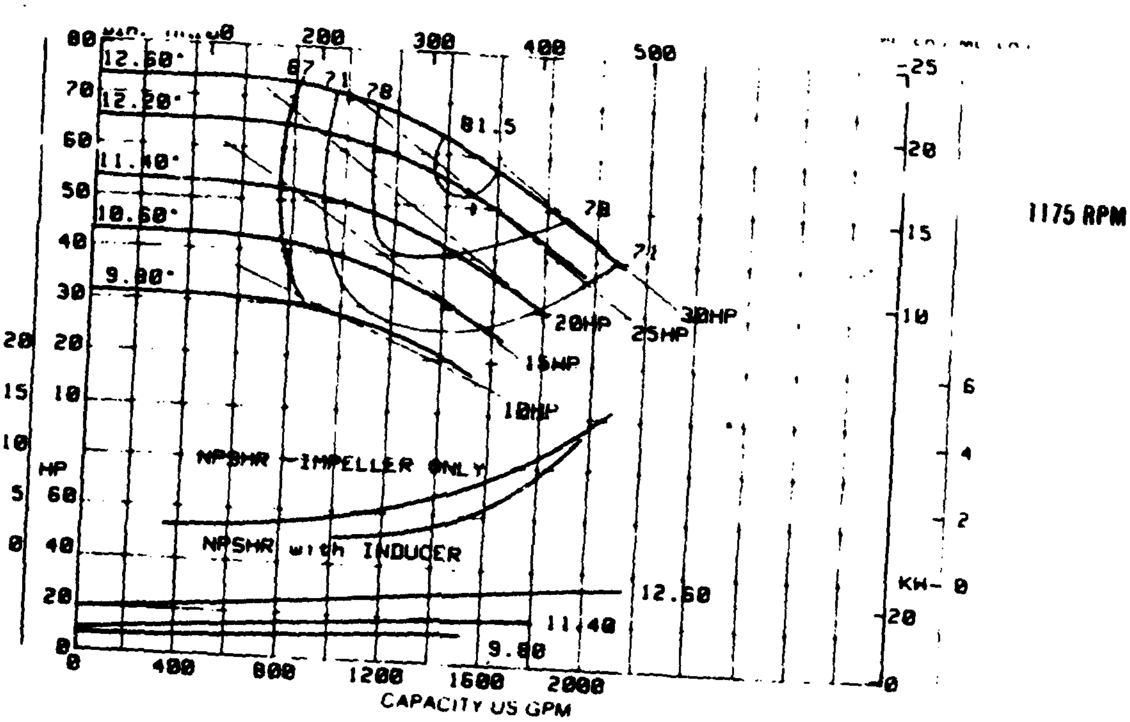

Figure A-12. Type 12 Pump Characteristic Curves

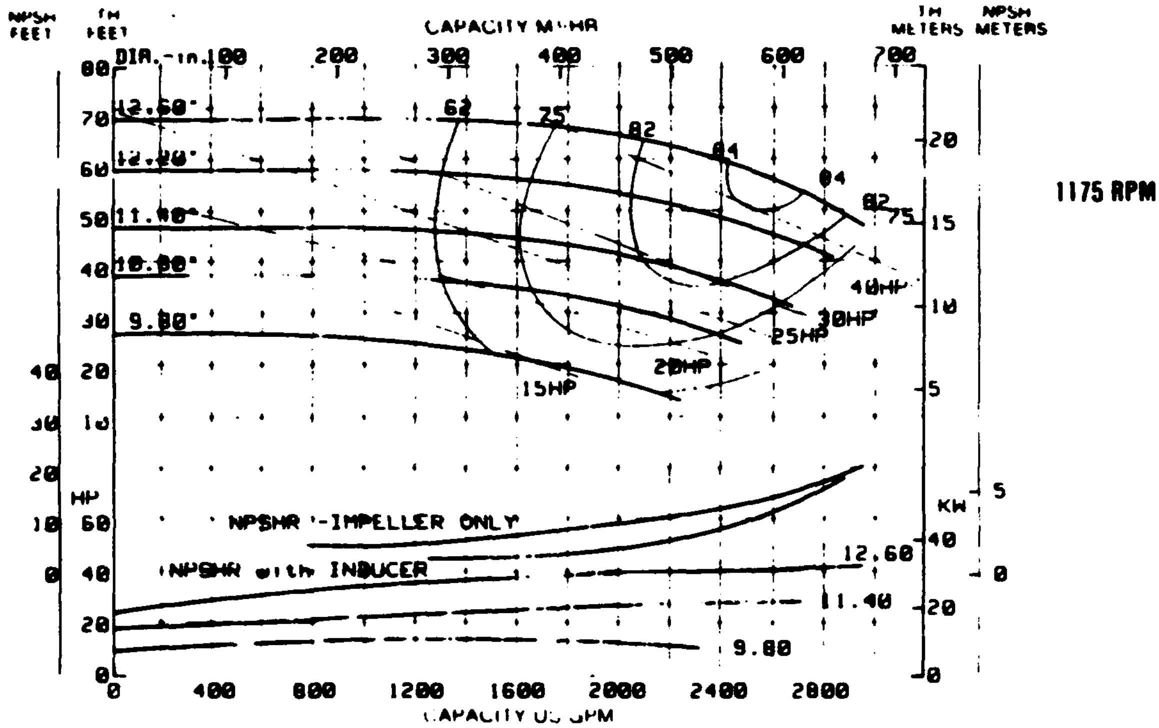

Figure A-13. Type 13 Pump Characteristic Curves

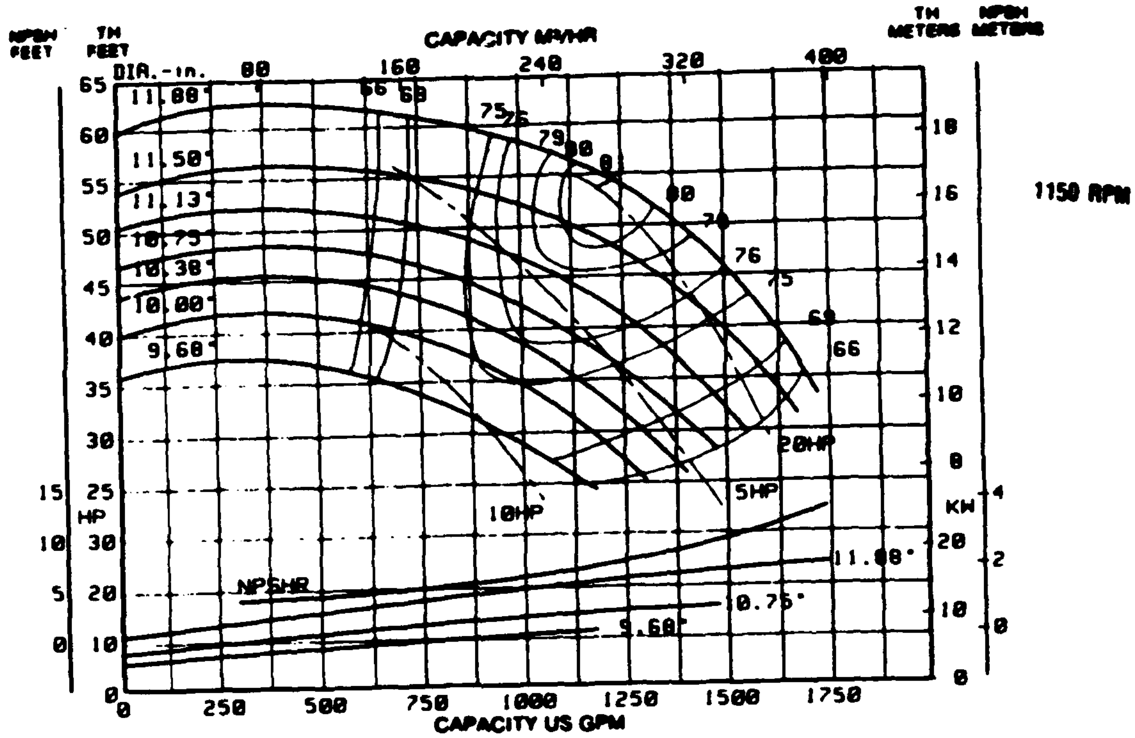

Figure A-14. Type 14 Pump Characteristic Curves

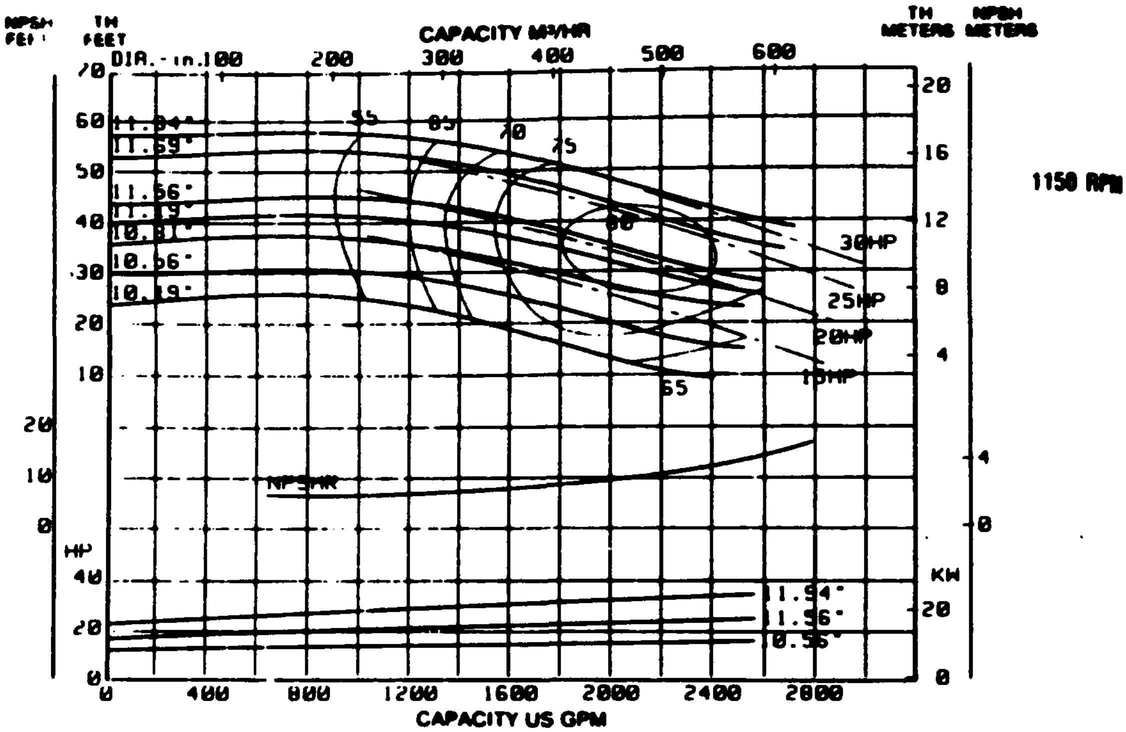

Figure A-15. Type 15 Pump Characteristic Curves

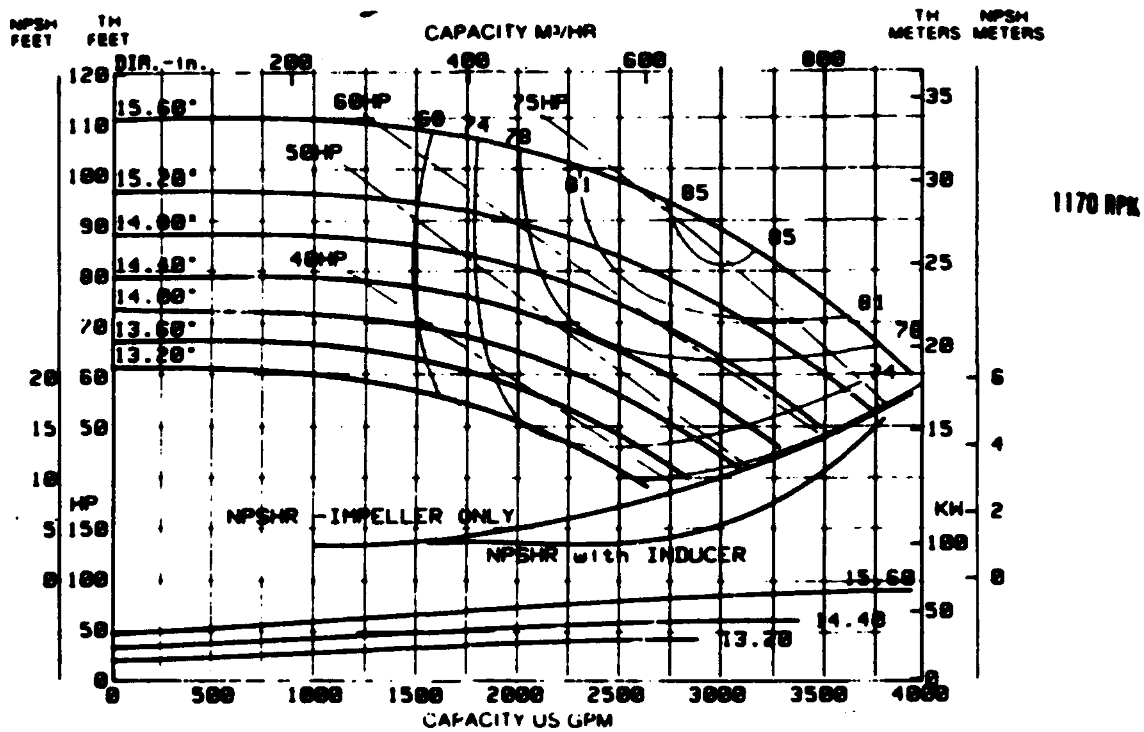

Figure A-16. Type 16 Pump Characteristic Curves

APPENDIX B

AIR BLOWER (FAN) PRICE LIST AND CAPACITY TABLES

TABLE B-1. FAN PRICE LIST

FAN TYPE		MOTOR HORSE POWER													
Type	Air Volume (cfm)	3/4	1	1.5	2	3	5	7.5	10	15	20	25	30	40	50
1	200 - 1400	1526	1537	1553	1627	1707	1855								
2	500 - 2500	1717	1722	1744	1813	1876	2025	2231							
3	800 - 3500	1950	1956	1993	2062	2125	2263	2544	2719						
4	600 - 3000	2237	2321	2343	2406	2480	2592	2830							
5	800 - 3600		2390	2422	2491	2549	2650	2936							
6	1000 - 4450			2544	2608	2676	2745	3026							
7	1200 - 5400			2809	2835	2941	3063	3371							
8	1500 - 6500			2973	3026	3090	3222	3514	3620						
9	2000 - 8000				3318	3371	3466	3774	3933						
10	2300 - 9800				3721	3774	3885	4176	4346	4500					
11	2700 - 11800					4070	4176	4404	4547	4839	5046				
12	3300 - 14500					4484	4574	4781	4982	5268	5475	5697			
13	4500 - 18000						5326	5544	5740	6005	6227	6519			
14	5100 - 22000						6455	6757	6943	7431	7658	7950			
15	6000 - 26000							7441	7637	8135	8390	8676	8979		
16	8000 - 32000								8803	9323	9630	9916	10234	10860	
17	10000 - 40000									10849	11231	11596	11909	12524	13107

Note : 1. Prices are 1989 based

TABLE B-2. TYPE 1 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
200	0.04	0.07	0.11	0.15	0.19	0.23	0.28	0.33	0.38	0.43	0.49	0.54	0.60	0.65	0.71	0.78	0.91	1.04
250	0.05	0.09	0.13	0.18	0.22	0.27	0.32	0.38	0.43	0.49	0.55	0.61	0.67	0.74	0.80	0.87	1.00	1.14
300	0.07	0.11	0.16	0.21	0.26	0.32	0.37	0.43	0.49	0.55	0.62	0.68	0.75	0.82	0.89	0.96	1.11	1.26
350	0.10	0.14	0.20	0.25	0.31	0.37	0.43	0.49	0.56	0.62	0.69	0.76	0.83	0.91	0.98	1.06	1.22	1.38
400	0.13	0.18	0.24	0.30	0.36	0.42	0.49	0.56	0.63	0.70	0.77	0.85	0.92	1.00	1.08	1.16	1.33	1.50
450	0.16	0.22	0.29	0.35	0.42	0.49	0.56	0.63	0.71	0.79	0.86	0.94	1.03	1.11	1.19	1.27	1.44	1.63
500	0.21	0.28	0.34	0.42	0.49	0.56	0.64	0.72	0.80	0.88	0.96	1.05	1.13	1.22	1.31	1.40	1.58	1.77
550	0.26	0.34	0.41	0.49	0.57	0.65	0.73	0.81	0.90	0.98	1.07	1.16	1.25	1.35	1.44	1.53	1.73	1.93
600	0.33	0.41	0.49	0.57	0.65	0.74	0.83	0.92	1.01	1.10	1.19	1.28	1.38	1.48	1.58	1.68	1.89	2.10
650	0.40	0.49	0.58	0.66	0.75	0.84	0.94	1.03	1.13	1.23	1.32	1.42	1.52	1.62	1.73	1.84	2.05	2.27
700	0.49	0.58	0.67	0.77	0.86	0.95	1.06	1.16	1.26	1.36	1.47	1.57	1.68	1.79	1.89	2.00	2.23	2.46
750	0.59	0.69	0.79	0.89	0.98	1.08	1.19	1.29	1.40	1.51	1.62	1.73	1.85	1.96	2.07	2.19	2.42	2.66
800	0.71	0.80	0.91	1.02	1.12	1.23	1.33	1.44	1.56	1.67	1.79	1.91	2.03	2.15	2.27	2.39	2.63	2.87
850	0.83	0.94	1.05	1.16	1.27	1.39	1.50	1.61	1.73	1.85	1.97	2.10	2.22	2.34	2.47	2.60	2.86	3.11
900	0.98	1.08	1.20	1.32	1.44	1.56	1.68	1.79	1.91	2.04	2.17	2.30	2.43	2.56	2.69	2.82	3.09	3.37
950	1.13	1.25	1.37	1.50	1.62	1.75	1.87	2.00	2.12	2.24	2.38	2.52	2.65	2.79	2.93	3.07	3.34	3.63
1000	1.31	1.43	1.55	1.69	1.82	1.95	2.09	2.22	2.35	2.48	2.61	2.75	2.89	3.04	3.18	3.33	3.62	3.91
1050	1.50	1.63	1.76	1.89	2.03	2.17	2.31	2.45	2.59	2.73	2.86	3.00	3.14	3.30	3.45	3.60	3.91	4.21
1100	1.72	1.85	1.98	2.12	2.27	2.42	2.56	2.71	2.85	3.00	3.14	3.28	3.42	3.57	3.73	3.89	4.21	4.53
1150	1.95	2.09	2.23	2.36	2.52	2.67	2.83	2.98	3.13	3.28	3.43	3.58	3.73	3.88	4.03	4.20	4.53	4.86
1200	2.20	2.35	2.49	2.63	2.79	2.95	3.11	3.27	3.43	3.59	3.75	3.90	4.06	4.22	4.37	4.53	4.87	5.22
1250	2.47	2.63	2.78	2.93	3.08	3.25	3.42	3.59	3.75	3.92	4.08	4.25	4.41	4.57	4.73	4.90	5.23	5.59
1300	2.77	2.93	3.09	3.24	3.40	3.57	3.75	3.92	4.09	4.27	4.44	4.61	4.78	4.95	5.12	5.29	5.63	5.98
1350	3.08	3.25	3.42	3.58	3.74	3.91	4.10	4.28	4.46	4.64	4.82	4.99	5.17	5.35	5.53	5.71	6.05	6.40
1400	3.43	3.60	3.77	3.94	4.11	4.28	4.47	4.66	4.84	5.03	5.22	5.40	5.59	5.77	5.96	6.14	6.51	6.87

Note :
1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses

TABLE B-3. TYPE 2 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
500	0.11	0.19	0.26	0.35	0.44	0.53	0.62	0.73	0.83	0.94	1.05	1.17	1.28	1.40	1.52	1.65	1.90	2.16
600	0.16	0.24	0.33	0.43	0.53	0.63	0.73	0.84	0.95	1.07	1.19	1.32	1.44	1.58	1.71	1.84	2.12	2.40
700	0.22	0.31	0.41	0.52	0.63	0.74	0.86	0.98	1.10	1.23	1.35	1.48	1.62	1.75	1.90	2.04	2.34	2.65
800	0.29	0.40	0.51	0.63	0.75	0.87	0.99	1.13	1.26	1.40	1.54	1.68	1.82	1.97	2.11	2.26	2.57	2.90
900	0.39	0.50	0.62	0.75	0.88	1.02	1.16	1.29	1.44	1.59	1.74	1.89	2.04	2.20	2.36	2.52	2.85	3.18
1000	0.50	0.63	0.76	0.90	1.04	1.19	1.34	1.49	1.64	1.79	1.95	2.12	2.29	2.45	2.62	2.79	3.15	3.50
1100	0.63	0.78	0.92	1.07	1.22	1.38	1.54	1.70	1.87	2.03	2.20	2.37	2.54	2.73	2.91	3.09	3.46	3.84
1200	0.79	0.95	1.11	1.27	1.42	1.59	1.77	1.94	2.12	2.30	2.48	2.66	2.84	3.02	3.21	3.41	3.80	4.21
1300	0.98	1.15	1.32	1.49	1.66	1.83	2.02	2.21	2.40	2.58	2.78	2.97	3.17	3.36	3.56	3.76	4.16	4.59
1400	1.20	1.37	1.56	1.75	1.93	2.11	2.29	2.49	2.70	2.90	3.10	3.31	3.52	3.73	3.94	4.15	4.58	5.01
1500	1.45	1.63	1.83	2.03	2.23	2.43	2.62	2.81	3.03	3.25	3.47	3.68	3.90	4.12	4.35	4.57	5.03	5.48
1600	1.73	1.93	2.13	2.35	2.56	2.77	2.98	3.19	3.40	3.62	3.85	4.08	4.32	4.55	4.78	5.02	5.50	5.99
1700	2.05	2.26	2.47	2.70	2.92	3.15	3.38	3.60	3.82	4.04	4.27	4.52	4.77	5.01	5.26	5.51	6.00	6.51
1800	2.41	2.63	2.85	3.09	3.33	3.57	3.80	4.04	4.28	4.51	4.74	4.99	5.25	5.51	5.77	6.03	6.55	7.08
1900	2.81	3.04	3.27	3.51	3.77	4.02	4.28	4.52	4.78	5.03	5.27	5.51	5.76	6.04	6.31	6.59	7.14	7.69
2000	3.25	3.50	3.73	3.98	4.25	4.52	4.78	5.05	5.31	5.57	5.84	6.10	6.35	6.61	6.89	7.19	7.76	8.35
2100	3.74	3.99	4.25	4.50	4.78	5.06	5.34	5.62	5.90	6.17	6.45	6.72	7.00	7.27	7.54	7.82	8.43	9.04
2200	4.27	4.54	4.80	5.07	5.35	5.64	5.94	6.23	6.52	6.81	7.11	7.39	7.68	7.97	8.26	8.54	9.13	9.77
2300	4.85	5.13	5.41	5.69	5.96	6.27	6.58	6.89	7.20	7.50	7.81	8.11	8.41	8.71	9.01	9.32	9.91	10.54
2400	5.49	5.78	6.07	6.37	6.65	6.96	7.28	7.60	7.92	8.24	8.56	8.87	9.19	9.51	9.83	10.14	10.76	11.38
2500	6.17	6.48	6.79	7.09	7.39	7.69	8.03	8.37	8.70	9.03	9.37	9.69	10.02	10.36	10.69	11.01	11.67	12.32

Note :
1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses

TABLE B-4. TYPE 3 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
800	0.18	0.30	0.42	0.56	0.70	0.85	0.99	1.15	1.32	1.49	1.67	1.85	2.04	2.22	2.42	2.61	3.01	3.42
900	0.23	0.35	0.49	0.64	0.79	0.94	1.11	1.27	1.44	1.62	1.81	2.00	2.20	2.39	2.60	2.80	3.22	3.66
1000	0.28	0.42	0.57	0.72	0.88	1.05	1.22	1.40	1.58	1.77	1.95	2.15	2.36	2.57	2.78	3.00	3.45	3.90
1100	0.34	0.49	0.65	0.82	0.98	1.16	1.35	1.53	1.73	1.93	2.13	2.33	2.54	2.75	2.97	3.20	3.67	4.15
1200	0.42	0.57	0.75	0.92	1.10	1.29	1.48	1.68	1.89	2.09	2.31	2.52	2.74	2.96	3.19	3.41	3.90	4.40
1300	0.50	0.67	0.85	1.04	1.23	1.43	1.63	1.84	2.06	2.27	2.50	2.72	2.95	3.19	3.42	3.66	4.15	4.65
1400	0.60	0.78	0.97	1.17	1.37	1.58	1.80	2.01	2.23	2.46	2.70	2.94	3.17	3.42	3.67	3.92	4.43	4.95
1500	0.70	0.90	1.10	1.31	1.53	1.75	1.97	2.20	2.43	2.66	2.92	3.16	3.41	3.67	3.92	4.19	4.72	5.27
1600	0.82	1.04	1.25	1.46	1.69	1.92	2.16	2.40	2.65	2.89	3.13	3.40	3.67	3.93	4.20	4.47	5.03	5.60
1700	0.96	1.19	1.41	1.63	1.87	2.12	2.37	2.62	2.87	3.13	3.39	3.65	3.92	4.20	4.49	4.77	5.34	5.93
1800	1.11	1.35	1.59	1.82	2.06	2.32	2.59	2.84	3.12	3.39	3.66	3.93	4.21	4.49	4.78	5.08	5.69	6.29
1900	1.29	1.53	1.78	2.03	2.28	2.55	2.82	3.09	3.37	3.66	3.95	4.23	4.52	4.81	5.09	5.41	6.03	6.67
2000	1.47	1.73	2.00	2.26	2.52	2.78	3.07	3.36	3.65	3.94	4.24	4.55	4.85	5.15	5.45	5.75	6.39	7.05
2100	1.68	1.94	2.22	2.50	2.78	3.05	3.34	3.64	3.95	4.25	4.56	4.87	5.19	5.51	5.82	6.14	6.78	7.46
2200	1.91	2.17	2.47	2.76	3.05	3.34	3.62	3.94	4.26	4.57	4.89	5.22	5.54	5.87	6.21	6.54	7.21	7.87
2300	2.15	2.43	2.74	3.04	3.34	3.65	3.94	4.25	4.58	4.92	5.26	5.59	5.91	6.26	6.61	6.96	7.65	8.35
2400	2.42	2.71	3.02	3.34	3.66	3.98	4.29	4.60	4.93	5.28	5.63	5.98	6.32	6.67	7.03	7.39	8.11	8.84
2500	2.71	3.01	3.33	3.67	4.00	4.33	4.66	4.98	5.30	5.66	6.02	6.39	6.75	7.11	7.47	7.84	8.59	9.34
2600	3.02	3.33	3.66	4.01	4.36	4.70	5.04	5.38	5.72	6.06	6.44	6.82	7.19	7.57	7.94	8.32	9.09	9.88
2700	3.36	3.69	4.02	4.38	4.74	5.10	5.45	5.81	6.16	6.51	6.87	7.26	7.66	8.04	8.43	8.83	9.60	10.42
2800	3.72	4.06	4.39	4.77	5.14	5.52	5.89	6.26	6.62	6.99	7.34	7.73	8.14	8.54	8.95	9.35	10.16	10.99
2900	4.10	4.46	4.81	5.19	5.58	5.96	6.35	6.73	7.11	7.49	7.86	8.24	8.64	9.07	9.48	9.90	10.74	11.58
3000	4.52	4.89	5.25	5.63	6.04	6.43	6.83	7.23	7.62	8.02	8.40	8.79	9.18	9.60	10.05	10.47	11.35	12.21
3100	4.96	5.34	5.71	6.09	6.52	6.93	7.34	7.75	8.17	8.57	8.98	9.37	9.77	10.18	10.62	11.07	11.97	12.87
3200	5.43	5.82	6.21	6.59	7.02	7.46	7.88	8.30	8.72	9.15	9.57	9.99	10.40	10.82	11.22	11.68	12.62	13.54
3300	5.93	6.34	6.74	7.13	7.56	8.01	8.45	8.88	9.32	9.76	10.20	10.62	11.06	11.48	11.91	12.33	13.30	14.25
3400	6.46	6.87	7.29	7.70	8.13	8.59	9.04	9.50	9.95	10.40	10.84	11.29	11.74	12.19	12.62	13.06	13.99	14.99
3500	7.02	7.45	7.86	8.30	8.73	9.20	9.67	10.14	10.60	11.07	11.53	11.99	12.45	12.91	13.36	13.82	14.71	15.73

Note : 1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses

TABLE B-5. TYPE 4 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
600	0.09	0.18	0.28	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
700	0.12	0.21	0.31	0.43	*	*	*	*	*	*	*	*	*	*	*	*	*	*
800	0.14	0.24	0.35	0.47	0.61	*	*	*	*	*	*	*	*	*	*	*	*	*
900	0.18	0.28	0.40	0.53	0.66	0.81	0.97	*	*	*	*	*	*	*	*	*	*	*
1000	0.22	0.33	0.46	0.59	0.73	0.88	1.05	1.22	1.40	*	*	*	*	*	*	*	*	*
1100	0.26	0.39	0.52	0.66	0.81	0.96	1.13	1.31	1.49	1.68	1.88	*	*	*	*	*	*	*
1200	0.32	0.45	0.59	0.74	0.89	1.05	1.23	1.41	1.59	1.79	2.00	2.21	2.42	*	*	*	*	*
1300	0.38	0.52	0.67	0.82	0.99	1.16	1.33	1.52	1.71	1.91	2.12	2.34	2.56	2.79	3.02	*	*	*
1400	0.45	0.60	0.76	0.92	1.09	1.27	1.45	1.64	1.84	2.05	2.26	2.47	2.70	2.94	3.18	3.42	*	*
1500	0.53	0.69	0.86	1.03	1.21	1.39	1.58	1.78	1.98	2.19	2.41	2.64	2.86	3.10	3.34	3.60	4.11	4.65
1600	0.62	0.79	0.97	1.15	1.33	1.53	1.72	1.93	2.14	2.35	2.58	2.81	3.04	3.28	3.53	3.78	4.31	4.86
1700	0.72	0.90	1.09	1.28	1.47	1.67	1.88	2.09	2.31	2.53	2.75	2.99	3.23	3.48	3.73	3.99	4.51	5.07
1800	0.84	1.03	1.22	1.42	1.62	1.83	2.04	2.26	2.49	2.72	2.95	3.19	3.43	3.69	3.95	4.21	4.75	5.31
1900	0.96	1.16	1.36	1.57	1.79	2.00	2.22	2.45	2.68	2.92	3.16	3.41	3.65	3.91	4.18	4.45	5.00	5.57
2000	1.10	1.31	1.52	1.74	1.96	2.19	2.42	2.65	2.89	3.13	3.39	3.64	3.90	4.16	4.42	4.69	5.27	5.85
2100	1.25	1.47	1.69	1.92	2.15	2.39	2.63	2.87	3.11	3.36	3.62	3.89	4.15	4.42	4.69	4.97	5.54	6.14
2200	1.41	1.64	1.88	2.11	2.36	2.60	2.85	3.10	3.35	3.61	3.88	4.15	4.42	4.70	4.98	5.26	5.84	6.45
2300	1.59	1.83	2.08	2.32	2.57	2.83	3.09	3.35	3.61	3.88	4.15	4.42	4.70	4.99	5.28	5.57	6.17	6.77
2400	1.78	2.04	2.29	2.55	2.81	3.07	3.34	3.61	3.88	4.16	4.44	4.72	5.00	5.30	5.60	5.90	6.51	7.13
2500	1.99	2.26	2.52	2.79	3.06	3.33	3.61	3.89	4.17	4.45	4.74	5.03	5.33	5.63	5.93	6.24	6.87	7.51
2600	2.22	2.49	2.77	3.04	3.32	3.61	3.89	4.18	4.47	4.77	5.07	5.37	5.67	5.98	6.28	6.60	7.25	7.91
2700	2.47	2.75	3.03	3.32	3.61	3.90	4.20	4.49	4.79	5.10	5.41	5.71	6.03	6.34	6.66	6.98	7.64	8.32
2800	2.73	3.02	3.31	3.61	3.91	4.21	4.52	4.83	5.13	5.45	5.76	6.08	6.40	6.73	7.05	7.38	8.05	8.74
2900	3.01	3.31	3.62	3.92	4.23	4.54	4.86	5.17	5.49	5.82	6.14	6.47	6.80	7.13	7.47	7.81	8.49	9.19
3000	3.31	3.62	3.94	4.25	4.57	4.89	5.22	5.54	5.87	6.21	6.54	6.88	7.22	7.56	7.90	8.25	8.95	9.66

Note :

1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-6. TYPE 5 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
800	0.13	0.23	0.36	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
900	0.15	0.27	0.40	0.54	0.70	*	*	*	*	*	*	*	*	*	*	*	*	*
1000	0.18	0.30	0.44	0.59	0.75	0.93	*	*	*	*	*	*	*	*	*	*	*	*
1100	0.22	0.35	0.49	0.64	0.81	0.99	1.19	*	*	*	*	*	*	*	*	*	*	*
1200	0.26	0.39	0.54	0.70	0.88	1.06	1.26	1.47	*	*	*	*	*	*	*	*	*	*
1300	0.30	0.45	0.61	0.77	0.95	1.14	1.34	1.55	1.78	2.01	*	*	*	*	*	*	*	*
1400	0.35	0.51	0.67	0.85	1.03	1.23	1.44	1.65	1.88	2.11	2.36	2.61	*	*	*	*	*	*
1500	0.41	0.58	0.75	0.93	1.12	1.32	1.54	1.76	1.98	2.22	2.48	2.73	3.00	*	*	*	*	*
1600	0.48	0.65	0.83	1.02	1.22	1.43	1.64	1.87	2.11	2.35	2.60	2.87	3.14	3.42	3.70	*	*	*
1700	0.55	0.73	0.92	1.12	1.33	1.54	1.76	1.99	2.24	2.49	2.74	3.00	3.28	3.57	3.86	4.16	*	*
1800	0.63	0.82	1.02	1.23	1.44	1.66	1.89	2.13	2.37	2.63	2.90	3.17	3.44	3.72	4.02	4.33	4.95	5.60
1900	0.71	0.92	1.13	1.34	1.57	1.79	2.03	2.28	2.53	2.79	3.06	3.34	3.62	3.90	4.20	4.50	5.15	5.81
2000	0.81	1.02	1.24	1.47	1.70	1.93	2.18	2.43	2.69	2.95	3.22	3.51	3.80	4.10	4.40	4.70	5.34	6.02
2100	0.92	1.14	1.37	1.60	1.84	2.09	2.34	2.60	2.86	3.13	3.41	3.70	4.00	4.30	4.61	4.92	5.56	6.24
2200	1.03	1.26	1.50	1.75	2.00	2.25	2.51	2.77	3.05	3.33	3.61	3.90	4.20	4.51	4.83	5.15	5.81	6.48
2300	1.15	1.40	1.64	1.90	2.16	2.42	2.69	2.96	3.24	3.53	3.82	4.12	4.42	4.73	5.05	5.39	6.06	6.75
2400	1.29	1.54	1.80	2.06	2.33	2.60	2.88	3.16	3.45	3.74	4.04	4.35	4.66	4.98	5.29	5.63	6.32	7.03
2500	1.44	1.70	1.97	2.24	2.52	2.80	3.08	3.37	3.67	3.97	4.28	4.59	4.91	5.24	5.56	5.89	6.59	7.31
2600	1.59	1.87	2.14	2.43	2.71	3.00	3.30	3.60	3.90	4.21	4.52	4.84	5.18	5.50	5.84	6.18	6.87	7.61
2700	1.76	2.04	2.33	2.62	2.92	3.22	3.52	3.83	4.14	4.46	4.78	5.11	5.45	5.79	6.13	6.48	7.18	7.92
2800	1.94	2.24	2.53	2.83	3.14	3.45	3.76	4.08	4.40	4.73	5.06	5.39	5.73	6.08	6.43	6.79	7.51	8.25
2900	2.14	2.44	2.75	3.06	3.37	3.69	4.02	4.34	4.67	5.01	5.34	5.69	6.03	6.39	6.75	7.12	7.85	8.61
3000	2.34	2.66	2.97	3.30	3.62	3.95	4.28	4.62	4.96	5.30	5.65	6.00	6.35	6.71	7.08	7.45	8.21	8.99
3100	2.56	2.89	3.21	3.54	3.88	4.22	4.56	4.91	5.25	5.61	5.96	6.32	6.68	7.05	7.42	7.81	8.58	9.37
3200	2.80	3.13	3.47	3.81	4.15	4.50	4.85	5.21	5.57	5.93	6.29	6.66	7.04	7.41	7.79	8.17	8.97	9.77
3300	3.05	3.39	3.74	4.09	4.44	4.80	5.16	5.53	5.89	6.27	6.64	7.01	7.40	7.78	8.17	8.56	9.36	10.19
3400	3.31	3.67	4.02	4.38	4.75	5.11	5.48	5.86	6.24	6.61	7.00	7.39	7.77	8.17	8.56	8.96	9.77	10.61
3500	3.59	3.96	4.32	4.69	5.06	5.44	5.82	6.20	6.59	6.98	7.38	7.77	8.17	8.57	8.98	9.38	10.21	11.06
3600	3.89	4.26	4.64	5.02	5.40	5.79	6.17	6.57	6.97	7.36	7.77	8.18	8.58	8.99	9.41	9.82	10.67	11.52

Note :
1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-7. TYPE 6 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
1000	0.16	0.29	0.45	0.62	*	*	*	*	*	*	*	*	*	*	*	*	*	*
1150	0.20	0.34	0.50	0.69	0.88	*	*	*	*	*	*	*	*	*	*	*	*	*
1300	0.25	0.40	0.57	0.76	0.96	1.19	*	*	*	*	*	*	*	*	*	*	*	*
1450	0.31	0.47	0.65	0.85	1.06	1.29	1.53	1.78	*	*	*	*	*	*	*	*	*	*
1600	0.37	0.55	0.74	0.95	1.17	1.40	1.65	1.91	2.19	2.48	*	*	*	*	*	*	*	*
1750	0.45	0.64	0.85	1.06	1.29	1.54	1.79	2.06	2.34	2.63	2.94	3.25	*	*	*	*	*	*
1900	0.54	0.75	0.96	1.19	1.43	1.68	1.95	2.22	2.51	2.80	3.12	3.44	3.77	4.11	*	*	*	*
2050	0.64	0.86	1.09	1.33	1.59	1.85	2.11	2.40	2.70	3.00	3.31	3.63	3.98	4.33	4.69	5.05	*	*
2200	0.76	0.99	1.24	1.49	1.75	2.03	2.31	2.59	2.90	3.22	3.54	3.87	4.21	4.56	4.93	5.30	6.08	*
2350	0.89	1.14	1.40	1.66	1.94	2.22	2.52	2.82	3.12	3.44	3.78	4.13	4.47	4.83	5.19	5.57	6.36	7.18
2500	1.03	1.30	1.57	1.85	2.14	2.43	2.74	3.05	3.37	3.70	4.04	4.39	4.75	5.12	5.49	5.87	6.66	7.50
2650	1.19	1.48	1.76	2.06	2.36	2.67	2.93	3.30	3.64	3.98	4.32	4.68	5.05	5.43	5.82	6.21	7.00	7.83
2800	1.38	1.67	1.97	2.28	2.60	2.92	3.24	3.58	3.92	4.28	4.63	5.00	5.37	5.75	6.15	6.55	7.38	8.22
2950	1.58	1.89	2.20	2.53	2.85	3.19	3.53	3.88	4.23	4.60	4.96	5.34	5.72	6.11	6.50	6.92	7.76	8.63
3100	1.79	2.12	2.45	2.79	3.13	3.48	3.83	4.19	4.56	4.93	5.31	5.70	6.10	6.50	6.90	7.31	8.17	9.07
3250	2.03	2.38	2.72	3.07	3.43	3.79	4.16	4.53	4.91	5.29	5.69	6.09	6.50	6.91	7.32	7.75	8.60	9.51
3400	2.30	2.65	3.01	3.38	3.75	4.12	4.51	4.90	5.29	5.68	6.08	6.49	6.91	7.34	7.77	8.20	9.09	9.98
3550	2.58	2.95	3.33	3.70	4.09	4.48	4.88	5.28	5.68	6.09	6.51	6.93	7.35	7.79	8.23	8.68	9.59	10.52
3700	2.89	3.27	3.66	4.06	4.46	4.86	5.27	5.69	6.11	6.53	6.96	7.39	7.83	8.27	8.73	9.19	10.13	11.07
3850	3.22	3.62	4.02	4.43	4.85	5.27	5.69	6.12	6.56	6.99	7.43	7.88	8.33	8.78	9.25	9.72	10.68	11.66
4000	3.58	3.99	4.41	4.84	5.27	5.70	6.14	6.59	7.03	7.48	7.94	8.39	8.86	9.33	9.80	10.27	11.26	12.27
4150	3.96	4.39	4.83	5.27	5.71	6.16	6.61	7.07	7.53	8.00	8.46	8.94	9.42	9.90	10.38	10.87	11.86	12.90
4300	4.37	4.82	5.27	5.73	6.19	6.65	7.12	7.58	8.06	8.54	9.02	9.51	10.00	10.50	10.99	11.50	12.52	13.56
4450	4.81	5.28	5.75	6.21	6.68	7.16	7.65	8.13	8.62	9.11	9.61	10.11	10.62	11.13	11.64	12.16	13.20	14.25

Note : 1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-8. TYPE 7 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
1200	0.19	0.35	0.54	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
1350	0.23	0.40	0.59	0.81	1.05	*	*	*	*	*	*	*	*	*	*	*	*	*
1500	0.28	0.46	0.66	0.88	1.13	1.39	*	*	*	*	*	*	*	*	*	*	*	*
1650	0.33	0.52	0.73	0.97	1.21	1.49	1.76	*	*	*	*	*	*	*	*	*	*	*
1800	0.39	0.59	0.82	1.06	1.32	1.59	1.89	2.20	*	*	*	*	*	*	*	*	*	*
1950	0.46	0.68	0.91	1.16	1.43	1.71	2.01	2.33	2.66	3.01	*	*	*	*	*	*	*	*
2100	0.53	0.77	1.01	1.27	1.55	1.84	2.15	2.47	2.81	3.16	3.53	3.91	*	*	*	*	*	*
2250	0.62	0.87	1.13	1.40	1.69	1.98	2.30	2.64	2.97	3.33	3.71	4.10	4.49	4.90	*	*	*	*
2400	0.72	0.98	1.25	1.54	1.83	2.14	2.46	2.81	3.16	3.52	3.89	4.29	4.70	5.12	5.54	*	*	*
2550	0.83	1.10	1.39	1.68	1.99	2.31	2.65	2.99	3.36	3.73	4.11	4.50	4.91	5.34	5.78	6.23	*	*
2700	0.94	1.24	1.54	1.85	2.16	2.50	2.84	3.20	3.56	3.95	4.34	4.75	5.16	5.57	6.03	6.49	7.42	8.39
2850	1.08	1.38	1.70	2.02	2.35	2.70	3.05	3.42	3.79	4.18	4.59	5.00	5.42	5.85	6.30	6.75	7.71	8.71
3000	1.22	1.54	1.87	2.21	2.55	2.91	3.28	3.65	4.04	4.43	4.84	5.27	5.70	6.15	6.60	7.06	8.01	9.02
3150	1.38	1.72	2.06	2.41	2.77	3.14	3.51	3.90	4.30	4.71	5.12	5.55	5.99	6.45	6.91	7.38	8.34	9.35
3300	1.56	1.90	2.26	2.63	3.00	3.38	3.77	4.17	4.58	5.00	5.42	5.86	6.30	6.76	7.24	7.72	8.71	9.72
3450	1.74	2.11	2.48	2.86	3.25	3.64	4.04	4.45	4.87	5.31	5.74	6.19	6.64	7.10	7.58	8.08	9.08	10.12
3600	1.95	2.33	2.71	3.11	3.51	3.92	4.33	4.75	5.18	5.63	6.08	6.53	7.00	7.47	7.94	8.44	9.47	10.54
3750	2.17	2.56	2.96	3.37	3.79	4.21	4.64	5.07	5.51	5.96	6.42	6.90	7.37	7.86	8.35	8.85	9.89	10.96
3900	2.40	2.81	3.23	3.65	4.08	4.52	4.96	5.41	5.86	6.32	6.80	7.28	7.77	8.27	8.77	9.28	10.31	11.42
4050	2.66	3.08	3.52	3.95	4.40	4.85	5.30	5.77	6.23	6.71	7.19	7.68	8.18	8.69	9.21	9.73	10.78	11.88
4200	2.94	3.38	3.82	4.27	4.73	5.19	5.66	6.14	6.62	7.11	7.60	8.10	8.62	9.14	9.66	10.20	11.28	12.38
4350	3.23	3.68	4.14	4.61	5.08	5.56	6.05	6.53	7.03	7.53	8.04	8.55	9.06	9.60	10.14	10.69	11.80	12.93
4500	3.54	4.01	4.48	4.96	5.45	5.94	6.45	6.95	7.46	7.97	8.49	9.02	9.54	10.09	10.64	11.20	12.34	13.49
4650	3.88	4.36	4.85	5.35	5.85	6.35	6.86	7.38	7.90	8.44	8.97	9.51	10.05	10.60	11.15	11.73	12.89	14.07
4800	4.23	4.73	5.24	5.74	6.26	6.78	7.30	7.84	8.38	8.92	9.46	10.01	10.58	11.14	11.71	12.28	13.46	14.67
4950	4.61	5.12	5.64	6.17	6.70	7.23	7.77	8.32	8.87	9.43	9.99	10.56	11.13	11.70	12.28	12.87	14.07	15.30
5100	5.01	5.53	6.07	6.61	7.16	7.70	8.26	8.82	9.39	9.96	10.53	11.11	11.70	12.29	12.88	13.47	14.69	15.95
5250	5.43	5.97	6.52	7.08	7.64	8.20	8.77	9.35	9.93	10.51	11.10	11.69	12.29	12.90	13.50	14.11	15.35	16.63
5400	5.88	6.44	7.00	7.57	8.15	8.72	9.31	9.90	10.49	11.08	11.69	12.29	12.91	13.53	14.15	14.78	16.04	17.32

Note :

1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-9. TYPE 8 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
1500	0.24	0.44	0.67	0.93	*	*	*	*	*	*	*	*	*	*	*	*	*	*
1700	0.30	0.51	0.75	1.01	1.31	*	*	*	*	*	*	*	*	*	*	*	*	*
1900	0.36	0.59	0.84	1.11	1.42	1.74	*	*	*	*	*	*	*	*	*	*	*	*
2100	0.43	0.68	0.94	1.23	1.54	1.87	2.23	2.60	*	*	*	*	*	*	*	*	*	*
2300	0.52	0.78	1.06	1.36	1.68	2.02	2.38	2.77	3.18	*	*	*	*	*	*	*	*	*
2500	0.62	0.90	1.19	1.51	1.84	2.19	2.57	2.95	3.37	3.80	4.24	*	*	*	*	*	*	*
2700	0.73	1.03	1.34	1.67	2.01	2.37	2.76	3.16	3.57	4.01	4.48	4.94	5.43	*	*	*	*	*
2900	0.85	1.17	1.50	1.84	2.20	2.58	2.98	3.39	3.82	4.26	4.71	5.20	5.70	6.21	6.73	*	*	*
3100	1.00	1.33	1.68	2.04	2.42	2.81	3.21	3.63	4.08	4.54	5.00	5.48	5.98	6.50	7.05	7.59	*	*
3300	1.16	1.51	1.88	2.26	2.65	3.06	3.47	3.91	4.35	4.82	5.31	5.80	6.30	6.81	7.37	7.93	9.08	10.26
3500	1.33	1.70	2.09	2.49	2.89	3.32	3.75	4.20	4.66	5.13	5.64	6.14	6.66	7.18	7.72	8.28	9.46	10.67
3700	1.53	1.92	2.33	2.74	3.17	3.60	4.05	4.52	4.99	5.48	5.97	6.50	7.03	7.57	8.13	8.69	9.85	11.11
3900	1.74	2.16	2.58	3.01	3.46	3.91	4.37	4.86	5.34	5.85	6.35	6.87	7.42	7.99	8.56	9.13	10.31	11.54
4100	1.98	2.41	2.86	3.31	3.77	4.24	4.72	5.21	5.72	6.24	6.76	7.30	7.84	8.41	8.99	9.59	10.80	12.05
4300	2.24	2.69	3.15	3.63	4.11	4.60	5.09	5.60	6.12	6.66	7.20	7.75	8.30	8.87	9.46	10.07	11.32	12.59
4500	2.52	3.00	3.48	3.97	4.47	4.98	5.49	6.02	6.55	7.09	7.65	8.22	8.80	9.39	9.97	10.57	11.85	13.17
4700	2.83	3.32	3.82	4.33	4.85	5.38	5.91	6.45	7.00	7.56	8.14	8.72	9.32	9.91	10.53	11.13	12.41	13.75
4900	3.16	3.67	4.19	4.72	5.26	5.81	6.36	6.92	7.49	8.06	8.65	9.25	9.86	10.48	11.10	11.73	13.02	14.36
5100	3.52	4.05	4.59	5.14	5.70	6.26	6.84	7.41	8.00	8.59	9.19	9.80	10.42	11.06	11.70	12.35	13.68	15.01
5300	3.91	4.46	5.02	5.59	6.17	6.75	7.34	7.93	8.54	9.15	9.77	10.39	11.02	11.67	12.33	13.00	14.36	15.74
5500	4.32	4.90	5.47	6.06	6.66	7.26	7.87	8.49	9.11	9.74	10.37	11.01	11.67	12.32	13.00	13.68	15.07	16.47
5700	4.76	5.36	5.96	6.57	7.18	7.80	8.43	9.07	9.71	10.36	11.00	11.67	12.33	13.01	13.68	14.39	15.81	17.26
5900	5.24	5.85	6.48	7.10	7.73	8.38	9.02	9.68	10.34	11.01	11.68	12.36	13.04	13.73	14.43	15.12	16.58	18.06
6100	5.75	6.38	7.03	7.67	8.32	8.99	9.65	10.33	11.00	11.68	12.38	13.07	13.78	14.48	15.19	15.92	17.39	18.90
6300	6.29	6.95	7.61	8.28	8.94	9.62	10.30	11.00	11.70	12.40	13.11	13.83	14.55	15.28	16.01	16.74	18.23	19.78
6500	6.86	7.54	8.22	8.91	9.60	10.29	11.00	11.70	12.43	13.16	13.88	14.61	15.34	16.10	16.84	17.61	19.14	20.69

Note :
1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-10. TYPE 9 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
2000	0.34	0.59	0.88	1.20	1.55	*	*	*	*	*	*	*	*	*	*	*	*	*
2250	0.42	0.69	0.99	1.32	1.68	2.07	*	*	*	*	*	*	*	*	*	*	*	*
2500	0.51	0.80	1.11	1.46	1.83	2.23	2.66	*	*	*	*	*	*	*	*	*	*	*
2750	0.62	0.93	1.26	1.62	2.01	2.42	2.85	3.32	3.80	*	*	*	*	*	*	*	*	*
3000	0.74	1.07	1.43	1.81	2.20	2.63	3.08	3.54	4.04	4.56	5.09	*	*	*	*	*	*	*
3250	0.88	1.24	1.61	2.01	2.42	2.86	3.33	3.81	4.30	4.83	5.39	5.94	6.53	*	*	*	*	*
3500	1.04	1.42	1.82	2.23	2.67	3.12	3.59	4.09	4.61	5.14	5.68	6.27	6.87	7.48	8.10	*	*	*
3750	1.22	1.62	2.04	2.48	2.93	3.41	3.89	4.40	4.93	5.48	6.05	6.62	7.22	7.85	8.49	9.15	*	*
4000	1.42	1.85	2.29	2.75	3.22	3.71	4.22	4.74	5.28	5.85	6.43	7.03	7.63	8.25	8.91	9.59	10.96	12.40
4250	1.64	2.09	2.57	3.04	3.54	4.05	4.58	5.12	5.67	6.24	6.84	7.46	8.08	8.72	9.37	10.03	11.46	12.92
4500	1.89	2.37	2.87	3.37	3.88	4.41	4.96	5.52	6.10	6.68	7.28	7.91	8.56	9.21	9.88	10.56	11.95	13.45
4750	2.17	2.67	3.19	3.72	4.25	4.81	5.36	5.94	6.54	7.15	7.76	8.39	9.04	9.73	10.41	11.11	12.55	14.01
5000	2.47	3.00	3.54	4.09	4.65	5.22	5.81	6.40	7.02	7.65	8.29	8.93	9.59	10.27	10.98	11.70	13.17	14.68
5250	2.80	3.36	3.92	4.50	5.08	5.68	6.29	6.90	7.53	8.18	8.84	9.51	10.18	10.87	11.57	12.31	13.82	15.37
5500	3.17	3.75	4.33	4.93	5.54	6.16	6.79	7.43	8.08	8.74	9.43	10.11	10.81	11.52	12.24	12.96	14.49	16.08
5750	3.57	4.17	4.78	5.40	6.04	6.68	7.33	7.99	8.67	9.34	10.04	10.75	11.47	12.20	12.94	13.68	15.21	16.84
6000	4.00	4.62	5.26	5.91	6.56	7.23	7.91	8.59	9.28	9.98	10.70	11.42	12.17	12.91	13.67	14.45	16.01	17.61
6250	4.46	5.11	5.78	6.45	7.13	7.82	8.52	9.22	9.93	10.66	11.39	12.14	12.89	13.67	14.44	15.24	16.84	18.47
6500	4.97	5.65	6.33	7.02	7.73	8.44	9.17	9.90	10.63	11.38	12.13	12.89	13.67	14.45	15.25	16.07	17.72	19.38
6750	5.51	6.21	6.93	7.64	8.36	9.10	9.85	10.61	11.36	12.13	12.91	13.70	14.48	15.29	16.09	16.94	18.63	20.35
7000	6.08	6.81	7.55	8.29	9.04	9.81	10.58	11.36	12.14	12.92	13.73	14.54	15.35	16.18	17.01	17.84	19.57	21.35
7250	6.71	7.46	8.23	9.00	9.77	10.56	11.34	12.14	12.95	13.77	14.59	15.42	16.27	17.10	17.94	18.81	20.56	22.37
7500	7.38	8.15	8.93	9.74	10.54	11.34	12.15	12.97	13.81	14.65	15.49	16.35	17.21	18.08	18.95	19.83	21.61	23.46
7750	8.08	8.88	9.70	10.52	11.34	12.17	13.00	13.86	14.72	15.59	16.44	17.32	18.20	19.09	20.00	20.89	22.72	24.58
8000	8.84	9.66	10.50	11.34	12.19	13.05	13.91	14.79	15.66	16.55	17.44	18.35	19.26	20.17	21.09	22.01	23.88	25.78

Note :
1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-11. TYPE 10 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
2300	0.38	0.67	1.01	1.40	*	*	*	*	*	*	*	*	*	*	*	*	*	*
2600	0.47	0.79	1.14	1.53	1.97	*	*	*	*	*	*	*	*	*	*	*	*	*
2900	0.57	0.91	1.28	1.70	2.13	2.62	3.13	*	*	*	*	*	*	*	*	*	*	*
3200	0.69	1.05	1.45	1.88	2.34	2.82	3.35	3.91	*	*	*	*	*	*	*	*	*	*
3500	0.83	1.22	1.64	2.08	2.56	3.07	3.60	4.17	4.77	5.38	*	*	*	*	*	*	*	*
3800	0.99	1.41	1.85	2.32	2.81	3.34	3.89	4.46	5.06	5.70	6.36	7.03	*	*	*	*	*	*
4100	1.16	1.62	2.08	2.58	3.09	3.63	4.20	4.80	5.41	6.04	6.71	7.41	8.12	8.86	*	*	*	*
4400	1.37	1.85	2.34	2.86	3.40	3.96	4.54	5.15	5.79	6.44	7.11	7.80	8.54	9.30	10.07	10.84	*	*
4700	1.60	2.10	2.63	3.17	3.73	4.32	4.92	5.53	6.19	6.87	7.57	8.27	9.00	9.76	10.55	11.35	13.00	*
5000	1.86	2.39	2.95	3.51	4.09	4.70	5.33	5.98	6.63	7.32	8.05	8.78	9.52	10.28	11.05	11.87	13.57	15.34
5300	2.14	2.70	3.29	3.88	4.49	5.12	5.77	6.44	7.12	7.81	8.54	9.30	10.08	10.87	11.65	12.47	14.16	15.97
5600	2.46	3.05	3.66	4.29	4.92	5.58	6.24	6.94	7.64	8.37	9.10	9.86	10.65	11.46	12.29	13.12	14.82	16.63
5900	2.81	3.43	4.07	4.73	5.38	6.06	6.76	7.47	8.20	8.95	9.71	10.49	11.27	12.10	12.95	13.81	15.56	17.36
6200	3.19	3.84	4.51	5.19	5.88	6.59	7.31	8.04	8.79	9.57	10.35	11.14	11.96	12.77	13.63	14.52	16.31	18.17
6500	3.60	4.29	4.99	5.69	6.42	7.16	7.89	8.65	9.42	10.22	11.04	11.85	12.69	13.54	14.38	15.25	17.11	19.02
6800	4.06	4.78	5.50	6.24	6.99	7.76	8.52	9.31	10.11	10.91	11.75	12.59	13.46	14.34	15.21	16.11	17.95	19.[illegible]
7100	4.56	5.30	6.06	6.83	7.60	8.39	9.19	10.00	10.83	11.67	12.51	13.37	14.27	15.17	16.08	16.98	18.84	20.[illegible]
7400	5.10	5.86	6.65	7.44	8.25	9.08	9.90	10.75	11.60	12.46	13.32	14.20	15.12	16.05	16.97	17.91	19.83	21.78
7700	5.68	6.48	7.28	8.11	8.95	9.80	10.66	11.53	12.41	13.29	14.19	15.08	16.01	16.96	17.92	18.89	20.86	22.85
8000	6.30	7.13	7.97	8.83	9.70	10.56	11.46	12.35	13.25	14.17	15.09	16.02	16.97	17.93	18.90	19.91	21.92	23.98
8300	6.96	7.83	8.70	9.59	10.47	11.38	12.29	13.23	14.15	15.09	16.05	17.02	17.98	18.96	19.94	20.96	23.04	25.14
8600	7.68	8.57	9.49	10.39	11.32	12.25	13.19	14.15	15.11	16.07	17.05	18.03	19.03	20.05	21.07	22.09	24.20	26.37
8900	8.45	9.37	10.31	11.26	12.20	13.17	14.14	15.12	16.11	17.10	18.11	19.14	20.15	21.18	22.23	23.27	25.40	27.61
9200	9.27	10.22	11.19	12.15	13.14	14.14	15.14	16.13	17.15	18.18	19.22	20.26	21.32	22.38	23.45	24.52	26.70	28.95
9500	10.13	11.12	12.13	13.11	14.13	15.15	16.18	17.22	18.25	19.32	20.39	21.45	22.52	23.62	24.70	25.81	28.03	30.30
9800	11.06	12.09	13.11	14.15	15.17	16.22	17.29	18.35	19.43	20.52	21.59	22.69	23.80	24.91	26.03	27.18	29.45	31.76

Note :

1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-12. TYPE 11 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
2700	0.32	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
3050	0.39	0.68	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
3400	0.46	0.78	1.13	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
3750	0.55	0.89	1.26	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
4100	0.65	1.02	1.41	1.83	*	*	*	*	*	*	*	*	*	*	*	*	*	*
4450	0.77	1.15	1.57	2.01	2.48	*		*	*	*	*	*	*	*	*	*	*	*
4800	0.89	1.31	1.74	2.21	2.70	3.21	*	*	*	*	*	*	*	*	*	*	*	*
5150	1.04	1.48	1.94	2.42	2.93	3.46	4.01	*	*	*	*	*	*	*	*	*	*	*
5500	1.20	1.67	2.16	2.65	3.18	3.74	4.30	4.89	*	*	*	*	*	*	*	*	*	*
5850	1.38	1.88	2.39	2.91	3.46	4.03	4.61	5.23	5.85	*	*	*	*	*	*	*	*	*
6200	1.58	2.10	2.65	3.19	3.75	4.35	4.96	5.59	6.23	6.89	*	*	*	*	*	*	*	*
6550	1.81	2.35	2.92	3.49	4.08	4.69	5.32	5.97	6.63	7.31	8.01	*	*	*	*	*	*	*
6900	2.05	2.62	3.21	3.82	4.43	5.05	5.70	6.38	7.06	7.77	8.48	9.21	9.96	*	*	*	*	*
7250	2.33	2.90	3.52	4.16	4.80	5.44	6.12	6.82	7.52	8.25	8.97	9.72	10.50	11.28	*	*	*	*
7600	2.62	3.22	3.87	4.53	5.21	5.87	6.55	7.27	8.01	8.75	9.50	10.27	11.06	11.87	12.68	*	*	*
7950	2.94	3.57	4.23	4.93	5.62	6.32	7.02	7.75	8.51	9.28	10.06	10.85	11.66	12.47	13.31	14.17	*	*
8300	3.29	3.94	4.62	5.34	6.07	6.80	7.53	8.27	9.03	9.83	10.64	11.46	12.28	13.12	13.97	14.82	16.62	*
8650	3.67	4.33	5.04	5.79	6.54	7.31	8.06	8.84	9.61	10.40	11.25	12.08	12.93	13.79	14.68	15.55	17.37	19.24
9000	4.08	4.77	5.50	6.26	7.04	7.84	8.63	9.43	10.23	11.03	11.88	12.74	13.62	14.51	15.40	16.31	18.16	20.04
9350	4.52	5.23	5.98	6.77	7.58	8.39	9.23	10.04	10.87	11.71	12.56	13.42	14.33	15.23	16.15	17.08	18.97	20.91
9700	4.99	5.73	6.48	7.31	8.14	8.99	9.85	10.69	11.54	12.40	13.28	14.16	15.06	16.00	16.95	17.91	19.83	21.83
10050	5.49	6.26	7.05	7.87	8.73	9.59	10.49	11.37	12.27	13.14	14.03	14.94	15.84	16.82	17.77	18.77	20.75	22.78
10400	6.03	6.82	7.63	8.48	9.36	10.25	11.17	12.09	13.00	13.91	14.83	15.75	16.69	17.63	18.62	19.65	21.66	23.75
10750	6.61	7.43	8.26	9.11	10.02	10.95	11.87	12.83	13.78	14.73	15.66	16.62	17.59	18.54	19.52	20.55	22.63	24.75
11100	7.22	8.07	8.91	9.78	10.72	11.67	12.62	13.60	14.60	15.58	16.55	17.52	18.49	19.50	20.49	21.52	23.63	25.80
11450	7.87	8.74	9.61	10.52	11.46	12.43	13.43	14.42	15.43	16.43	17.44	18.44	19.45	20.47	21.49	22.55	24.68	26.89
11800	8.56	9.46	10.36	11.27	12.22	13.23	14.24	15.27	16.30	17.34	18.39	19.43	20.47	21.50	22.55	23.61	25.73	28.01

Note :

1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-13. TYPE 12 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
3300	0.39	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
3700	0.46	0.82	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
4100	0.55	0.93	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
4500	0.64	1.05	1.51	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
4900	0.75	1.18	1.67	2.18	*	*	*	*	*	*	*	*	*	*	*	*	*	*
5300	0.87	1.34	1.84	2.37	*	*	*	*	*	*	*	*	*	*	*	*	*	*
5700	1.00	1.50	2.03	2.59	3.18	*	*	*	*	*	*	*	*	*	*	*	*	*
6100	1.15	1.69	2.23	2.82	3.43	4.07	*	*	*	*	*	*	*	*	*	*	*	*
6500	1.32	1.88	2.45	3.06	3.71	4.37	5.06	*	*	*	*	*	*	*	*	*	*	*
6900	1.51	2.10	2.71	3.32	4.00	4.69	5.39	6.13	*	*	*	*	*	*	*	*	*	*
7300	1.72	2.33	2.97	3.62	4.31	5.03	5.76	6.51	7.30	*	*	*	*	*	*	*	*	*
7700	1.94	2.59	3.27	3.94	4.65	5.38	6.15	6.92	7.72	8.57	*	*	*	*	*	*	*	*
8100	2.20	2.86	3.57	4.29	5.00	5.77	6.56	7.36	8.19	9.03	9.91	*	*	*	*	*	*	*
8500	2.47	3.17	3.90	4.65	5.40	6.17	6.98	7.82	8.66	9.53	10.43	11.36	*	*	*	*	*	*
8900	2.77	3.48	4.24	5.03	5.82	6.61	7.43	8.31	9.17	10.07	10.99	11.91	12.87	*	*	*	*	*
9300	3.09	3.83	4.62	5.45	6.26	7.08	7.92	8.80	9.72	10.63	11.58	12.53	13.50	14.50	15.52	*	*	*
9700	3.45	4.21	5.02	5.88	6.73	7.58	8.45	9.33	10.27	11.21	12.19	13.15	14.17	15.17	16.20	17.25	*	*
10100	3.82	4.60	5.46	6.33	7.23	8.11	9.01	9.92	10.85	11.84	12.83	13.82	14.84	15.88	16.94	18.00	*	*
10500	4.23	5.05	5.91	6.82	7.74	8.68	9.60	10.53	11.48	12.48	13.49	14.54	15.56	16.64	17.70	18.80	21.05	*
10900	4.67	5.51	6.40	7.34	8.28	9.25	10.22	11.18	12.15	13.15	14.19	15.25	16.34	17.42	18.51	19.61	21.87	24.25
11300	5.14	6.01	6.91	7.88	8.85	9.86	10.86	11.86	12.85	13.86	14.92	16.02	17.11	18.22	19.35	20.48	22.78	25.20
11700	5.65	6.54	7.47	8.45	9.46	10.50	11.52	12.57	13.59	14.65	15.69	16.78	17.94	19.05	20.21	21.38	23.75	26.16
12100	6.18	7.11	8.04	9.07	10.11	11.16	12.25	13.30	14.37	15.43	16.52	17.62	18.76	19.94	21.13	22.30	24.73	27.22
12500	6.75	7.70	8.69	9.72	10.78	11.87	12.96	14.09	15.17	16.27	17.40	18.51	19.63	20.85	22.04	23.29	25.75	28.26
12900	7.36	8.33	9.34	10.40	11.48	12.59	13.74	14.87	16.00	17.14	18.27	19.46	20.62	21.79	23.02	24.26	26.79	29.36
13300	8.00	9.02	10.03	11.11	12.23	13.37	14.53	15.70	16.89	18.04	19.21	20.40	21.60	22.81	24.03	25.30	27.90	30.50
13700	8.67	9.72	10.77	11.85	13.02	14.18	15.39	16.59	17.79	19.01	20.19	21.41	22.62	23.87	25.08	26.37	29.00	31.71
14100	9.40	10.47	11.56	12.67	13.85	15.04	16.24	17.49	18.73	19.97	21.23	22.46	23.70	24.95	26.24	27.49	30.17	32.91
14500	10.17	11.25	12.38	13.51	14.70	15.92	17.16	18.42	19.70	20.99	22.26	23.54	24.82	26.11	27.40	28.73	31.37	34.18

Note :
1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-14. TYPE 13 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
4500	0.56	1.00	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
5000	0.66	1.13	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
5500	0.78	1.28	1.84	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6000	0.91	1.44	2.04	2.66	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6500	1.05	1.63	2.25	2.90	*	*	*	*	*	*	*	*	*	*	*	*	*	*
7000	1.22	1.84	2.48	3.17	3.90	*	*	*	*	*	*	*	*	*	*	*	*	*
7500	1.41	2.07	2.73	3.45	4.22	5.01	*	*	*	*	*	*	*	*	*	*	*	*
8000	1.62	2.31	3.10	3.77	4.56	5.37	6.22	*	*	*	*	*	*	*	*	*	*	*
8500	1.85	2.58	3.33	4.09	4.92	5.78	6.65	7.55	*	*	*	*	*	*	*	*	*	*
9000	2.10	2.87	3.67	4.46	5.30	6.20	7.09	8.04	9.01	*	*	*	*	*	*	*	*	*
9500	2.40	3.19	4.03	4.86	5.72	6.64	7.58	8.55	9.54	10.56	*	*	*	*	*	*	*	*
10000	2.71	3.53	4.41	5.29	6.18	7.13	8.08	9.10	10.10	11.14	12.22	*	*	*	*	*	*	*
10500	3.05	3.91	4.81	5.75	6.67	7.61	8.63	9.67	10.71	11.80	12.89	14.03	*	*	*	*	*	*
11000	3.43	4.31	5.25	6.23	7.19	8.17	9.21	10.26	11.35	12.45	13.58	14.73	15.91	*	*	*	*	*
11500	3.83	4.75	5.73	6.73	7.75	8.76	9.80	10.91	12.01	13.15	14.33	15.47	16.67	17.92	19.19	*	*	*
12000	4.27	5.21	6.22	7.29	8.34	9.40	10.46	11.55	12.72	13.91	15.10	16.29	17.50	18.74	20.06	21.35	*	*
12500	4.76	5.72	6.77	7.85	8.97	10.04	11.16	12.29	13.46	14.66	15.90	17.13	18.38	19.66	20.95	22.28	*	*
13000	5.26	6.27	7.35	8.46	9.61	10.74	11.91	13.06	14.23	15.48	16.72	17.99	19.29	20.61	21.94	23.25	26.07	*
13500	5.82	6.86	7.97	9.11	10.29	11.50	12.66	13.86	15.08	16.29	17.61	18.93	20.23	21.59	22.92	24.31	27.12	30.02
14000	6.40	7.48	8.61	9.79	11.02	12.25	13.47	14.73	15.96	17.21	18.49	19.85	21.24	22.60	23.97	25.40	28.24	31.18
14500	7.04	8.15	9.29	10.52	11.79	13.04	14.32	15.60	16.87	18.17	19.51	20.85	22.23	23.64	25.10	26.53	29.44	32.46
15000	7.71	8.87	10.03	11.30	12.59	13.90	15.21	16.53	17.86	19.17	20.55	21.87	23.31	24.76	26.22	27.69	30.69	33.73
15500	8.43	9.63	10.82	12.11	13.43	14.75	16.12	17.50	18.88	20.24	21.63	22.99	24.41	25.91	27.37	28.88	31.96	35.08
16000	9.20	10.42	11.64	12.96	14.30	15.68	17.10	18.52	19.94	21.31	22.75	24.16	25.62	27.05	28.60	30.16	33.27	36.48
16500	10.01	11.27	12.54	13.86	15.25	16.69	18.13	19.56	21.04	22.46	23.95	25.41	26.87	28.34	29.86	31.47	34.67	37.91
17000	10.86	12.15	13.46	14.82	16.24	17.70	19.15	20.67	22.17	23.65	25.14	26.65	28.16	29.68	31.25	32.76	36.05	39.37
17500	11.77	13.09	14.45	15.81	17.28	18.75	20.26	21.79	23.34	24.88	26.43	27.98	29.55	31.06	32.62	34.24	37.53	40.94
18000	12.75	14.10	15.49	16.87	18.35	19.89	21.45	22.99	24.55	26.17	27.75	29.36	30.92	32.53	34.15	36.76	39.05	42.48

Note :
1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-15. TYPE 14 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
5100	0.61	1.13	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
5750	0.74	1.29	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6400	0.88	1.47	2.14	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
7050	1.04	1.67	2.37	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
7700	1.23	1.91	2.65	3.43	*	*	*	*	*	*	*	*	*	*	*	*	*	*
8350	1.44	2.17	2.95	3.78	4.65	*	*	*	*	*	*	*	*	*	*	*	*	*
9000	1.68	2.47	3.27	4.14	5.04	6.00	*	*	*	*	*	*	*	*	*	*	*	*
9650	1.94	2.79	3.63	4.53	5.49	6.47	7.51	*	*	*	*	*	*	*	*	*	*	*
10300	2.25	3.12	4.03	4.96	5.97	6.98	8.05	9.16	*	*	*	*	*	*	*	*	*	*
10950	2.58	3.50	4.47	5.46	6.48	7.54	8.54	9.78	10.95	*	*	*	*	*	*	*	*	*
11600	2.97	3.93	4.95	5.96	7.02	8.14	9.29	10.45	11.64	12.89	*	*	*	*	*	*	*	*
12250	3.37	4.38	5.45	6.53	7.62	8.76	9.93	11.15	12.40	13.66	14.99	*	*	*	*	*	*	*
12900	3.84	4.89	6.00	7.12	8.27	9.43	10.64	11.92	13.22	14.50	15.83	17.22	18.64	*	*	*	*	*
13550	4.34	5.42	6.58	7.76	8.97	10.16	11.42	12.72	14.04	15.42	16.75	18.17	19.63	21.09	*	*	*	*
14200	4.88	5.99	7.22	8.45	9.70	10.96	12.25	13.55	14.93	16.32	17.76	19.18	20.63	22.16	23.70	*	*	*
14850	5.49	6.65	7.88	9.18	10.51	11.80	13.11	14.45	15.86	17.31	18.75	20.28	21.78	23.31	24.86	26.47	*	*
15500	6.12	7.33	8.61	9.95	11.31	12.67	14.06	15.42	16.82	18.33	19.83	21.36	22.92	24.50	26.10	27.71	31.01	*
16150	6.83	8.08	9.38	10.77	12.20	13.63	15.04	16.47	17.94	19.39	20.95	22.54	24.16	25.74	27.39	29.05	32.39	35.93
16800	7.58	8.86	10.23	11.66	13.12	14.61	16.08	17.56	19.05	20.57	22.16	23.76	25.37	27.07	28.71	30.43	33.86	37.46
17450	8.39	9.72	11.10	12.60	14.10	15.62	17.20	18.71	20.26	21.79	23.40	25.01	26.69	28.44	30.14	31.85	35.39	38.97
18100	9.26	10.64	12.04	13.59	15.12	16.71	18.30	19.90	21.51	23.11	24.73	26.37	28.11	29.86	31.62	33.38	37.03	40.72
18750	10.19	11.61	13.09	14.64	16.24	17.85	19.51	21.19	22.82	24.48	26.16	27.80	29.51	31.33	33.14	34.96	38.65	42.44
19400	11.18	12.68	14.16	15.73	17.41	9.05	20.78	22.49	24.18	25.90	27.59	29.35	31.06	32.84	34.71	36.59	40.39	44.22
20050	12.26	13.77	15.32	16.93	18.64	20.35	22.10	23.88	25.64	27.38	29.13	30.96	32.73	34.50	36.33	38.26	42.18	46.12
20700	13.38	14.96	16.55	18.18	19.92	21.70	23.47	25.26	27.13	28.97	30.79	32.62	34.45	36.28	38.18	39.99	44.03	48.08
21350	14.56	16.19	17.85	19.51	21.26	23.07	24.90	26.76	28.64	30.60	32.44	34.34	36.16	38.13	40.01	41.96	45.92	50.09
22000	15.85	17.52	19.21	20.89	22.72	24.54	26.45	28.39	30.27	32.23	34.15	36.12	38.08	39.96	41.98	43.91	47.95	52.15

Note :
1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-16. TYPE 15 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
6000	0.68	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
6800	0.82	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
7600	0.97	1.68	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
8400	1.16	1.90	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
9200	1.36	2.16	3.05	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
10000	1.59	2.46	3.38	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
10800	1.86	2.78	3.73	4.78	*	*	*	*	*	*	*	*	*	*	*	*	*	*
11600	2.16	3.15	4.16	5.24	*	*	*	*	*	*	*	*	*	*	*	*	*	*
12400	2.49	3.54	4.61	5.72	6.90	*	*	*	*	*	*	*	*	*	*	*	*	*
13200	2.88	3.96	5.10	6.26	7.47	8.79	*	*	*	*	*	*	*	*	*	*	*	*
14000	3.31	4.42	5.64	6.85	8.10	9.46	10.81	*	*	*	*	*	*	*	*	*	*	*
14800	3.79	4.94	6.21	7.48	8.77	10.15	11.57	13.04	*	*	*	*	*	*	*	*	*	*
15600	4.31	5.50	6.82	8.18	9.51	10.91	12.37	13.91	15.47	*	*	*	*	*	*	*	*	*
16400	4.89	6.10	7.48	8.89	10.30	11.76	13.25	14.81	16.39	*	*	*	*	*	*	*	*	*
17200	5.51	6.74	8.21	9.67	11.16	12.66	14.15	15.74	17.39	19.10	*	*	*	*	*	*	*	*
18000	6.20	7.48	8.95	10.50	12.07	13.60	15.17	16.80	18.49	20.21	21.98	23.79	*	*	*	*	*	*
18800	6.93	8.29	9.78	11.37	13.02	14.64	16.23	17.88	19.57	21.36	23.20	25.08	26.92	*	*	*	*	*
19600	7.74	9.13	10.65	12.29	13.98	15.68	17.39	19.06	20.84	22.62	24.46	26.41	28.32	30.24	*	*	*	*
20400	8.62	10.05	11.57	13.30	15.03	16.81	18.56	20.30	22.09	23.91	25.83	27.78	29.76	31.75	33.75	*	*	*
21200	9.56	11.05	12.59	14.37	16.14	17.97	19.83	21.65	23.45	25.35	27.20	29.20	31.24	33.30	35.37	37.52	*	*
22000	10.57	12.10	13.70	15.49	17.35	19.21	21.15	22.99	24.93	26.84	28.77	30.71	32.78	34.90	37.04	39.17	*	*
22800	11.64	13.22	14.86	16.68	18.56	20.51	22.51	24.46	26.41	28.39	30.39	32.40	34.42	36.55	38.75	40.95	45.51	*
23600	12.79	14.46	16.14	17.92	19.89	21.87	23.95	25.98	28.01	29.99	32.07	34.15	36.24	38.33	40.61	42.88	47.48	52.09
24400	14.01	15.72	17.44	19.23	21.29	23.34	25.45	27.52	29.68	31.74	33.81	35.97	38.13	40.29	42.43	44.78	49.51	54.24
25200	15.35	17.11	18.86	20.69	22.74	24.82	27.01	29.16	31.41	33.55	35.70	37.85	40.08	42.31	44.52	46.81	51.59	56.46
26000	16.73	18.53	20.36	22.21	24.27	26.43	28.64	30.87	33.13	35.43	37.65	39.88	42.10	44.40	46.69	48.94	53.73	58.73

Note :

1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-17. TYPE 16 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
8000	0.95	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
9000	1.14	1.99	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
10000	1.37	2.27	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
11000	1.62	2.58	3.64	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
12000	1.91	2.95	4.05	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
13000	2.23	3.35	4.50	5.75	*	*	*	*	*	*	*	*	*	*	*	*	*	*
14000	2.61	3.82	5.01	6.31	7.70	*	*	*	*	*	*	*	*	*	*	*	*	*
15000	3.03	4.29	5.58	6.93	8.37	*	*	*	*	*	*	*	*	*	*	*	*	*
16000	3.52	4.83	6.20	7.61	9.08	10.64	*	*	*	*	*	*	*	*	*	*	*	*
17000	4.06	5.42	6.89	8.37	9.87	11.47	13.14	*	*	*	*	*	*	*	*	*	*	*
18000	4.68	6.06	7.63	9.17	10.72	12.40	14.10	15.90	*	*	*	*	*	*	*	*	*	*
19000	5.33	6.78	8.39	10.02	11.67	13.33	15.16	16.99	18.84	*	*	*	*	*	*	*	*	*
20000	6.08	7.56	9.24	10.97	12.67	14.42	16.21	18.12	20.05	22.05	*	*	*	*	*	*	*	*
21000	6.89	8.39	10.14	11.95	13.77	15.57	17.39	19.30	21.32	23.40	25.47	*	*	*	*	*	*	*
22000	7.77	9.34	11.11	13.02	14.89	16.77	18.69	20.67	22.71	24.80	26.95	29.14	*	*	*	*	*	*
23000	8.73	10.37	12.17	14.10	16.13	18.10	20.05	22.06	24.12	26.26	28.49	30.76	33.06	*	*	*	*	*
24000	9.76	11.46	13.31	15.29	17.37	19.44	21.48	23.58	25.73	27.84	30.08	32.44	34.82	37.12	*	*	*	*
25000	10.87	12.64	14.47	16.61	18.73	20.88	23.04	25.16	27.33	29.53	31.83	34.18	36.64	39.02	41.51	*	*	*
26000	12.11	13.94	15.80	17.94	20.17	22.42	24.61	26.90	29.08	31.37	33.68	36.07	38.53	40.99	43.56	46.12	*	*
27000	13.40	15.28	17.24	19.41	21.68	23.95	26.36	28.63	30.99	33.29	35.69	38.11	40.47	43.13	45.67	48.31	53.66	*
28000	14.82	16.77	18.77	20.89	23.27	25.64	28.07	30.53	32.89	35.28	37.78	40.18	42.68	45.22	47.97	50.58	56.09	61.73
29000	16.29	18.34	20.39	22.51	24.93	27.41	29.95	32.43	34.97	37.35	39.94	42.44	45.03	47.60	50.21	53.03	58.59	64.25
30000	17.91	20.02	22.10	24.29	26.75	29.26	31.81	34.39	37.03	39.61	42.19	44.78	47.34	50.01	52.77	55.44	61.16	66.98
31000	19.58	21.79	23.98	26.20	28.66	31.19	33.85	36.53	39.24	41.95	44.52	47.20	49.86	52.61	55.34	58.15	63.95	69.79
32000	21.41	23.67	25.89	28.21	30.66	33.30	35.97	38.76	41.47	44.27	47.06	49.71	52.59	55.31	58.13	60.89	66.67	72.84

Note :
1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

TABLE B-18. TYPE 17 FAN CAPACITY TABLE

S.P.	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	9.0	10.0
CFM	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP	BHP
10000	1.19	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
11250	1.45	2.50	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
12500	1.74	2.86	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
13750	2.07	3.25	4.55	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
15000	2.44	3.71	5.08	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
16250	2.87	4.25	5.68	7.25	*	*	*	*	*	*	*	*	*	*	*	*	*	*
17500	3.35	4.83	6.35	7.97	9.67	*	*	*	*	*	*	*	*	*	*	*	*	*
18750	3.91	5.47	7.07	8.72	10.50	12.37	*	*	*	*	*	*	*	*	*	*	*	*
20000	4.55	6.17	7.88	9.61	11.42	13.40	*	*	*	*	*	*	*	*	*	*	*	*
21250	5.25	6.92	8.75	10.60	12.46	14.48	16.53	*	*	*	*	*	*	*	*	*	*	*
22500	6.02	7.77	9.71	11.61	13.58	15.62	17.77	19.97	*	*	*	*	*	*	*	*	*	*
23750	6.91	8.70	10.72	12.73	14.76	16.86	19.07	21.37	23.68	*	*	*	*	*	*	*	*	*
25000	7.84	9.69	11.80	13.96	16.08	18.22	20.46	22.84	25.26	27.65	*	*	*	*	*	*	*	*
26250	8.90	10.75	12.95	15.18	17.47	19.73	22.01	24.36	26.90	29.39	31.94	*	*	*	*	*	*	*
27500	10.05	11.99	14.24	16.54	18.94	21.33	23.63	26.10	28.61	31.21	33.85	36.54	*	*	*	*	*	*
28750	11.30	13.31	15.55	17.97	20.45	22.92	25.43	27.92	30.46	33.09	35.84	38.63	41.44	44.39	*	*	*	*
30000	12.65	14.79	17.00	19.57	22.10	24.77	27.31	29.82	32.48	35.17	37.91	40.80	43.72	46.63	49.68	*	*	*
31250	14.10	16.32	18.55	21.18	23.83	26.58	29.29	31.91	34.69	37.38	40.21	43.05	46.07	49.09	52.10	55.23	*	*
32500	15.73	18.02	20.32	22.96	25.66	28.54	31.36	34.10	36.88	39.69	42.63	45.44	48.51	51.64	54.75	57.99	64.34	*
33750	17.40	19.76	22.19	24.84	27.68	30.49	33.46	36.39	39.29	42.21	45.14	48.06	51.10	54.26	57.48	60.83	67.39	*
35000	19.20	21.69	24.17	26.82	29.70	32.75	35.74	38.77	41.80	44.71	47.75	50.78	53.94	57.06	60.30	63.76	70.53	77.40
36250	21.20	23.75	26.27	28.91	31.92	35.00	38.12	41.28	44.42	47.44	50.61	53.76	56.87	60.11	63.29	66.78	73.76	80.84
37500	23.24	25.85	28.49	31.27	34.26	37.36	40.61	43.77	47.06	50.29	53.57	56.68	60.08	63.26	66.55	69.96	77.09	84.17
38750	25.51	28.16	30.94	33.75	36.71	39.95	43.21	46.49	49.91	53.24	56.50	59.88	63.23	66.52	69.93	73.45	80.51	87.81
40000	27.91	30.61	33.42	36.36	39.28	42.65	45.92	49.32	52.88	56.26	59.69	63.20	66.66	70.07	73.60	77.05	84.26	91.54

Note :
1. S.P. (Static Pressure; in-H_2O)
2. BHP does not include drive losses
3. * : Unstable Operating Range

APPENDIX C

REFERENCES FOR COMPOUND PROPERTY DATA

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APPENDIX D

ASDC PROGRAM

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