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**LA THÈSE A ÉTÉ
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AIR STRIPPING MASS TRANSFER CORRELATIONS
FOR VOLATILE ORGANICS

by

Philippe Lamarche

A thesis
submitted under the supervision of
Dr. Ronald L. Droste

presented to the University of Ottawa
in partial fulfillment of the
requirements for the degree of
Master of Applied Science
in
Civil Engineering

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April, 1986

Philippe Lamarche, Ottawa, Canada, 1986.

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0 Philippe Lamarche

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ABSTRACT

It was discovered a few years ago that groundwater under a Gloucester landfill site, near Ottawa, Ontario, was contaminated with organic chemicals, many of which were known to be toxic. As the contaminated groundwater was moving towards water supply wells, methods of treatment had to be considered.

In recent years, many studies on the treatment by packed column air stripping of water contaminated with volatile organics were carried out. In most cases, the single phase resistance model of Sherwood and Holloway (1940) was used to predict mass transfer rate constants. A study by Roberts et al. (1982), however, showed that a two phase resistance model such as the model of Onda et al. (1968) may be more appropriate for air stripping of organics.

The study of Roberts et al. was carried out using one type of packing only. Experiments were undertaken using three other packing types and sizes, to verify the results of Roberts et al. (1982). For each packing type, experiments were carried out at three liquid and gas flow rates, and at three or four packing depths. Six volatile organic chemicals found in the Gloucester contaminated groundwater were stripped.

As the Henry's law constants were not available for all compounds at all experimental conditions, they were deter-

mined by a closed system method at two temperatures, and temperature correlations were developed.

For 12.7 mm Raschig rings, the experimental mass transfer rate constants, computed by a method presented by Kavanaugh and Trussell (1980), were compared to mass transfer rate constants predicted by the models of Onda et al. (1968), Sherwood and Holloway (1940), and Shulman et al. (1955c). The model of Onda et al. (1968) yielded better estimates than the other two models.

Experimental mass transfer rate constants were also compared to Onda's estimates for 12.7 mm Intalox® saddles, a packing for which Onda's model was not initially derived; again, the estimates were good.

It was concluded that the model of Onda et al. yielded better estimates of mass transfer rate constants than the other two models considered. The estimates of Sherwood and Holloway's model for the most volatile compounds were reasonable.

The present work also showed that empty column tests should be performed to evaluate end effects (removal above and below the packing). The end effects obtained by extrapolation of mass transfer data obtained at various packing depths to a depth of zero were unreliable.

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GLOSSARY

- A cross sectional area of column (m^2)
- a specific interfacial area (m^2/m^3)
- a_t total specific surface area of packing (m^2/m^3)
- a_w wetted specific surface area of packing (m^2/m^3)
- B_{ij} empirical coefficient relevant to a system comprised of components i and j
- B_0 constant, in H vs T correlation
- B_1 constant, in H vs T correlation ($^{\circ}K$)
- B_2 constant, in H vs T (and C) correlation
- B_3 compound dependent constant in NTUC vs Q_L equation (dimensionless)
- B_4 compound dependent constant in NTUC vs Q_L equation (s/m^3)
- B_5 compound dependent constant in NTUC vs Q_L equation (s^2/m^4)
- b_0 constant, in H vs T_A correlation
- b_1 constant, in H vs T_A correlation ($^{\circ}K$)
- C_E solute mass concentration in effluent liquid (kg/m^3 ; $\mu g/l$)
- C_F packing pressure drop factor (dimensionless)
- C_{EG} solute mass concentration in effluent gas (kg/m^3)
- C_{EI} solute mass concentration in influent gas (kg/m^3)
- C_E
- C_m gas phase mass concentration in equilibrium with the liquid phase concentration (kg/m^3)
- C_m
- C_{om} gas phase molar concentration in equilibrium with the liquid phase concentration ($kmole/m^3$)
- C_I solute mass concentration in influent liquid (kg/m^3 ; $\mu g/l$)
- C_L average mass concentration in the liquid phase (kg/m^3)
- C_{LM} average molar concentration in the liquid phase ($kmole/m^3$)
- C_{Lu} mass concentration in the liquid phase, after u equilibrations (kg/m^3)
- C_{Lo} average mass concentration in the liquid phase, at time $t = 0$ (kg/m^3)
- C_{L1} mass concentration after one day, accounting for possible losses (kg/m^3)
- C_L
- C_L liquid phase mass concentration in equilibrium with the gas phase concentration (kg/m^3)
- C_L
- C_{LM} liquid phase molar concentration in equilibrium with the gas phase concentration ($kmole/m^3$)
- C_{om} molar density of pure water ($kmole/m^3$)
- C_{om} solubility of the solute in the liquid phase ($mole/m^3$)

- D_G molecular diffusion coefficient of compound in gas (air; m^2/s)
 D_L molecular diffusion coefficient of compound in liquid (water; m^2/s)
 d empirical parameter in Shulman et al.'s model for interfacial area
 d_p nominal packing size (m)
 d_s diameter of a sphere having the same surface area as a unit of packing (m)
- Fr Froude number (dimensionless)
 f fugacity of solute (atm)
- G gas mass flux ($kg/m^2 \cdot s$)
 G_m molar flux of gas ($kmole/m^2 \cdot s$)
 g gravitational acceleration constant ($9.81 m/s^2$)
- H Henry's law constant (mass concentration/mass concentration)
 H_a Henry's law constant (atm)
 H_b Henry's law constant ($atm \cdot m^3/mole$)
 H_m Henry's law constant (mole fraction/mole fraction)
 H_{ij} Henry's law constant of component i of solution in solvent j (mass concentration/mass concentration)
 H_{im} Henry's law constant of component i of solution in a mixture of two solvents (mass concentration/mass concentration)
- HTU height of a transfer unit (m)
 h empirical parameter in Shulman et al.'s model for interfacial area
- i intercept, in the equation of the line of best fit
- J rate of mass transfer per unit volume of packing ($kmole/s$)
- K constant in H vs T correlation
 K_a ratio of activities of species (equilibrium constant)
 K_G overall mass transfer coefficient based on the gas phase driving force (m/s)
 K_L overall mass transfer coefficient, based on the liquid phase driving force (m/s)
 K_{La} overall transfer rate constant based on the liquid phase driving force (s^{-1})
 k_G gas phase mass transfer coefficient (m/s)
 k_{Ga} gas phase transfer rate constant (s^{-1})
 k_{om} gas phase mass transfer coefficient ($kmole/s \cdot m^2 \cdot atm$)
 k_L liquid phase mass transfer coefficient (m/s)
 k_{La} liquid phase transfer rate constant (s^{-1})
- L liquid mass flux ($kg/m^2 \cdot s$)
 L_m molar flux of liquid ($kmole/m^2 \cdot s$)

M_A	molar weight of air (28.97 g/mole)
M_G	gas phase molar weight (kg/mole)
M_L	liquid phase molar weight (kg/mole)
M_O	molar weight of solute (g/mole)
M_R	molar weight ratio (mole/g)
N	number of observations
NTU	number of transfer units (dimensionless)
$NTUC$	number of transfer units equivalent to end effects (dimensionless)
$NTUN$	net number of transfer units, representing removal in the packing only (dimensionless)
$NTUT$	total number of transfer units (dimensionless)
n	empirical packing parameter in Sherwood and Holloway's model
P	power input (W)
p_D	barometric (ambient) pressure (mm Hg)
p_F	total rotameter's inlet pressure (mm Hg)
p_F	partial pressure of contaminant (atm)
p_{RA}	gauge pressure at rotameter's inlet (mm Hg)
p_T	ambient pressure (atm)
p_v	vapour pressure of contaminant (atm)
Q_G	gas volumetric flow rate (m^3/s)
Q_{GC}	gas volumetric flow rate at standard temperature and pressure (m^3/s)
Q_{GR}	gas volumetric flow rate read from rotameter conversion chart (m^3/s)
Q_L	liquid volumetric flow rate (m^3/s)
q	empirical parameter in Shulman et al.'s model for interfacial area
R	universal gas constant (1.987 kcal/kmole-°K; 0.082057 l-atm/moles-°K)
Re	Reynolds number (dimensionless)
R_G	gas phase resistance to mass transfer (s)
R_L	liquid phase resistance to mass transfer (s)
R_T	total (overall) resistance to mass transfer (s)
r^2	coefficient of determination (dimensionless)
res	residual
S	stripping factor (dimensionless)
Sc	Schmidt number (dimensionless)
Sh	Sherwood number (dimensionless)
S_w	standard deviation of a set of variables w
$\bar{S}_y$	variance of the mean estimated value of y
$\bar{S}_{yw}$	variance of y , estimated by the regression line
SEE	standard error of estimate (dimensionless)
s	slope, in the equation of the line of best fit

T temperature ($^{\circ}\text{C}$)
 T_A absolute temperature ($^{\circ}\text{K}$)
 T_{CR} compressed air absolute temperature ($^{\circ}\text{R}$)
 T_K packed column room absolute temperature ($^{\circ}\text{K}$)
 t Student's t statistic
 t time (s)
 t₀ initial time (s)
 u number of equilibrations (in multiple equilibrations technique)
 V_A molar volume of air (20.1 cm³/mole)
 V_D molar volume of solute, estimated by (LeBas incremental method (cm³/mole)
 V_C empty bed volume (m³)
 V_G gas volume (m³)
 V_L liquid volume (m³)
 V_O molar volume of solute, estimated by the incremental method used by Fuller, Schettler, and Giddings (cm³/mole)
 V_w coefficient of variation of a set of variables w
 We Weber number (dimensionless)
 w independent variable
 $\bar{w}$ average of a set of variables w
 Y_E mole fraction of solute in effluent liquid (mole/mole)
 Y_D mole fraction of contaminant in the gas phase (mole/mole)
 Y_{OE} mole fraction of solute in effluent gas (mole/mole)
 Y_{OI} mole fraction of solute in influent gas (mole/mole)
 Y_O^E mole fraction of contaminant in the gas phase, in equilibrium with the liquid phase (mole/mole)
 Y_I mole fraction of solute in influent liquid (mole/mole)
 Y_i mole fraction of component i of solution in the liquid phase (mole/mole)
 Y_L mole fraction of contaminant in the liquid phase (mole/mole)
 Y_L^E mole fraction of contaminant in the liquid phase, in equilibrium with the gas phase (mole/mole)
 Y_B solubility of the solute in the liquid phase, expressed as mole fraction (mole/mole)
 y dependent variable
 Z packing depth (m)
 Z_{HO} rotameter's manometer liquid level, low pressure side (mm H₂O)
 Z_{HL} column's manometer liquid level, low pressure side (mm)
 Z_{LO} rotameter's manometer liquid level, high pressure side (mm H₂O)

- Z_{LL} column's manometer liquid level, high pressure side (mm)
 Z_T total submergence of gas inlet (water depth; m)
 α empirical packing parameter in Sherwood and Holloway's model
 β constant in the total holdup equation
 γ activity coefficient of a solute
 $\gamma_{i,j}^\infty$ activity coefficient of component i in solvent j at infinite dilution
 ΔH° enthalpy change at standard state (kJ/kmole)
 Δp_g gas pressure drop in packing (N/m²)
 Δp_{gc} pressure drop correction for end effects (N/m²)
 Δp_{ot} total pressure drop in column (N/m²)
 ϵ operating porosity (volume of voids/total volume, dimensionless)
 ϵ_D dry packing porosity (dimensionless)
 θ_D superficial hydraulic residence time (s)
 μ_g gas (air) viscosity (kg/m-s)
 μ_L liquid (water) viscosity (kg/m-s)
 ρ_g gas density (kg/m³)
 ρ_L liquid density (kg/m³)
 ρ_M packed column manometer fluid density (kg/m³)
 σ_c critical surface tension of packing material (N/m)
 σ_L surface tension of liquid (N/m)
 Φ constant (diffused aeration H determination technique; m⁻¹)
 ϕ_t total holdup (volume of liquid in bed/total volume, dimensionless)
 Ψ_i ratio of transfer rate constant of compound i to that of oxygen (s/s)

Subscripts

- A based on total specific interfacial area
 A referring to system A
 $ass. S$ based on assumed S value
 $act. S$ based on actual S value
 B referring to system B
 D based on characteristic diameter
 G of gas
 i of compound i

L of liquid
O2 of oxygen
obsd observed
pred predicted
W based on wetted specific interfacial area

Abbreviations

PVC polyvinyl chloride
TCE trichloroethylene
UHP ultra-high purity
1,1-DCA 1,1-dichloroethane
1,2-DCA 1,2-dichloroethane

Acronyms

AWWA American Water Works Association
ESE Environmental Science and Engineering, Inc.
U.S. EPA U.S. Environmental Protection Agency

CHAPTER 1

INTRODUCTION

1.1 Organics in the Environment

Finding an uncontaminated water source is increasingly difficult in today's world. Wolman (1984) states that "pristine" sources of water no longer exist. There is concern with the apparent accumulation of hydrocarbons, nitrates, heavy metals, and toxic organics in groundwater (Jackson, 1983). A similar situation can be observed for surface waters.

Of these contaminants, the organics are of particular concern. Many organic species are not captured, even by advanced (tertiary level) treatment operations. The species that survive are generally highly volatile, low molecular weight, relatively non-polar organics (Al-Dhowalia, 1982). Due to the increasing water demand, water sources contaminated with organics must also be used; for example, recent surveys of water supply wells in Michigan, Minnesota, and Wisconsin, (U.S.) detected volatile organic chemicals in 4 to 8% of the sites (AWWA, 1985b). Wolman (1984) mentions that although the significance of the health effects of organics in water is still unknown, organics represent a threat to present and future populations. The U.S. Environ-

mental Protection Agency (U.S. EPA) recently published final and proposed recommended maximum contaminant levels, ranging from 0 to 2000 µg/l, for 8 volatile organic chemicals and 26 synthetic organic chemicals (AWWA, 1985a).

Air stripping is a promising method for removing volatile contaminants, such as volatile organics, from water (Roberts et al., 1982; Al-Dhowalia, 1982). Packed towers can be used to achieve air stripping at relatively low cost (Roberts et al., 1982).

1.2 Organics at Gloucester

A landfill site in Gloucester (near Ottawa, Ontario, Canada) was used in the 1960's and 1970's to dispose of hospital and laboratory wastes, among others. Studies carried out by the National Hydrology Research Institute (Environment Canada) identified plumes of organically contaminated groundwater from this site migrating slowly towards populated areas where wells are used as potable water sources (Jackson and Graham, 1983). These plumes contained chloroform and benzene in concentrations exceeding the proposed World Health Organization drinking water guidelines. Toluene, tetrahydrofuran, diethyl ether, dichloromethane, 1,1-dichloroethane, and many other chemicals were also identified (Jackson and Graham, 1983).

Since water supply wells were threatened, methods to contain and treat the groundwater had to be found. Packed column air stripping was one of the alternatives considered.

3

Roberts et al. (1982; 1985) studied packed column air stripping, concentrating particularly on verifying the accuracy of existing mass transfer rate constant correlations for air stripping of volatile organics, and on relating the organics mass transfer to the readily measurable oxygen transfer. The methods available to evaluate end effects (air stripping above and below the packing) in the packed column were also compared.

These studies were carried out with precision, but for only one packing material, namely 12.7 mm Berl saddles, and at loading rates different from typical full scale applications rates. It was thus felt that there was room for further studies.

1.3 Objectives

The objectives of this work were:

1. To verify the performance of the mass transfer rate constants correlation models of Onda et al. (1968), Sherwood and Holloway (1940), and Shulman et al. (1955b,c), for another packing material, namely 12.7 mm Raschig rings, at operating conditions typical of full scale applications, for air stripping of volatile organics covering a wide range of volatilities.
2. To verify the performance of the model of Onda et al. (1968) to predict mass transfer rate constants for a packing for which it was not initially derived, namely Intalox® saddles.

3. To verify the statement of Roberts et al. (1982; 1985)
that end effects must be determined by empty column tests
rather than extrapolation.

CHAPTER 2

LITERATURE REVIEW: PACKED COLUMN AIR STRIPPING

2.1 Organics Removal

2.1.1 Organics Removal Processes

Many sources of water are contaminated with various organic compounds, some of which are toxic (Al-Dhowalia, 1982). Literature currently refers to four categories of organics removal processes: carbon adsorption, chemical oxidation, reverse osmosis, and aeration (Al-Dhowalia, 1982).

Activated carbon adsorption was observed to be very effective in removing some low solubility, high molecular weight compounds of non-polar nature, but not so effective for some low molecular weight halogenated organics such as trihalomethanes (Al-Dhowalia, 1982). Studies in Miami showed that breakthrough of trihalomethanes and several other volatile organics in a 3.05 m (10 ft) deep bed occurred after 70 to 100 days; vinyl chloride broke through in 30 days (Singley et al., 1980).

Chemical oxidation is usually accomplished by addition of chlorine, chloramines, or ozone. Due to the doses commonly added in regular water treatment applications, chlorine usually causes formation of chlorinated organics. Chloramine addition has less potential for producing chlori-

nated organics. Ozone was shown not to oxidize organics completely to CO_2 and H_2O , but to produce alkanes, aldehydes, and some carcinogens (Al-Dhowalia, 1982).

Reverse osmosis was shown to be very effective in removing some categories of organics from water, but ineffective in removing polar compounds and low molecular weight organics such as trihalomethanes (Al-Dhowalia, 1982).

Trihalomethanes and many other organics with a boiling point under 200°C were removed very efficiently by air stripping (Al-Dhowalia, 1982). Some air stripping processes are discussed in the following section.

2.1.2 Selection of Air Stripping Process

Many aeration processes can be used for air stripping purposes. Based on removal efficiency data, Kavanaugh and Trussell (1981) developed a qualitative diagram showing the zones of economic feasibility for some of these processes. These zones were shown as a function of the degree of removal and Henry's law constant, H , the two main parameters controlling process selection (Kavanaugh and Trussell, 1981).

Fig. 2.1, adapted from their diagram, shows that for removals below 90%, spray towers, air diffusers, and mechanical aerators may be economically attractive. The spray towers are more advantageous at H values lower than 0.75 if energy requirements are the same for all processes. For removal levels above 90%, Kavanaugh and Trussell (1981) be-

Figure 2.1: Zones of economic feasibility of common air stripping processes

lieve that packed towers may be the only alternative, and Ball et al. (1984) say that they are often the most cost-effective process, but Roberts and Levy (1985) state that mechanical surface aeration could be competitive, especially if the aeration is achieved in multiple stages.

Roberts and Levy (1985) explain that mechanical surface aeration provides the contaminated water with a large air volume (the atmosphere) with which to equilibrate, allowing better removal than diffused aeration of compounds with moderately low H values. They believe that surface aeration is often ignored for air stripping because it is associated with diffused aeration which has similar cost characteristics for oxygen transfer. However, oxygen has a much higher H value (100 to 1000 times) than many common volatile organics and the comparison is not generally valid. For low H volatile organics, the small bubbles of diffused air may become saturated after rising only a few centimetres in the basin, not achieving any removal thereafter (Roberts and Levy, 1985). Diffused aeration is thus best suited for gas dissolution (Kavanaugh and Trussell, 1980), which is not necessarily the case for mechanical surface aeration.

For removal levels above 90% of compounds with very low H values, the high gas flows required for stripping cannot be handled by countercurrent, packed towers, and cross flow packed towers should be considered (Kavanaugh and Trussell, 1981).

In Fig. 2.1, the boundary between the zone where air stripping was considered feasible and the zone where it was not was established assuming a maximum height of transfer unit, HTU, of 1 m, and a maximum packed height, Z, of 10 m (Kavanaugh and Trussell, 1981). The ratio of gas to liquid volumetric flow rates, Q_G/Q_L , was assumed to be 100, a value believed to be in the range of practical feasibility (Ball et al., 1984). Eqs. (2.19), (2.21), and (2.22), developed later in this chapter, were used to compute the fractional removal, $100[1 - (C_x/C_i)]$ corresponding to each H value. An asymptote is seen at $H = 10^{-2}$, because at that point the stripping factor, S, has a value of 1 [Eqs. (2.19) and (2.21)]. This diagram, like that of Kavanaugh and Trussell (1981), is only qualitative.

In terms of capital costs, Singley et al. (1980) underline the advantages of the packed tower as being easier to build than the tray tower, requiring fewer packing supports and only a few liquid redistributors. Modification of the tower by changing the packing type or depth will also be easier than modification of spray or tray towers (Singley et al., 1980).

2.2 Theoretical Background for Air Stripping

2.2.1 Physical Chemistry of Aeration

Air stripping relies on the principle that molecules of dissolved gases can move freely between the gas and the liq-

uid phases until equilibrium is reached (Kavanaugh and Trussell, 1980).

For ideal solutions, this equilibrium would be expressed by Raoult's law (Kavanaugh and Trussell, 1980):

$$p_P = p_v Y_L \quad (2.1)$$

and Dalton's law (Kavanaugh and Trussell, 1980):

$$p_P = Y_G p_T \quad (2.2)$$

where p_P = partial pressure of contaminant (atm)
 p_T = ambient pressure (atm)
 p_v = vapour pressure of contaminant (atm)
 Y_G = mole fraction of contaminant in the gas phase (mole/mole)
 Y_L = mole fraction of contaminant in the liquid phase, in equilibrium with the gas phase (mole/mole)

However, most solutions encountered in water treatment do not show ideal behaviour. For very dilute non-ideal solutions, Henry's law applies (Kavanaugh and Trussell, 1980; Munz and Roberts, 1982):

$$p_P = H_A Y_L \quad (2.3)$$

where H_A = Henry's law constant (atm)

Henry's law constants are discussed in more detail in Chapter 3.

The amount of contaminant in the liquid and gas phases can be related by combining Eqs. (2.2) and (2.3) (Kavanaugh and Trussell, 1980):

$$Y_G = \frac{H_A}{p_T} Y_L \quad (2.4)$$

This equation shows that mass transfer from the liquid to the gas phase will be favoured by keeping the gas phase con-

centration of the contaminant as low as possible and that compounds with higher H (or H_A) values will be easier to remove from water, because their equilibrium gas phase concentration is higher (Kavanaugh and Trussell, 1980).

2.2.2 Two-Resistance Theory

The steady-state rate of mass transfer across a gas-liquid interface can be expressed, for a unit volume of packing, as (Kavanaugh and Trussell, 1980):

$$J = K_L a (C_{LM}^* - C_{LM}) \quad (2.5)$$

where a = specific interfacial area (m^2/m^3)
 C_{LM} = average molar concentration in the liquid phase ($kmole/m^3$)
 C_{LM}^* = liquid phase molar concentration in equilibrium with the gas phase concentration ($kmole/m^3$)
 J = rate of mass transfer per unit volume of packing ($kmole/s$)
 K_L = overall mass transfer coefficient, based on the liquid phase driving force (m/s)

Roberts and Levy (1985) point out that $K_L a$, the overall mass transfer rate constant, is in fact a first order rate constant.

The two-resistance, or two-film, theory is based on the assumption that overall resistance to mass transfer is the sum of a liquid phase and a gas phase resistance (Ball et al., 1984; Roberts et al., 1985; Roberts and Levy, 1985):

$$R_T = R_L + R_G \quad (2.6)$$

where R_G = gas phase resistance to mass transfer (s)
 R_L = liquid phase resistance to mass transfer (s)
 R_T = overall resistance to mass transfer (s)

If the resistances are defined as the reciprocals of their respective rate constants, and assuming that Henry's law applies (Roberts et al, 1985; Roberts and Levy, 1985):

$$\frac{1}{K_{La}} = \frac{1}{k_{La}} + \frac{1}{Hk_{Ga}} \quad (2.7)$$

where k_G = gas phase mass transfer coefficient (m/s)
 k_L = liquid phase mass transfer coefficient (m/s)

The corresponding transfer rate constants are k_{La} and k_{Ga} . If H_A (atm) is used instead of H , some authors (Kavanaugh and Trussell, 1980; 1981; Ball et al., 1984) use a different gas phase mass transfer coefficient, k_{Ga} (kmole/s·m²·atm). Then:

$$\frac{1}{K_{La}} = \frac{1}{k_{La}} + \frac{C_{Om}}{H_A k_{Ga}} \quad (2.8)$$

where C_{Om} = molar density of pure water (kmole/m³)

The contribution of the liquid phase resistance to the overall resistance can be found by rearranging the above equations, yielding (Kavanaugh and Trussell, 1981; Roberts et al., 1985; Roberts and Levy, 1985):

$$\frac{R_L}{R_T} = \frac{1}{1 + \frac{k_L}{k_{Ga}H}} \quad (2.9)$$

$$\frac{R_L}{R_T} = \frac{1}{1 + \frac{k_L C_{Om}}{k_{Ga}H_A}} \quad (2.10)$$

Similarly, the contribution of the gas phase resistance can be expressed as:

$$\frac{R_G}{R_T} = \frac{1}{\frac{Hk_G}{k_L} + 1} \quad (2.11)$$

$$\frac{R_G}{R_T} = \frac{1}{\frac{Hk_{Ga}}{C_o m k_L} + 1} \quad (2.12)$$

Thus, for very volatile compounds (high H or H_A value), in situations where the k_G/k_L ratio is large enough (high gas to liquid flow rate ratio), the gas phase resistance can be considered negligible (Kavanaugh and Trussell, 1980; Ball et al., 1984; Roberts and Levy, 1985). The value of k_L will then be insensitive to variations in the gas flow rate (Kavanaugh and Trussell, 1980). Gas phase resistance is more important for compounds with low H values (Kavanaugh and Trussell, 1980).

2.3 Design of Packed Columns

2.3.1 Stripping Packed Columns Design Equations

The countercurrent packed column air stripping process can be represented schematically as shown in Fig. 2.2. In that figure:

C_{Gx} = solute mass concentration in effluent gas (kg/m^3)
 C_{Gi} = solute mass concentration in influent gas (kg/m^3)
 Y_{Gx} = mole fraction of solute in effluent gas (mole/mole)

The other symbols are defined as they appear in the text. In a layer of packing of depth dZ , the rate of mass transfer

Figure 2.2: Process schematic of counter-current packed column

per unit volume of packing can be expressed as (Kavanaugh and Trussell, 1980):

$$J = \frac{\text{(amount removed)}}{\text{(time)(volume of packing)}} = \frac{d(Q_L C_{LM})}{AdZ} \quad (2.13)$$

where A = cross sectional area of column (m^2)
 Q_L = liquid volumetric flow rate (m^3/s)
 Z = packing material depth (m)

Kavanaugh and Trussell (1980) point out that changes in solution volume due to air stripping of the solute and evaporation of the solution are negligible, and that Q_L can thus be considered constant:

$$J = \frac{Q_L}{A} \times \frac{dC_{LM}}{dZ} \quad (2.14)$$

Combining Eqs. (2.14) and (2.5), and converting the volumetric flow rate to a molar flux and concentrations to mole fractions, yields the following differential equation, shown with the proper boundary conditions for integration over the total depth of the column (Kavanaugh and Trussell, 1980):

$$\int_0^Z dZ = \frac{L_M}{K_L a C_{OM}} \int_{Y_X}^{Y_\infty} \frac{dY_L}{Y_X (Y_L - Y_L)} \quad (2.15)$$

where L_M = molar flux of liquid ($kmole/m^2 \cdot s$)
 Y_∞ = mole fraction of contaminant in the effluent liquid (mole/mole)
 Y_X = mole fraction of contaminant in the influent liquid (mole/mole)
 Y_L = mole fraction of contaminant in the liquid phase (mole/mole)

The first term, $L_M/K_L a C_{OM}$, characterizes the efficiency of mass transfer from liquid to gas phase, and is called height of a transfer unit, HTU (Kavanaugh and Trussell,

1980). It has the units of length (m), and can be expressed in terms of mass flux of liquid, as (Roberts et al., 1985):

$$HTU = \frac{L}{\rho_L K_L a} \quad (2.16)$$

where L = liquid mass flux ($\text{kg/m}^2\cdot\text{s}$)
 ρ_L = liquid density (kg/m^3)

The integral term is called number of transfer units, NTU (dimensionless), and characterizes the difficulty in removing the solute from the liquid phase (Kavanaugh and Trussell, 1980). It corresponds to Eq. 8.40 of Treybal (1980, p. 308) in which the term $(1/2)\ln[(1-Y_w)/(1-Y_x)]$ is negligible for dilute solutions. For dilute solutions, a mass balance around the bottom of the column yields (Kavanaugh and Trussell, 1980):

$$Y_w = \frac{L_M}{G_M} (Y_L - Y_w) + Y_{w,i} \quad (2.17)$$

where G_M = molar flux of gas ($\text{kmole/m}^2\cdot\text{s}$)
 $Y_{w,i}$ = mole fraction of contaminant in the influent gas (mole/mole)

Combining Eqs. (2.17) and (2.4) and assuming that the influent gas does not contain any of the contaminants, that is $Y_{w,i} = 0$ (Kavanaugh and Trussell, 1980; Roberts et al., 1985), yields (Kavanaugh and Trussell, 1980):

$$NTU = \left[\frac{S}{S-1} \right] \ln \left\{ \frac{\frac{Y_x}{Y_w} (S-1) + 1}{S} \right\} \quad (2.18)$$

or (Roberts et al., 1985):

$$NTU = \left[\frac{S}{S-1} \right] \ln \left\{ \frac{\frac{C_x}{C_e} (S-1) + 1}{S} \right\} \quad (2.19)$$

where C_e = solute mass concentration in effluent liquid (kg/m^3)

C_x = solute mass concentration in influent liquid (kg/m^3)

S = stripping factor (dimensionless)

The two forms of expressing NTU are equivalent, and the stripping factor can be expressed in two equivalent forms (Kavanaugh and Trussell, 1980):

$$S = \frac{H_A}{P_T} \times \frac{G_M}{L_M} \quad (2.20)$$

or (Roberts et al., 1985):

$$S = H \times \frac{Q_G}{Q_L} \quad (2.21)$$

where Q_G = gas volumetric flow rate (m^3/s)

The integrated form of Eq. (2.15) is thus (Kavanaugh and Trussell, 1980; Roberts et al., 1985):

$$Z = (HTU) (NTU) \quad (2.22)$$

2.3.2 Packed Columns Design Procedure

Ball et al. (1984) and Kavanaugh and Trussell (1981) suggest design procedures that are very similar. Other authors, approaching the problem in different ways, obtained design equations different from those discussed previously, and the resultant design procedures are also different (e.g., Singley et al., 1980). Table 2.1 shows the procedure of Ball et al. (1984), modified slightly.

Most design procedures require information on Henry's law constants, air pressure drop, and mass transfer coefficients. Henry's law constants are discussed in Chapter 3; the following sections will deal with the two other parameters.

Table 2.1: Suggested Design Procedure

Select	Obtain from literature or pilot studies	Compute
1. S (or $\frac{Q_G}{Q_L}$)	H at design T^*	$\frac{Q_G}{Q_L}$ from Eq. (2.21)
2.	ρ_G^{**} and ρ_L at design T	$\frac{G^{***} Q_G \rho_G}{L Q_L \rho_L}$
3. Δp_G	Curve of Δp_G as a function of G and L	G from curve $L = G/(G/L)$
4.	K_{La} for given Q_G and Q_L	HTU from Eq. (2.16)
5.	C_i and desired C_e	NTU from Eq. (2.19)
6.		Z from Eq. (2.22)
7.	Q_L	$A = \frac{Q_L \rho_L}{L}$

* T = temperature ($^{\circ}\text{C}$)

** ρ_G = gas density (kg/m^3)

*** G = gas mass flux ($\text{kg}/\text{m}^2\text{-s}$)

Δp_G = gas pressure drop in packing (N/m^2)

2.4 Gas Pressure Drop

The gas pressure drop allowed in a column will affect the operation costs by directly influencing the energy re-

quirement of the air blower (Ball et al., 1984; Roberts and Levy, 1985). Careful selection is a must.

In a packed tower, increasing the liquid loading rate at constant gas rate will eventually lead to a situation where liquid fills up the column; similarly, increasing the gas loading rate at constant liquid rate will promote entrainment of the liquid upwards by the gas. In both cases, the gas pressure drop will increase very rapidly. When this happens, the tower is "flooded" (Al-Dhowalia, 1982; Kavanaugh and Trussell, 1981; Treybal, 1980).

Packed columns are usually designed to operate below flooding conditions (Kavanaugh and Trussell, 1981; Treybal, 1980, p. 194) and Treybal (1980, p. 195) states that strippers usually operate at gas pressure drops of 200 to 400 N/m² per metre of packing. Kavanaugh and Trussell (1981), however, suggest that lower pressure drops may be more cost-effective for stripping of volatile organic chemicals with high H values (over 0.075), while Roberts et al. (1982) state that economical design usually corresponds to operation near or in the loading zone (zone in which the rate of increase of the pressure drop as liquid or gas flow rates are increased is higher than the rate of increase of the pressure drop at lower flows; see Fig. 2.3).

For design, information relating pressure drop to gas and liquid loading rates can be obtained from manufacturers for specific packings, or from generalized correlations between the gas pressure drop, gas loading rate, and gas to

Figure 2.3: Typical gas pressure drop in countercurrent packed column operation (Treybal, 1980)

liquid ratio, such as Fig. 6.34 of Treybal (1980, p. 195). Fig. 2.4 is a reproduction of Treybal's graph showing the operating conditions used in this study. Kavanaugh and Trussell (1980; 1981) warn that tower efficiency is reduced when the abscissa value of the generalized correlation rises above 4 (liquid loading too high; unstable hydrodynamic behaviour) or drops below 0.02 (gas loading too high; liquid entrainment), and that pilot studies should then be conducted; additional packing depth may be needed to compensate for efficiency loss. Packing factors, C_F (dimensionless), used to compute the ordinate of the generalized correlation chart, can be obtained from manufacturers' handbooks (Perry et al., 1984; Table 18-5, p. 18-23), or from Table 6.3 of Treybal (1980).

2.5 Mass Transfer Coefficients

Mass transfer coefficients are needed to evaluate the HTU [Eq. (2.16)]. Conversely, they can be evaluated from pilot studies when all other parameters (Z , S , C_x , C_e , L) are known. Kavanaugh and Trussell (1980; 1981) recommend that K_{La} values be obtained from pilot studies, their value depending on many factors such as packing type, temperature, and liquid and gas flow rates, among others.

If K_{La} values for one packing are found, K_{La} for other packings may be obtained by multiplying these K_{La} values by the ratio of the relative K_{oa} values of the packings considered, these relative values being available from the litera-

Figure 2.4: Generalized gas pressure drop correlation (Treybal, 1980)

μ_L = liquid (water) viscosity (kg/m·s)

ture (Eckert, 1975; Kavanaugh and Trussell, 1980). However, this method relies on the assumption that liquid phase resistance dominates the mass transfer process, since then Eq. (2.7) becomes (Kavanaugh and Trussell, 1980):

$$\frac{1}{K_{La}} \approx \frac{1}{k_{La}} \quad (2.23)$$

and the equivalent equation for the overall mass transfer coefficient based on the gas phase driving force K_{Ga} (m/s), becomes:

$$\frac{1}{K_{Ga}} = \frac{H}{k_{La}} + \frac{1}{k_{Ga}} \approx \frac{H}{k_{La}} \quad (2.24)$$

Therefore,

$$K_{La} = HK_{Ga} \quad (2.25)$$

which allows Kavanaugh and Trussell (1980) to make the above statement. But liquid phase resistance may not always dominate in volatile organics air stripping, as discussed later (Section 2.11).

Another way to obtain mass transfer data for primary design estimates, or to extrapolate available mass transfer data to conditions other than those studied (including other packing types) is to use correlations (Ball et al., 1984; Kavanaugh and Trussell, 1980). The following sections will examine some possible correlation formulae.

2.6. Mass Transfer Correlations

2.6.1 Mass Transfer Rate Constant Models

Many correlations have been developed for gas and liquid phase mass transfer coefficients (k_G , k_L) and for specific interfacial areas (a) in countercurrent packed columns. Roberts et al. (1982) point out that finding one model suitable to all situations is a challenge, due to the variability of the nature of the liquid flow (e.g., thin films flowing on packing surfaces as opposed to drops sometimes formed at edges) and of the flow paths (e.g., channeling which is concentration of the liquid flow at the column walls while gas flows mainly in the center of the column) as packing size and type changes, and even within the same packing as flow rates are changed.

Sherwood and Holloway's (1940) correlation, probably the most widely used model for volatile organics air stripping, is one of many empirical, single phase resistance models developed (Roberts et al., 1985). It involves the assumption that the gas phase resistance is negligible compared to the liquid phase resistance. These models are of the general form (Roberts et al., 1982):

$$K_L a = (\text{constant}) L^{(\text{constant})} \quad (2.26)$$

Similar models were developed from volatile organics air stripping studies (Al-Dhowalia, 1982; Singley, 1990).

Other empirical models, such as those of Shulman et al. (1955c) and Onda et al. (1968), account for the contribution

of gas and liquid phase resistance to total mass transfer resistance. As for some single phase resistance models, correlations for k_o and k_L are sometimes expressed in terms of packing-related parameters and fluid properties (Roberts et al., 1985).

The literature provides many reviews of mass transfer correlations (Au-Yeung and Ponter, 1983; Perry et al., 1984). Besides their own work, Roberts et al. (1982; 1985) found that none of the models had been validated for trace volatile organics air stripping. Thus Roberts et al. (1982; 1985) compared the performance of three of the most widely accepted models when applied to volatile organics removal. The models they compared are presented in the following sections.

2.6.2 Sherwood and Holloway

According to Au-Yeung and Ponter (1983) this correlation, being well tested, remains the most useful to estimate the liquid film mass transfer rate constant for flow rates up to the loading point. It was developed from laboratory data on desorption of hydrogen, oxygen, and carbon dioxide from water in a countercurrent packed column at various temperatures, and liquid and gas loading rates (Sherwood and Holloway, 1940).

The gas phase mass transfer resistance was estimated by Sherwood and Holloway (1940) to be lower than one percent of the total resistance, which is understandable considering

the high volatility and relatively low solubility of the compounds studied. It was thus considered negligible as further shown by the constant k_{La} value observed by Sherwood and Holloway (1940) at different gas flow rates up to the loading point (beginning of the loading zone). The mass transfer data gathered for 76.2 mm (3 in.) spiral tiles, 9.5 mm ($3/8$ in.) to 50.8 mm (2 in.) ceramic Raschig rings, and 12.7 mm ($1/2$ in.) to 38.1 mm ($1\ 1/2$ in.) rough ceramic Berl saddles was correlated in terms of liquid phase properties only (Sherwood and Holloway, 1940).

Sherwood and Holloway (1940) point out that since the correlation is not dimensionally consistent, its constants need modification depending on the system of units used. The correlation formula is given in Table 2.2, with the constants (10.764 and 0.3048) necessary to convert from the original to SI units (Roberts et al., 1982; 1985). In this equation, the " α " and " n " values given by Sherwood and Holloway (1940) can be used directly. Other authors (Au-Yeung and Ponter, 1983) multiply α by $(10.764)(0.3048)^{1-n}$ and tabulate modified values of α for use in the original equation.

2.6.3 Shulman et al.

These correlations were first presented in a series of three papers (Shulman et al., 1955a; 1955b; 1955c) and sub-

Table 2.2: Mass transfer rate constant models

Model	Eq. No.	Flow rate Range (kg/m ² .s)	Ref.
<u>Sherwood and Holloway</u>			
$\frac{k_L a}{D_L} = 10.764 \alpha \left[\frac{0.3048 L}{\mu_L} \right]^{1-n} S_{CL}^{0.5}$	(2.27)	0.27 < L < 43 0.04 < G < 1.8	1
where			
$S_{CL} = \frac{\mu_L}{\rho_L D_L}$	(2.28)		
<u>Shulman et al.</u>			
$Sh_L = \frac{k_L d_o}{D_L} = 25.1 Re_{LD}^{0.45} S_{CL}^{0.5}$	(2.29)	0.27 < L < 43	1
$Sh_o = \frac{k_o d_o}{D_o} = 1.195 (1-\epsilon)^{0.34} Re_{oo}^{0.44} \times S_{Co}^{0.33}$	(2.30)	0.14 < G < 1.4	1
$a = d \left[\frac{8086}{\epsilon_o \gamma_o} \right] \frac{1}{\rho_o} L^n$	(2.31)	0.68 < L < 6.1	2
$\epsilon = \epsilon_o - \epsilon_t$	(2.32)		2
$\epsilon_t = \frac{(2.09 \times 10^{-4}) (737.5 L)^n}{d_o^2}$	(2.33)		2
where			
$Re_{LD} = \frac{d_o L}{\mu_L}$	(2.34)		
$Re_{oo} = \frac{d_o G}{\mu_o}$	(2.35)		

Table 2.2: (continued)

Model	Eq. No.	Flow rate Range (kg/m ² .s)	Ref.
$Sc_o = \frac{\mu_o}{\rho_o D_o}$	(2.36)		
$\beta = 1.508 d_s^{0.374}$	(2.37)		2
<u>Onda et al.</u>			
$k_L \left[\frac{\rho_L}{\mu_L g} \right]^{1/3} = 0.0051 Re_{LW}^{2/3} Sc_L^{-0.5} \times (a_t d_p)^{0.4}$	(2.38)	0.8 < L < 43	1
$\frac{k_o}{a_t D_o} = 5.23 Re_{oA}^{0.7} Sc_o^{1/3} (a_t d_p)^{-2}$	(2.39)	0.014 < G < 1.7	1
$\frac{a_w}{a_t} = 1 - \exp \left\{ -1.45 \left[\frac{\sigma_c}{\sigma_L} \right]^{0.75} Re_{LA}^{0.1} \times Fr_L^{-0.05} We_L^{0.2} \right\}$	(2.40)		1
where			
$Fr_L = \frac{L^2 a_t}{\rho_L g}$	(2.41)		
$Re_{oA} = \frac{G}{a_t \mu_o}$	(2.42)		
$Re_{LA} = \frac{L}{a_t \mu_L}$	(2.43)		
$We_L = \frac{L^2}{\rho_L \sigma_L a_t}$	(2.44)		

Table 2.2: (continued)

Model	Eq. No.	Flow rate Range (kg/m ² .s)	Ref.
$Re_{LW} = \frac{L}{a_w \mu_L}$	(2.45)		

* 1. Roberts et al. (1985); 2. Treybal (1980)

Table 2.2 Glossary

- a_t = total specific surface area of packing (m²/m³)
 a_w = wetted specific surface area of packing (m²/m³)
 D_g = molecular diffusion coefficient of compound in gas (m²/s)
 D_L = molecular diffusion coefficient of compound in liquid (m²/s)
 d = empirical parameter in Shulman et al.'s model
 d_p = nominal packing size (m)
 d_o = diameter of a sphere having the same surface area as a unit of packing (m)
 Fr = Froude number (dimensionless)
 g = gravitational acceleration constant (9.81 m/s²)
 h = empirical parameter in Shulman et al.'s model
 n = empirical packing parameter in Sherwood and Holloway's model
 q = empirical parameter in Shulman et al.'s model
 Re = Reynolds number (dimensionless)
 Sc = Schmidt number (dimensionless)
 Sh = Sherwood number (dimensionless)
 We = Weber number (dimensionless)
 α = empirical packing parameter in Sherwood and Holloway's model
 β = constant in the total holdup equation
 ϵ = porosity (volume of voids/total volume, dimensionless)
 ϵ_o = dry packing porosity (dimensionless)
 μ_g = gas viscosity (kg/m.s)
 σ_c = critical surface tension of packing material (N/m)
 σ_L = surface tension of liquid (N/m)
 ϕ_t = total holdup (volume of liquid/total volume, dimensionless)

Subscripts:

- A = based on total specific interfacial area
 D = based on characteristic diameter
 G = of gas
 L = of liquid
 W = based on wetted specific interfacial area

sequently improved (Shulman and Delaney, 1959; Shulman et al., 1963). Treybal (1980) also presents the model.

From vaporization of naphthalene packing, gas phase mass transfer coefficient values were obtained; these were used to compute gas and liquid phase mass transfer coefficients (k_G , k_L) and specific interfacial area (a) values from literature mass transfer rate constant (k_{Ga} , k_{La}) data, and to correlate k_G and k_L to fluid and packing properties (Shulman et al., 1955c). The resulting equations are presented in Table 2.2. The k_L equation is that found by Shulman et al. (1955c), while the k_G equation is a modified version given by Roberts et al. (1985), who rearranged the terms and neglected the solute concentration in the gas phase (equivalent to assuming that the stripping gas was uncontaminated). The model, derived for 12.7 mm (1/2 in.) to 38.1 mm (1 1/2 in.) Raschig rings and 12.7 mm and 25.4 mm (1 in.) Berl saddles, was found to apply to 50.8 mm (2 in.) Raschig rings and 38.1 mm (1 1/2 in.) Berl saddles (Shulman et al. 1955c).

Roberts et al. (1985) point out that a problem of this model is the cumbersome way in which the effective interfacial areas for absorption or desorption must be estimated through a series of graphs (Shulman et al., 1955c). The correlation equation for effective interfacial areas given in Table 2.2 was presented by Treybal (1980) and is said to represent the graphs well. However, while the k_G and k_L correlations are dimensionless and can thus be used in any

consistent system of units (Roberts et al., 1982; 1985), the correlation equation for areas is to be used in SI units only (Treybal, 1980). The constants to be used in this equation can be found in Treybal (1980; Table 6.4, p. 205).

The porosity term, ϵ , in the gas phase equation can be obtained by subtracting the total holdup, Φ_t (total liquid volume in the packing during column operation; Shulman et al., 1955b) from the porosity of the dry packing, ϵ_0 (Shulman et al., 1955a). Equations for total and static holdup (liquid volume that does not drain from the packing when liquid supply to the column is discontinued; Shulman et al., 1955b) in ceramic rings and saddles were derived for totally wetted packing by Shulman et al. (1955b), and graphs to correct holdup values for departure from the viscosity, density, and surface tension of water at 20°C were prepared (Shulman et al., 1955a). The values of the constants in the holdup equations were modified by Treybal (1980) so that SI units could be used. Treybal (1980; Table 6.5, p. 206) also presents equations of correction factors, that correspond to the graphs mentioned above, for the operating holdup (the difference between static and total holdup). The total holdup equation in Table 2.2 is that given by Treybal (1980) for water at ordinary temperatures and ceramic Raschig rings.

Knowledge of the total and operating holdup and of the correction factors for liquid properties allows one to apply the correlations for vaporization as well as for absorption

(the ratio of effective interfacial areas for vaporization to area for absorption is proportional to the ratio of total to operating holdup), and for other systems than water at environmental temperatures (Shulman et al., 1955a; 1955b; 1963). The gas phase mass transfer coefficient correlation was also modified slightly for situations where the gas phase solute concentration is important (Shulman and Delaney, 1959).

2.6.4 Onda et al.

The starting point of this model is a correlation formula between wetted and total specific packing area. Onda et al. (1968) believe that this equation, given in Table 2.2, is accurate within 20% for Raschig rings, Berl saddles, spheres, and rods, made of ceramic, glass, polyvinylchloride (PVC), or coated with a paraffine film. Charpentier (1976) sees it as the most general interfacial area correlation for first approximation in design.

From this correlation, and laboratory and literature data on gas and liquid phase mass transfer rate constants (k_{Ga} , k_{La}), for packing 4 to 50 mm in size, correlations for k_G and k_L were developed (Onda et al., 1968). The k_L correlation (Table 2.2) was observed to be accurate within 20% for absorption and desorption with either water or an organic solvent as the liquid phase, as long as the surface tension of the liquid remained close to that of water (Onda et al., 1968). Dimensionless, it can be used in any consis-

tent system of units (Roberts et al., 1985). The k_{La} correlation presented in Table 2.2 is the SI version from Roberts et al. (1982; 1985). Onda et al. (1968) suggest that a value of 2.00 be substituted for the constant 5.23 if the equation is applied to packing smaller than 15 mm.

This model's main disadvantage is that it cannot be used reliably outside the range of operating variables for which it was obtained because it does not express the correct fundamental dependency of k_L on system properties and operating conditions (Au-Yeung and Ponter, 1983). It was shown by Shulman et al. (1955c; 1960) that wetted and effective interfacial areas are unrelated.

2.6.5 Field Tests of the Models

The validity of these models for estimations in full scale air stripping operations must still be shown (Roberts and Levy, 1985).

Umphres et al. (1983) correlated air stripping data for trihalomethanes and 25 mm polypropylene saddles using the model of Sherwood and Holloway, but their observed values were two times smaller than the values predicted by the model for ceramic saddles. Ball et al. (1984) were also able to correlate data using Sherwood and Holloway's model, but they had to modify the empirically determined packing parameters; and they did not find good agreement between observed and predicted values for bromoform, which has a low

Henry's law constant (the gas phase resistance may have been important in this case; Ball et al., 1984).

Roberts et al. (1985) report that Cummins and Westrick (1983) used Onda's model, but had to reduce Henry's law constant values by a factor of 3 to obtain good results.

Since these correlations would be more useful if they could be used without necessitating parameter adjustment for each new situation, Roberts et al. (1985) compared the 3 models mentioned above with their original empirical parameters, as described in following sections.

2.7 Selection of Parameters for Pilot Studies

The stripping factor, S , is probably the most important parameter to be selected. It can be seen as an "equilibrium capacity factor"; if $S > 1$, 100% removal is possible, but if $S < 1$, Eqs. (2.19) and (2.22) show that fractional removal will asymptotically tend towards S [Eq. (2.46)] as column depth Z tends towards infinity (Roberts et al., 1985; Roberts and Levy, 1985).

$$1 - \frac{C_E}{C_I} = 1 - \left[\frac{1}{(S - 1)} \left\{ S \exp \left[\frac{Z}{HTU} \frac{S - 1}{S} \right] - 1 \right\} \right]^{-1} \quad (2.46)$$

In selecting S values, it must be taken into account that for low S values, mass transfer rate constant (K_{La}) values computed from experimental data will be very sensitive to errors in S values, while at high S values, K_{La} will be almost independent of S (Ball et al., 1984; Roberts et al., 1985; Umphres et al., 1983). This is shown in Fig.

2.5, which is based on the following assumptions: liquid volumetric flux, $L/\rho_L = 0.01 \text{ m}^3/\text{m}^2\cdot\text{s}$; $Z = 1.0 \text{ m}$; and, 75% removal achieved.

Errors in K_{La} and S were defined as:

$$\% \text{ error in } S = \left[\frac{S_{\text{assumed}} - S_{\text{actual}}}{S_{\text{assumed}}} \right] 100 \quad (2.47)$$

$$\% \text{ error in } K_{La} = \left[\frac{K_{La(\text{ass. } S)} - K_{La(\text{act. } S)}}{K_{La(\text{ass. } S)}} \right] 100 \quad (2.48)$$

where $K_{La(\text{ass. } S)} = K_{La}$ computed from assumed S value

$K_{La(\text{act. } S)} = K_{La}$ computed from actual S value

Eqs. (2.16), (2.19) and (2.22) were rearranged to yield:

$$K_{La} = \frac{L}{\rho_L Z} \frac{S}{(S-1)} \ln \left\{ \frac{(C_x/C_e)(S-1) + 1}{S} \right\} \quad (2.49)$$

Roberts et al. (1985) also plotted the coefficient of variation (standard deviation divided by mean) for mass transfer rate constants (K_{La}) against S values (Roberts et al., 1985; Fig. 2). This coefficient of variation increased very rapidly as S values dropped below 0.8. Since Eq. (2.21) shows that S is directly proportional to Henry's law constant and gas to liquid ratio values, and since uncertainty surrounds H values at the present time (Chapter 3), a relatively high gas to liquid ratio (and high S values) should be aimed for (Ball et al., 1984).

According to Kavanaugh and Trussell (1980), optimum column designs are typically based on stripping factors between 1.2 and 5. A plot of NTU against S for various fractional removal values (Fig. 2.6) shows that little improve-

Figure 2.5: Dependence of mass transfer rate constants, K_La , on stripping factor, S

Figure 2.6: Dependence of required number of transfer units, NTU, on stripping factor, S, and degree of removal

ment can be made for $S > 3$, (Kavanaugh and Trussell, 1980; 1981). Thus S values between 2 and 5 are believed to provide the most economical design (Kavanaugh and Trussell, 1980; Roberts and Levy, 1985); values below 2 yield uneconomically large packed height (Z) values, while achieving S values above 5 may require a gas to liquid ratio too large to be economical (Roberts and Levy, 1985).

The packing depth, Z , should also be high enough, so that end effects (removal occurring above or below the packing; discussed in the following Section) can be accounted for (Roberts et al., 1985).

2.8 Isolation of End Effects

Volatile organics air stripping above and below the packing, in the column, can be accounted for in many ways. Roberts et al. (1985) measured removal in their column when it was empty (no packing section) for each set of experimental conditions (gas and liquid flow rates) and expressed the removal as a number of transfer units equivalent to end effects, NTUC (dimensionless). From the data gathered, two empirical correlations for NTUC were derived: one for the case of constant liquid flow rates, and one for the case of constant gas flow rates. A temperature correction term was included in the correlations (Roberts et al., 1982). The removal observed for each run of the packed column was expressed as the total number of transfer units, NTUT, and the

net number of transfer units, due to packed sections alone, was obtained as:

$$NTUN = NTUT - NTUC \quad (2.50)$$

Mass transfer rate constants in the packing were computed from NTUN.

Another way to account for end effects consists of running each set of conditions at many different packing depths, Z , and plotting the observed NTUT against Z (Ball et al., 1984; Roberts et al., 1985; Umphres et al., 1983). Then the assumption that mass transfer inside and outside of the packing are additive leads to the relationship:

$$NTUT = \frac{1}{HTU} Z + NTUC \quad (2.51)$$

in which:

$$NTUN = \frac{1}{HTU} Z \quad (2.52)$$

The intercept of the plot of Eq. (2.51) is NTUC, and the slope yields $1/HTU$.

The same principle was applied by Al-Dhowalia (1982), who plotted mass transfer rate constants, K_{La} , against $1/Z$. The intercept of the plot was the mass transfer rate constant corresponding to an infinite depth of packing, or the constant due to packing alone.

Roberts et al. (1985) applied both methods and obtained different results for compounds with relatively low Henry's law constant values (i.e., chloroform, tetrachloroethylene, trichloroethylene). They suggested as an explanation for

this difference that the flow conditions below the packing support plate were too different from plug flow counter-current conditions assumed to prevail in the packed sections for the NTU's to be additive. Roberts et al. (1985) did, however, point out that for the low H compounds, the stripping factor (S) value was very low (below 1) and NTU and K_{La} values were thus more sensitive to errors in H or S values (Section 2.7). They also observed, for low H compounds, a departure from linearity on the plot of NTUT against Z, while for compounds with higher H values, data points correlated very well with a straight line. They still assumed that the first method (measuring removal for an empty column) was a better way to account for end effects.

2.9 Effect of Flow Rates and Packing Height on Mass Transfer

The results of Roberts et al. (1985) showed that packed height, Z, had no effect on mass transfer rate constant, K_{La} , for compounds with high Henry's law constant, H, as would be expected from the available models. The decrease in K_{La} observed with increasing Z, for low H compounds, is believed to be due to the low values of S for these compounds (Roberts et al., 1985).

Roberts et al. (1985) also observed an increase in K_{La} for increasing liquid flow rate values, Q_L , as could be expected from the models, for most compounds except the two low H value compounds, for which the low S value was again implicated. This claim would be supported by the observa-

tions of Ball et al., (1984) who used higher S values and obtained increasing K_{La} values with increasing L values for two low H compounds, chloroform and trichloroethylene, mentioned above. Al-Dhowalia (1982) also observed an increase in K_{La} for increasing L up to a point, after which K_{La} started decreasing for increasing L, probably because liquid started filling gaps between the packing, reducing the effective interfacial area.

Finally, Roberts et al. (1985) found an increase in K_{La} with increasing gas flow rate, Q_g , for the compounds with low H values. The fact that the magnitude of the effect of Q_g on K_{La} was increasing as compound H value decreased suggests that gas phase resistance to mass transfer may have been the factor coming into play (Roberts et al., 1985; Section 2.2.2). Al-Dhowalia (1982) also observed an increase in K_{La} as the gas flow rate increased up to a certain value, after which K_{La} seemed to remain fairly constant. He attributed this variation of K_{La} to a variation in effective interfacial area, as was reported by Shulman et al. (1955c), without considering the possible role of gas phase resistance.

2.10 Comparison of Models

2.10.1 Parameters Used

Roberts et al. (1985) compared the three mass transfer rate constant (K_{La}) models mentioned in Section 2.6, to find out which model's predictions would be closer to the experi-

mentally determined K_{La} values. Parameters needed can be classified as: solute properties (molecular diffusion coefficients in liquid and gas, Henry's law constant); water and air properties (viscosity, density, surface tension of water); and packing properties (specific areas, characteristic lengths, packing factors) (Roberts and Levy, 1985).

Parameters from the first two categories will be affected to various extents by temperature, and since temperature varied slightly from one experimental run to the next, predicted values were computed for the appropriate experimental temperature by using the corresponding values of parameters as obtained from correlations or tables (Roberts et al., 1985). The variation of the molecular diffusion coefficients in liquids with temperature can be accounted for using the correlation of Wilke and Chang (1955) (Ball et al., 1984; Roberts and Levy, 1985), while Roberts and Levy (1985) used the method suggested by Hirschfelder et al. (1964) to estimate the molecular diffusion coefficient in gases.

Packing parameters can be found in textbooks (Treybal, 1980), handbooks (Perry et al., 1984), and the literature.

2.10.2 Performance of Models

Roberts et al. (1985) plotted, for each compound at each set of experimental conditions, K_{La} values on three different figures (one per model). Roberts et al. (1985) found that Onda's model appeared to be best, the points be-

ing more closely grouped near the line representing a perfect fit, while Shulman's model underpredicts the low K_La values and overpredicts the high ones; Sherwood and Holloway's model predicts the same K_La value for a whole range of observed values. The poor results of Sherwood and Holloway's model may be due to the fact that it neglects gas phase resistance (Roberts et al., 1985). However, results from the Shulman et al. model oppose the widely accepted view that Shulman's method of estimating interfacial area was intrinsically superior to Onda's assumption that interfacial and wetted packing area were proportional (Roberts et al., 1985).

The coefficient of determination, r^2 , and the standard error of estimate, SEE, were used to quantify the goodness of fit. Roberts et al. (1985) state that:

$$SEE = \left[\frac{\sum [\log(K_La)_{pred} - \log(K_La)_{obsd}]^2}{N} \right]^{1/2} \quad (2.53)$$

where N = number of observations

obsd, pred = refer to observed and predicted values, respectively

Again, Onda's model performed best, having the highest r^2 and the lowest SEE; Sherwood and Holloway's model had a lower r^2 but much lower SEE value than Shulman's model, and would thus fit most of the data better (Roberts et al., 1985).

Roberts et al. (1985) also compared the response of observed and predicted values to changes in the gas and liquid flow rates. Onda's model predictions always were close to

observed values, and, as could be expected, Sherwood and Holloway's model predictions were also good for the compounds with high Henry's law constant values (gas phase resistance thus negligible) (Roberts et al., 1985). The agreement of observed and predicted values was deemed remarkable by Roberts et al. (1982) in view of the fact that gas flow rates used in their studies were less than 1/2 to 1/16 of the minimum flows used in developing the correlations.

In spite of the general agreement, some exceptions were observed, such as the decrease of mass transfer coefficients, K_La , for chloroform and trichloroethylene as packing height increased, or their failure to increase with increasing liquid flow rates (Roberts et al., 1982). Roberts et al. (1982) attributed this to deviations of the physical flow conditions from the ideal plug flow assumption made in the considered models, but concluded that in view of the good results obtained the additional computational effort involved in using models that would account for dispersion was not worthwhile.

Finally, at each set of conditions investigated, the R_L/R_0 value computed from Onda's model, and the ratio of observed mass transfer rate constants for each compound to the mass transfer rate constant of oxygen, Ψ_1 , was plotted against R_L/R_0 (Roberts et al., 1985):

$$\Psi_i = \frac{(K_L a)_i}{(K_L a)_{O_2}} \quad (2.54)$$

where i, O₂ = refer to compound i and oxygen, respectively

The ratio Ψ_i predicted by Onda's model was also computed from the formula (Roberts et al., 1985):

$$\Psi_i = \left[\frac{(D_L)_i}{(D_L)_{O_2}} \right]^{0.5} \left[\frac{R_L/R_O}{1 + R_L/R_O} \right] \quad (2.55)$$

This equation can be obtained from Eqs. (2.6), (2.7) and (2.38), remembering that liquid phase resistance will prevail in oxygen mass transfer [Eq. (2.23)]. The predicted Ψ_i was plotted against R_L/R_O on the same graph as the observed Ψ_i , but predicted Ψ_i increased much more smoothly than observed Ψ_i (Roberts et al., 1985). Roberts et al. (1985) suggest that this discrepancy may result from experimental errors (the area of disagreement was for low S values) or from a deficiency of the model, but that it shows that the doubts expressed by King (1964; on the theoretical grounds that local hydrodynamic conditions were different) on the applicability of the two resistance model in the mixed resistance domain may be justified. But as pointed out by various authors (Roberts et al., 1985; Roberts and Levy, 1985), the two resistance model is still better than a single resistance model even if it is not the best possible.

2.11 Importance of Gas Phase Resistance

Kavanaugh and Trussell (1980; 1981) initially stated that they believed liquid phase resistance should generally control mass transfer applications in water treatment, except for ammonia stripping, but they did mention additional data on gas phase mass transfer coefficients were needed to confirm it. Ball et al., (1984) and Umphres et al., (1983) also made the assumption that liquid phase resistance controlled, but suggested the possible importance of gas phase resistance as an explanation of the poor agreement of their data for bromoform with the results predicted by Sherwood and Holloway's model.

The assumption of liquid phase resistance control was sometimes supported by taking Henry's law constant values for the compounds to be stripped, assuming a k_G/k_L value of 100, and applying Eq. (2.9) (Kavanaugh and Trussell, 1981). The value of $k_G/k_L = 100$, however, is recommended for natural systems, such as rivers (Kavanaugh and Trussell, 1981; Roberts et al., 1985; Roberts and Levy, 1985).

For countercurrent packed column air stripping of compounds with H values ranging between 0.2 and 30, using Q_G/Q_L ranging between 1 and 10, Roberts et al. (1985) applied Onda et al.'s model to quantify the relative magnitude of k_G and k_L and found the k_G/k_L ratio to vary between 3 and 11. Eq. (2.9) shows that a lower value of k_G/k_L implies gas phase resistance will be more important (Roberts et al., 1985). In a design simulation, Roberts and Levy (1985) showed that

neglecting gas phase resistance for bromoform could result in overestimation of fractional removal by as much as 15%.

Findings of Roberts et al. (1985) and Roberts and Levy (1985) lead to the conclusion that gas phase resistance should be considered in many volatile organics air stripping applications. The relative importance of gas phase resistance at various Henry's law constant values is shown by Fig. 2.7, which is a plot of Eq. (2.11) assuming a k_a/k_L value of 10.

2.12 Design Optimization

2.12.1 Design Optimization Using Energy Requirements

Energy requirements that are expected to vary with each design are those of the air blower and water pump. They are part of the operation and maintenance cost. Ball et al. (1984) computed the blower power requirement using an adiabatic compression equation and assuming an efficiency of 70%, and the pumping horsepower as that needed to pump the water to height Z while assuming an efficiency of 80%. Roberts and Levy (1985) used a similar procedure for pumping energy requirement but based their evaluation of blower energy requirement on a simple function of the pressure drop through the packing instead of the more complex adiabatic compression equation; they also accounted for piping energy losses by considering them as an additional metre of packing. This resulted in the following equation:

Figure 2.7: Relative importance of gas phase resistance to mass transfer at various Henry's law constant values

$$\frac{P}{Q_L} = \left[\frac{Q_G}{Q_L} \times \frac{\Delta p_G}{Z} + \rho_L g \right] (Z + 1) \quad (2.56)$$

where P = power input (W)

To this theoretical energy requirement, they applied an overall efficiency of 60%, in accordance with experience in the chemical process industries (Roberts and Levy, 1985). The pressure drop per unit packing depth, $\Delta p_G/Z$, can be obtained from pressure drop correlations such as Fig. 2.4.

For optimization purposes, the energy requirement can be related to many parameters. Since the stripping factor, S, and allowable air pressure drop, Δp_G , are the parameters to be selected in the suggested design procedure (Section 2.3.2), plotting the energy requirement or corresponding cost against these two parameters would be convenient. Ball et al. (1984) plotted constant horsepower requirement lines against S and $\Delta p_G/Z$ for a hypothetical situation. As could be expected, these plots showed the energy requirement to increase with increasing $\Delta p_G/Z$ at constant S values. They also showed optimum S values to exist for each allowable $\Delta p_G/Z$; that is, at constant $\Delta p_G/Z$ value, increasing S will decrease the power requirement down to a point, after which the power requirement will start increasing again. Similarly, Roberts and Levy (1985) plotted constant removal level lines against the energy requirement and the gas to liquid ratio, and found that for a constant removal level, the energy requirement decreased as gas to liquid ratio increased down to a point, and then increased as the gas to

liquid ratio increased. The explanation for these optimum values (Ball et al., 1984; Roberts and Levy, 1985) is that as S (or Q_G/Q_L) increased the tower height (or Z) and associated pumping and blower costs decreased. This decrease was offset at a certain point (past the optimum value) by the increasing importance of the pressure drop multiplied by the high gas flow rate.

2.12.2 Design Optimization Using Packing Volume

The volume of packing in the column is another parameter expected to vary as the design is changed. It is a part of the capital costs. Roberts and Levy (1985) point out that the superficial hydraulic residence time may be conveniently used to estimate the packing volume:

$$\theta_b = \frac{Z \rho_L}{L} = \frac{V_C}{Q_L} \quad (2.57)$$

where V_C = empty bed volume (m^3)

θ_b = superficial hydraulic residence time (s)

As for energy requirements, the stripping factor, S , and pressure drop, Δp_a , should be the important variables when optimizing packing volume. Ball et al. (1984) plotted lines of constant packing volume against S and $\Delta p_a/Z$. This plot shows that at constant S , increasing the allowable $\Delta p_a/Z$ will decrease the required packing volume, by allowing higher liquid loading rates for the same gas loading rate (Fig. 2.4) (Ball et al., 1984). However, if S is increased at constant $\Delta p_a/Z$ value, the packing volume required will decrease down to a point due to the required tower height

decreasing, and then start increasing again as the effect of increasing tower cross sectional area (required to keep the pressure drop at a fixed value as the gas to liquid ratio increases) offsets the decreasing tower height (Ball et al., 1984).

2.12.3 Overall Design Optimization

As mentioned by Ball et al. (1984), the optimum design will be found by evaluating the total cost (capital and operation and maintenance) for a range of key parameters (here, S and Δp_0 were selected as key parameters), under the most difficult design conditions (temperature, among others) for the compound(s) whose effluent standard(s) is (are) most difficult to achieve.

The general assumptions made by Ball et al. (1984) in their total cost optimization were:

- a) Capital costs were amortized over a 20 year life with an assumed 10% interest rate.
- b) Cost estimates were made for capital costs that will vary from one design to the next, relating the costs to suitable criteria. For example, packing cost was related to tower volume, tower structural costs were related to surface area of tower, and pump and blower costs can be related to tower height.
- c) Operation and maintenance costs that were assumed to vary from one design to the next are the energy costs of the blowers and pumps.

- d) All costs that were constant between alternative designs were neglected.

Ball et al. (1984) then plotted lines of constant costs against S and $\Delta p/Z$, and found that the optimum solution seemed to be at very low pressure drops.

Singley et al. (1980) made some similar assumptions in estimating air stripping costs. They give cost estimates as a series of curves. One of them shows total air stripping column cost (including 1 in. ceramic saddles packing, carbon steel tower shell, flow distributor and redistributors, and packing support plate) as a function of total column area required and packing depth. The pump and influent column piping costs were related to total plant flow and packing depth, but the blower costs were related to required air flow and discharge static heads. The operation costs accounted for by Singley et al. (1980), were the pumping and blower operation costs. Like Ball et al. (1984) and Roberts and Levy (1985), they related the pumping costs to depth; the blower operation cost was plotted as a function of air to water ratio for various blower discharge static heads. They even gave curves of maintenance and labour costs and of airwell costs as a function of maximum plant capacity.

2.13 Effect of Various Parameters on Pilot Unit Performance

2.13.1 Effect of Temperature

It was mentioned earlier that designs must be evaluated under the most difficult conditions. One condition is the

ambient temperature. An increase in temperature will cause a slight increase in K_La and a more important increase in H (Kavanaugh and Trussell, 1981; Roberts and Levy, 1985). Lamarre et al. (1983) show the increase of mass transfer coefficients for 2 propanol with increasing temperature. ESE (Environmental Science and Engineering, Inc.; 1981) compared diffusivity coefficients computed from mass transfer coefficients obtained at average temperatures of 16 and 31°C under otherwise similar conditions, and observed a significant increase in diffusivity (about 2.4 times); an empirical correlation was used to compute diffusivity coefficients from mass transfer coefficients.

Thus for a given column and operating conditions, increasing temperature will increase the removal (Roberts and Levy, 1985), or for a given removal level, increasing the temperature will decrease the energy and packing volume requirements (Kavanaugh and Trussell, 1981). Designs should thus be evaluated at the lowest temperature anticipated.

Temperature may have another effect on packed tower design. Kavanaugh and Trussell (1980) mention that at high gas to liquid ratios, a temperature gradient may develop in the column. If this happens, the mass transfer rates may be affected by cooling and evaporation of water. Kavanaugh and Trussell (1980) recommend that a heat balance analysis be performed at final design stage when in doubt.

2.13.2 Effect of Other Variables

The composition of the background water could affect the mass transfer. Singley et al. (1980), for example, observed a reduction of chloroform removal in waters with a free chlorine residual as opposed to chlorine-free waters.

ESE (1981) observed that diffusivity coefficients, and thus the mass transfer coefficients from which they were computed, for the volatile organics analysed varied as the type of water pre-treatment varied. Molecular level inter-reactions were suspected of causing this, but nothing was proven, and no other specific cause was found. Stover (1982) also observed different K_La values for the same compounds found in water from two adjacent wells. Umphres et al. (1983), however, studied organics air stripping from a lime-softened groundwater and a conventionally treated surface water with different characteristics, and found no significant difference of K_La .

Roberts et al. (1982) performed a tracer study to characterize the flow in their packed column. The liquid holdup and axial liquid dispersion coefficients observed agreed reasonably well with predicted values. Agreement of axial dispersion coefficients surprised Roberts et al. (1982), since the experimental flow rates were well below the flow rates for which the correlation was developed, the bed used in the study was much shorter than the one used for the correlation, and the experimental bed was "carefully" packed rather than "randomly" packed. The agreement of observed

and predicted values led Roberts et al. (1982) to the conclusion that the experimental conditions of their work were similar to those of other works. Umphres et al. (1983) stated that the linearity of their NTU vs Z curves suggested that lateral dispersion and channeling in the column were insignificant, since the effect of channeling, if present, would have increased with increasing depth.

CHAPTER 3

LITERATURE REVIEW: SUBJECTS RELATED
TO PACKED COLUMN AIR STRIPPING

3.1 Henry's Law Constants

3.1.1 Liquid Vapour Equilibrium of Dilute Solutions

Henry's law states that the following linear relationship describes the equilibrium between the solute in each of the two (liquid and vapour) phases, if concentrations are low (Munz and Roberts, 1982):

$$\lim_{Y_L \rightarrow 0} \frac{f}{Y_L} = H_A \quad (3.1)$$

where f = fugacity of solute (atm)

For very dilute solutions (mole fraction $Y_L < 0.01$ according to Munz and Roberts, 1982; $Y_L < 0.001$ according to Kavanaugh and Trussell, 1980), thermodynamic developments lead to another way of expressing Henry's law (Kavanaugh and Trussell, 1980; Munz and Roberts, 1982):

$$p_p = H_A Y_L \quad (3.2)$$

Mackay and Wolkoff (1973) derived the following expression:

$$p_p = Y_L \frac{p_v}{Y_g} \quad (3.3)$$

where Y_g = solubility of the solute in the liquid phase, expressed as mole fraction (mole/mole).

Thus, Henry's law constant can be expressed as:

$$H_p = \frac{p_v}{Y_g} \quad (3.4)$$

But the constant can be expressed in many other ways.

The usual literature form is (Munz and Roberts, 1982):

$$H_p = \frac{p_v}{C_{gm}} \quad (3.5)$$

where H_p = Henry's law constant (atm-m³/mole).

C_{gm} = solubility of the solute in the liquid phase (mole/m³)

Munz and Roberts (1982) and Roberts and Levy (1985) found the dimensionless form of Henry's law constant based on mass concentrations to be best suited for mass transfer calculations. Then:

$$H = \frac{C_g^e}{C_L^e} = \frac{C_{gm}^e}{C_{LM}^e} \quad (3.6)$$

where C_g^e = gas phase mass concentration in equilibrium with the liquid phase concentration (kg/m³)

C_{gm}^e = gas phase molar concentration in equilibrium with the liquid phase concentration (kmole/m³)

C_L^e = liquid phase mass concentration in equilibrium with the gas phase concentration (kg/m³)

This last form of the constant should not be mistaken for the dimensionless form of Henry's law constant based on mole fractions, mentioned by Munz and Roberts (1982):

$$H_M = \frac{Y_G}{Y_L} \quad (3.7)$$

where H_M = Henry's law constant (mole fraction/mole fraction)

Y_G = mole fraction of solute in the gas phase, in equilibrium with the liquid phase (mole/mole)

Mackay and Shiu (1981) and Munz and Roberts (1982) give the relationships among some of these forms of Henry's law constant (the third relationship was given by Munz and Roberts (1982) only):

$$H_A = H_M \frac{P_L}{M_L} \quad (3.8)$$

$$H_G = H_M R T_A \quad (3.9)$$

$$\text{and } H_A = H_M \frac{P_G}{M_G} R T_A \quad (3.10)$$

where M_G = gas phase molar weight (kg/mole)

M_L = liquid phase molar weight (kg/mole)

R = universal gas constant (82.057×10^{-4} atm·m³/mole·°K)

T_A = absolute temperature (°K)

3.1.2 Determination of Henry's Law Constants

3.1.2.1 Methods for Determining Henry's Law Constants

Singley et al. (1980) point out that Henry's law constant, H , can be obtained from solubility and vapour pressure data if: (a) H does not change as the solute's concen-

tration in water changes, up to the solubility limit of the solute; and (b) the vapour above the solute's saturated solution behaves like an ideal gas whose composition can be determined from vapour pressures. The first condition could be met by the low solubility volatile organics of concern, while the second condition seems reasonable at ambient temperatures and pressures (Singley et al., 1980).

Dilling (1977) and Singley et al. (1980) give equations relating H to p_v and C_{am} . These equations, derived from Eq. (3.6) and the perfect gas law, can also be easily obtained from Eqs. (3.5) and (3.9), yielding:

$$H = \frac{p_v}{RT_a C_{am}} \quad (3.11)$$

Mackay and Shiu (1981) state that using vapour pressure and solubility data to estimate Henry's law constants is acceptable if the solute's solubility expressed as a mole fraction is less than a few percent. However, there are problems associated with this method of obtaining H . Singley et al. (1980) plotted H values estimated from vapour pressure and solubility data against values obtained experimentally by a method described in Section 3.1.2.3; the data showed an increase in estimated H as experimental H increased, but deviation from the perfect agreement curve (H estimated = H experimental) was large.

Dilling (1977) pointed out that if vapour pressure values were similar from one author to the next, solubilities, which are difficult to measure accurately (Munz and Roberts,

1982), varied a lot. Mackay et al. (1979) note that for compounds of high molecular weight, vapour pressure data at environmental temperature may have to be extrapolated from high temperature data, making it less reliable.

It thus appears that experimental determination of H would be preferable to determination using vapour pressure and solubility data (Dilling, 1977; Singley et al., 1980). Besides eliminating the above sources of inaccuracy, experimental measurement may allow H to be found at low concentrations typical of environmental conditions (Munz and Roberts, 1982).

The "conventional" experimental method of obtaining H consisted of measuring the liquid phase concentration and gas phase partial pressure of the solute of interest in a system that had reached equilibrium (Mackay et al., 1979; Mackay and Shiu, 1981; Munz, 1985). However, the very low environmental concentrations sometimes encountered and very low vapour pressures are difficult to measure precisely on an absolute basis (Mackay et al., 1979; Mackay and Shiu, 1981). A method that would require only relative concentrations measurement would be as accurate and much more convenient.

3.1.2.2 H Determination in a Bubble Column

Mackay et al. (1979) and Munz and Roberts (1982) determined H by bubbling air through a solution of the solutes of interest and observing the change in aqueous solute con-

centration with time. This change was theoretically expressed as (Munz and Roberts, 1982):

$$-\ln \frac{C_L}{C_{Lo}} = \frac{Q_G H}{V_L} [1 - \exp(-\Phi Z_T)] (t - t_0) \quad (3.12)$$

in which

$$\Phi Z_T = \frac{K_L a V_L}{H Q_G} \quad (3.13)$$

where C_L = average mass concentration in the liquid phase (kg/m^3)

C_{Lo} = average mass concentration in the liquid phase at time $t = 0$ (kg/m^3)

t = time (s)

t_0 = initial time (s)

V_L = liquid volume (m^3)

Z_T = total submergence of gas inlet (water depth; m)

Φ = constant specific to each run (m^{-1})

If the effluent gas (air) is saturated with solute, or if ΦZ_T is much larger than one (say $\Phi Z_T > 5$), then (Mackay et al., 1979; Munz and Roberts, 1982):

$$-\ln \frac{C_L}{C_{Lo}} = \frac{Q_G H}{V_L} (t - t_0) \quad (3.14)$$

Thus, a plot of $-\ln(C_L/C_{Lo})$ against $(t - t_0)$ would have a slope of $Q_G H/V_L$, from which H can be obtained (Mackay et al., 1979; Munz and Roberts, 1982).

On the other hand, if the effluent gas is far from saturation, or if ΦZ_T is much smaller than one (say $\Phi Z_T < 0.1$), as it may happen for solutes with large H values or when large gas flow rates are used, then (Munz and Roberts, 1982):

$$-\ln \frac{C_L}{C_{Lo}} = K_L a (t - t_0) \quad (3.15)$$

and the overall mass transfer rate constant can be found from the slope of a $-\ln(C_L/C_{L0})$ against $(t - t_0)$ plot.

Mackay et al., (1979) and Mackay and Shiu (1981) note that this method only requires data on the relative concentration changes in the liquid phase with time; no absolute partial pressure or concentration measurement is necessary. Values of H within 3% of reported values were obtained by Mackay et al. (1979). Another advantage of the method is that any possible dependence of H on concentration will be observed as a curvature of the line of $-\ln(C_L/C_{L0})$ against $(t-t_0)$.

3.1.2.3 H Determination in a Closed System

Many methods of determining H values by measurements performed on a closed system were devised. The general procedure consists of putting a solution of the chemicals of interest in contact with air in a closed system (vial or syringe), and measuring the concentration in one or both phases (depending on the analytical capabilities, and the knowledge of the initial concentrations) after equilibrium has been reached.

"Direct determination" of H , by measurement of the gas and liquid phase concentrations once equilibrium is attained, can be performed in a closed system. Measurement of concentrations in one phase only and mass balance relationships can also be used to obtain H .

Munz and Roberts (1982) used this approach. They transferred a solution of organics into syringes and immediately analysed a portion of the solution to determine initial concentration. Known volumes of solution and air were kept in the syringes that were closed with rubber stoppers and allowed to equilibrate over a one day period. The syringes were shaken 3 or 4 times during that day. Another portion of the solution was then analysed to find the equilibrium liquid concentration.

A mass balance between the initial and final states was expressed as (Munz and Roberts, 1982):

$$C_{Lo}V_L = C_LV_L + C_gV_g \quad (3.16)$$

where V_g = gas volume (m^3)

Solving the preceding equation for C_g and substituting it into Eq. (3.6) yields:

$$H = \frac{(C_{Lo} - C_L)V_L}{C_LV_g} = \left[\frac{C_{Lo}}{C_L} - 1 \right] \frac{V_L}{V_g} \quad (3.17)$$

Singley et al. (1980) and ESE (1981) determined H using a similar method. The initial concentration was computed from the volume of organic compound added to a certain volume of water in a syringe. After standing two hours in a temperature controlled room at 4 or 20°C, the syringes were shaken and a vapour phase sample was analyzed to find final concentrations.

Munz and Roberts (1982) point out that their method yielded lower H values than the diffused aeration column

values, although the values were still often in agreement with other literature values. They attribute this partly to the fact that equilibrium may not have been reached due to the short contact time and little shaking. Volatilization during sample transfer for liquid-liquid extraction is also a possible source of error, and would explain the large standard deviations observed (Munz and Roberts, 1982).

Munz (1985) describes improvements of this method. One improvement, called "Equilibrium Partitioning in Closed Systems", was based on a comparison of mass balances in two similar systems (vials), at the same temperature, containing the same total mass of solute ($C_{Lo}V_L$), but different liquid volumes. Equating the expressions of total mass in terms of equilibrium concentrations for both systems [Eq. (3.16)], and using Henry's law [Eq. (3.6)] yields (Munz, 1985):

$$H = \frac{\begin{bmatrix} E \\ C_{LB} \\ -E \\ C_{LA} \end{bmatrix} V_{LB} - V_{LA}}{V_{OA} - \begin{bmatrix} E \\ C_{LB} \\ -E \\ C_{LA} \end{bmatrix} V_{OB}} \quad (3.18)$$

or, in terms of gas phase concentrations (Munz, 1985):

$$H = \frac{\begin{bmatrix} E \\ C_{OA} \\ -E \\ C_{OB} \end{bmatrix} V_{LA} - V_{LB}}{V_{OB} - \begin{bmatrix} E \\ C_{OA} \\ -E \\ C_{OB} \end{bmatrix} V_{OA}} \quad (3.19)$$

where A, B = subscripts referring to systems A or B

Munz (1985) applied this method, measuring concentrations in both phases, which allowed him to obtain H values in 3 different ways: by direct determination [Eq. (3.6)], and using the two preceding equations. Gas chromatographic analysis was performed with direct injection of both the gas and liquid phase samples. The results obtained were inconsistent: H values computed in different ways were different. Losses of gas from the gas-tight injection syringes and losses from equilibration vials were possible causes (Munz, 1985).

The "Multiple Equilibrations technique", another improvement of the original closed system method evaluated by Munz (1985), consists of measuring the concentration in one phase after equilibration; expelling the gas phase; introducing a given volume of fresh, uncontaminated gas (air) (a volume such that the gas to liquid volume ratio remains constant); letting the system equilibrate; and, going through the same procedure again. A variable volume vessel, such as a syringe, is needed to keep the gas to liquid volume ratio constant if the liquid phase is sampled.

From Eqs. (3.6) and (3.16), it can be seen that (Munz, 1985):

$$C_{Lo} = C_L \left[1 + H \frac{V_G}{V_L} \right] \quad (3.20)$$

After the first equilibration, C_L becomes the C_{Lo} of the next equilibration. For u equilibrations (Munz, 1985):

$$\ln C_{Lu} = \ln C_{Lo} - u \left[\ln \left\{ 1 + H \frac{V_G}{V_L} \right\} \right] \quad (3.21)$$

where C_{Lu} = mass concentration in the liquid phase, after u equilibrations (kg/m^3)

Thus, $-\ln[1+H(V_G/V_L)]$ will be the slope of a plot of $\ln(C_{Lu})$ against u , which allows H to be computed (Munz, 1985).

Munz (1985) applied multiple equilibration using 100 ml gas-tight glass syringes with Teflon® plungers, on which a microvalve and septum were attached. Only liquid phase measurements were taken. At the time of this writing, the outcome of these experiments was not known.

Munz and Roberts (1982) mentioned that the closed system methods for determining H were simple and inexpensive, and could be very useful.

3.1.3 Factors Affecting H Values

The vapour-liquid equilibrium relationship depends on pressure, temperature, and composition of the phases (Al-Dhowalia, 1982; Mackay and Shiu, 1981; Roberts and Levy, 1985; Singley et al., 1980). However, since ambient conditions prevail in packed tower air stripping, the pressure is almost constant and its effect becomes negligible (Al-Dhowalia, 1982; Roberts and Levy, 1985; Singley et al., 1980).

When determining H values by diffused aeration column experiments, Munz and Roberts (1982) could not explain their observation that H decreased with increasing turbulence; theoretically, H being a thermodynamic property of the so-

lute, it should be independent of such factors. Subsequent experiments by Lalezary et al., (1984) showed no statistically significant dependence of H on hydrodynamic conditions, as stated by Roberts and Levy (1985).

3.1.3.1 Temperature Effect on H

Since temperature affects both the solubility and vapour pressure of a solute, Henry's law constant will surely be dependent on temperature (Mackay and Shiu, 1981).

Kavanaugh and Trussell (1980) obtained, from thermodynamic principles, a van't Hoff type equation relating H to temperature. The van't Hoff equation is (Stumm and Morgan, 1981, p. 69):

$$\frac{d \ln(K_A)}{dT_A} = \frac{\Delta H^\circ}{RT_A^2} \quad (3.22)$$

where K_A = ratio of activities of species (equilibrium constant)

ΔH° = enthalpy change at standard state (kJ/kmole)

Henry's law constant expressed as the ratio of partial pressure to mole fraction in the liquid phase, H_A , is the ratio of activities in a vapour-liquid system in equilibrium (Stumm and Morgan, 1981, p. 44). If the enthalpy change at standard state caused by dissolution of the solute in water, ΔH° , is considered independent of temperature, integration of the above equation yields (Kavanaugh and Trussell, 1980; Stumm and Morgan, 1981, p. 70):

$$\ln H_A = \frac{-\Delta H^\circ}{RT_A} + K \quad (3.23)$$

where $K = \text{constant}$

Kavanaugh and Trussell (1980) correlated data from Kruis (1976), using $\log_{10} H_A$ instead of $\ln H_A$, to find the values of ΔH° and K .

Singley et al. (1980), using another route, arrived at a relationship very similar to Eq. (3.23). They state that over reasonable temperature ranges:

$$\ln H = B_0 + B_1/T_A \quad (3.24)$$

where $B_0, B_1 = \text{constants}$

Singley et al. (1980) and ESE (1981) computed B_0 and B_1 by correlating H data they obtained in triplicate by the syringes method, at two temperatures (4 and 20°C).

3.1.3.2 Effect on H of Solute's Concentration

The solute's concentration in the solution could affect its H value since its activity coefficient in water varies with concentration (Mackay and Shiu, 1981). Kavanaugh and Trussell (1981) stated that H values obtained from vapour pressure and solubility data would be suitable for highly concentrated solutions, but that the extrapolated values for low environmental concentrations may be too low.

Munoz and Roberts (1982) also mention that an increase in H with decreasing concentration could be observed if high initial concentrations (near the solubility limit) and low final concentrations were studied. They present this argu-

ment as a possible reason for Mackay's statement that H depends on concentration, a dependence they did not observe when determining H values by the diffused aeration method (the $\ln(C_L/C_{Lo})$ against $(t - t_0)$ curve was a straight line). Munz and Roberts (1982) even showed theoretically that H was constant for very dilute solutions.

Mackay had mentioned in a preceding paper (Mackay et al., 1979) that the assumption that the volume of solute vapour formed was negligible compared to the stripping gas volume may not be true at the beginning of diffused aeration treatment of highly concentrated solutions, which would explain the curvature of the first part of the logarithm of concentration against time curve. Mackay and Shiu (1981) believe the effect of solute concentration to be negligible if the concentration is low and solutes are non-associating.

Singley et al. (1980), however, gathered H data, at two temperatures, covering a range of initial concentrations between 0.1 and 100 $\mu\text{g/l}$, by the syringe method, and correlated their results to find the value of the constants in the formula:

$$\ln H = B_0 + B_1/T_A + B_2 C_L \quad (3.25)$$

where $B_2 = \text{constant}$

Contrary to their expectations, all three constants were statistically significant (B_2 less than B_0 and B_1) and compound dependent. However, the coefficient of determination obtained when fitting the data to the above formula was 95.64%, while r^2 obtained by fitting the data to Eq. (3.24)

was 94.65%. Concentration thus explained very little of the sum of squared error, and its effect was neglected.

Lalezary et al. (1984) also determined H values by diffused aeration column, observing a non-linear behaviour of the logarithm of concentration against time curve outside a certain concentration range for chloroform. The H value of chloroform found in the linear concentration range compared well with some literature values, both theoretical and experimental, but was lower than literature experimental values found at much higher (at least 10 times) initial concentrations. Lalezary et al. (1984) concluded that H values may depend on initial solute concentration.

3.1.3.3 Effect on H of Solution's Composition

The composition of the water can affect H values. Roberts et al. (1984) determined, in a diffused air column, H values for four organics dissolved in clean, deionized water, and then in filtered secondary wastewater effluent; H values were 4 to 27% larger in the wastewater effluent.

Of course, the secondary effluent had a composition significantly different from deionized water: conductance was 1625 times larger, COD 50 times larger and TOC 40 times larger (Roberts et al., 1984). Singley et al. (1980) mention that organics being present at trace levels in the waters considered, the low concentration of other organics should not affect the Henry's law constant value.

However, other compounds such as methanol are sometimes added to the water to increase organics solubility (Munz and Roberts, 1982). The amount added can be relatively significant, and Munz and Roberts (1982) developed equations to account for this addition.

Henry's law constant for a compound in a mixture of solvents can be expressed as (Munz and Roberts, 1982):

$$\ln H_{2m} = Y_1 \ln H_{21} + Y_3 \ln H_{23} - B_{13} Y_1 Y_3 \quad (3.26)$$

where B_{13} = empirical coefficient relevant to a system comprised of components 1 and 3

H_{1j} = Henry's law constant of component 1 of solution in solvent j (mass concentration/mass concentration)

H_{1m} = Henry's law constant of component 1 of solution in a mixture of two solvents (mass concentration/mass concentration)

Y_1 = mole fraction of component 1 of solution in the liquid phase (mole/mole)

and the solution composition is:

component 1 = solvent (e.g., water)

component 2 = solute (organic compound)

component 3 = solvent (e.g., methanol)

This equation can be rearranged as follows:

$$\ln(H_{2m}/H_{21}) = (Y_1 + Y_3 - 1) \ln H_{21} + Y_3 \ln(H_{23}/H_{21}) - B_{13} Y_1 Y_3 \quad (3.27)$$

If it is assumed that components 2 and 3 are infinitely dilute in solvent 1, and that component 2 is also infinitely dilute in solvent 3, or expressed differently:

for the ternary system: $Y_2 \ll 1$, $Y_3 \ll 1$, $Y_1 \approx 1$

for the binary systems: $Y_2 \ll 1$, $Y_1 \approx 1$

$Y_3 \ll 1$, $Y_1 \approx 1$

$Y_2 \ll 1$, $Y_3 \approx 1$

where $Y_1 \ll 1$ means $Y_1 < 0.01$

then empirical coefficients B_{1j} can be found from (Munz and Roberts, 1982):

$$B_{1j} = \ln Y_{1j} \quad (3.28)$$

where Y_{1j} = activity coefficient of component 1 in solvent j at infinite dilution

The ratio H_{23}/H_{21} can be computed from the following relationship (Munz and Roberts, 1982):

$$B_{23} = B_{12} + \ln(H_{23}/H_{21}) \quad (3.29)$$

Munz and Roberts (1982) recommend that experimental values of activity coefficients be used whenever possible. Otherwise, general correlations can be used; Munz and Roberts (1982) found that the correlation of Pierro et al. (1959) gave reasonable estimates for the water-methanol system. For slightly soluble compounds, activity coefficients can be estimated from solubility (Munz and Roberts, 1982):

$$Y = 1/Y_{\infty} \quad (3.30)$$

where Y = activity coefficient of solute

Munz and Roberts (1982) used the above equations to evaluate the effect of methanol ($Y_2 = 1.8 \times 10^{-4}$) on H values of chloroform and carbon tetrachloride. The anticipated effect was found negligible, $(H_{2m}/H_{21}) = 0.9986$ for carbon tetrachloride (Munz and Roberts, 1982). Munz and Roberts (1982) also conducted diffused air column experiments to determine H at various methanol concentrations. H variations were random, leading to the conclusion that they were caused

by experimental inaccuracies and that methanol indeed had no significant effect.

Munz and Roberts (1982) mention that the octanol-water partition coefficient for methanol is smaller than one, indicating that methanol acts chemically more like water than alcohol, which would support the above results.

3.2 Packed Column Air Stripping Studies

3.2.1 Equipment Required for Packed Column Studies

3.2.1.1 The Column and Its Internals

There are some general considerations related to packed column design. Leva (1958) states that although there is no general liquid distribution device design, initial liquid distribution is important because it affects the degree to which the packing will be wetted, even for randomly dumped packing that already favours liquid distribution. To avoid liquid maldistribution, such as channeling (concentration of the liquid flow at the walls of the column while most of the gas flows through the center of the column), Treybal (1980) recommends that a column-to-packing diameter ratio of at least 8 to 1, and preferably up to 15 to 1, be used; flow redistributors should also be inserted at depths varying between 2 and 10 times the column diameter (Treybal, 1980).

As for packing support, Morris and Jackson (1953) mention that the packing support grid or perforated plate should have a free space at least equal to the voidage of

the packing to prevent premature flooding. Leva (1953) recommends using "gas-injection weir-type" support plates (Fig. 3.1) to provide adequate free area while being structurally strong; this type of plate also provides better gas-liquid contact through the column. (Leva, 1953).

In packed column volatile organics air stripping studies, these recommendations were generally followed. A column-to-packing diameter ratio greater than 11 (Ball et al., 1984; Lamarre et al., 1983; Stover and Kincannon, 1983, Umphres et al., 1983) and sometimes greater than 15 (Roberts et al., 1985; Ruggiero and Feige, 1983; Singley et al., 1980; Stover, 1982) was used in many studies. The need for such high ratios is recognized by authors that used lower ratios (Al-Dhowalia, 1982). Some authors used redistributors (Ball et al., 1984; Umphres et al., 1983), at spacing equivalent to two column diameters, while others (Singley et al., 1980) mention that redistributors were available if required. Initial liquid distribution was obtained from orifices (Singley et al., 1980) or nozzles (Roberts et al., 1985; Umphres et al., 1983) in the bottom of a distribution basin or bucket, or from a shower head (Al-Dhowalia, 1982).

The column was often made of glass (Roberts et al., 1985; Singley et al., 1980; Stover, 1982; Stover and Kincannon, 1983), sometimes of clear polyvinyl chloride (PVC) (Al-Dhowalia, 1982) or stainless steel (Lamarre et al., 1983). It was often made of sections of pipe 0.5 to 0.6 m

Figure 3.1: Gas-injection weir-type support plate.

long (Ball et al., 1984; Roberts et al., 1985; Singley et al., 1980; Umphres et al., 1983).

The packings used include 25 mm saddles made of polypropylene (Ball et al., 1984; Ruggiero and Feige, 1983; Umphres et al., 1983) or ceramic (Al-Dhowalia, 1982), 12.5 mm ceramic Berl saddles (Roberts et al., 1985), 6.25 mm ceramic Intalox® saddles (Singley et al., 1980), 25 mm stainless steel Pall rings (Lamarre et al., 1983), and 6.5 mm glass Raschig rings (Stover, 1982; Stover and Kincannon, 1983). The packing was supported by stainless steel screens (Al-Dhowalia, 1982; Stover, 1982; Stover and Kincannon, 1983) or a gas injection type plate made of ceramic (Singley et al., 1980) or Teflon® (Roberts et al., 1985).

The way in which the packing was loaded in the column is addressed only by Roberts et al. (1982), who mention having loaded a water filled column, but having filled manually all detected voids to improve bed homogeneity. This resulted in 15% more specific surface area but pressure drops much larger than anticipated. The recommended way to "dump" packing randomly is to load it into a water filled column without filling up the voids manually (Norton Company, 1977). It can be assumed that this loading method was used for the other studies.

3.2.1.2. Equipment Surrounding the Column

Some investigators were careful to use only Teflon® tubing, and even Teflon® fittings and gaskets, wherever pos-

sible, to prevent adsorption (Roberts et al., 1985; Stover, 1982; Stover and Kincannon, 1983), while others used regular PVC piping and valves (Al-Dhowalia, 1982).

Accurate air and water flow measurement devices are important components of a packed column air stripping system (Ball et al., 1984). Liquid flows were often measured with a rotameter (Al-Dhowalia, 1982; Roberts et al., 1985; Singley et al., 1980; Umphres et al., 1983), and controlled by a rheostat on the peristaltic liquid pump (Roberts et al., 1985) or by a metering valve (Singley et al., 1980). Gas flows, supplied by a compressor (Al-Dhowalia, 1982), a blower (Lamarre, 1983; Singley et al., 1980; Umphres et al., 1983), or a tank of compressed nitrogen (Roberts et al., 1985) or compressed air (Stover, 1982; Stover and Kincannon, 1983), were controlled by two regulators in series (Roberts et al., 1985), or by a metering valve (Singley et al., 1980) or gate valve (Lamarre et al., 1983). They were measured with a rotameter (Al-Dhowalia, 1982; Singley et al., 1980; Stover, 1982; Stover and Kincannon, 1983), a pitot tube (Lamarre et al., 1983), an orifice flowmeter (Umphres et al., 1983), or a precision mass flowmeter (Roberts et al., 1985).

3.2.2 Packed Column Air Stripping Experiments

3.2.2.1 Experimental Conditions

Volatile organics air stripping experiments have been conducted on groundwater (Lamarre et al., 1983; Ruggiero and

Feige, 1983; Stover, 1982; Stover and Kincannon, 1983; Umphres et al., 1983), treated surface water spiked with organics (Umphres et al., 1983), treated wastewater, spiked (Ball et al., 1984) or not spiked (Al-Dhowalia, 1982), and synthetic waste made by spiking pure water with organics (Al-Dhowalia, 1982; Roberts et al., 1982; 1985). When the solution was spiked, organics were usually selected to cover a wide range of volatilities (Al-Dhowalia, 1982; Ball et al., 1984; Roberts et al., 1982; 1985), and were first dissolved in ethanol (Umphres et al., 1983), methanol (Roberts et al., 1982), or a mixture of methanol and isopropyl alcohol (Ball et al., 1984).

Experimenters varied liquid loadings in the column at constant gas-to-liquid ratio (Umphres et al., 1983), or allowed both the liquid loading and gas to liquid ratio to vary (Al-Dhowalia, 1982; Ball et al., 1984; Lamarre et al., 1983; Roberts et al., 1985; Ruggiero and Feige, 1983; Singley et al., 1980; Stover, 1982; Stover and Kincannon, 1983; Umphres et al., 1983). Some authors also collected data at the same flow rates at many packed depths, usually to isolate end effects (Al-Dhowalia, 1982; Ball et al., 1984; Roberts et al., 1982; 1985; Singley et al., 1980; Umphres et al., 1983).

3.2.2.2 Sampling and Analysis

To insure that steady state was reached, experimenters allowed the column to run one-half hour (Singley et al.,

1980) to one hour (Ball et al., 1984; Ruggiero and Feige, 1983) before sampling. Roberts et al. (1982) started sampling after 40 minutes of run, and sampled at regular intervals until their influent reservoir was empty; they assumed the last five samples they collected were at steady state. Samples were collected in 15 ml glass bottles (Roberts et al., 1982), or in 60 ml (Ball et al., 1984; Singley et al., 1980) or 200 ml (Umphres et al., 1983) amber glass bottles, all capped with Teflon-lined septa. Ball et al. (1984) put 0.5 ml of 2N sodium sulfite to quench any residual free chlorine in the sample bottles.

Water analysis for volatile organics will be discussed in the following sections. In volatile organics air stripping studies, the organics were extracted from water by liquid-liquid extraction using pentane as a solvent (Ball et al., 1984; Roberts et al., 1985; Umphres et al., 1983), by static headspace analysis (Singley et al., 1980), or by dynamic headspace analysis, also called purge and trap analysis (Ruggiero and Feige, 1983).

3.3 Water Analysis for Organics

Analysis for organics usually includes the following steps: (i) sample preparation (collection, extraction, and concentration); (ii) components separation; and (iii) components identification and concentrations measurement (Al-Dhowalia, 1982; Trussell and DeBoer, 1983). Currently, extraction and concentration of the sample are the limiting

factors in trace volatile organics analysis (Al-Dhowalia, 1982). The gas chromatograph is essential for separating the many organics that may be present in a sample (Al-Dhowalia, 1982; Trussell and DeBoer, 1983). Some aspects of these steps are discussed in the following sections.

3.3.1 Extraction and Concentration of Organics

There are many ways of extracting and concentrating an aqueous solution of organic chemicals. For volatile organics, liquid-liquid extraction and "purge and trap" are probably the most commonly used techniques. These two techniques are discussed in the following paragraphs.

3.3.1.1 General Extraction Procedures

In liquid-liquid extraction, the sample is shaken in the presence of an organic solvent immiscible with water (Al-Dhowalia, 1982). Many volatile organics, being more soluble in the solvent (pentane, hexane, methylcyclohexane) than in water, will be transferred to the solvent phase (Trussell and DeBoer, 1983). The phases are then allowed to separate, and a portion of the solvent phase is injected into the gas chromatograph (Al-Dhowalia, 1982). Partitioning between the phases is a function of temperature, compounds, and ratio of volumes of phases, and controlled conditions will yield reproducible extractions (Trussell and DeBoer, 1983). Most liquid-liquid extraction procedures

also provide a certain degree of concentration (Trussell and DeBoer, 1983).

In purge and trap analysis, an inert gas is bubbled through the sample, forcing the organics out of the sample; the inert gas stream then goes through a column of sorbent, the trap, that retains the organics while letting the carrier gas out (Al-Dhowalia, 1982; Trussell and DeBoer, 1983). The organics are then thermally desorbed from the trap into the gas chromatograph (Al-Dhowalia, 1982). By purging large volumes of sample, 1000 fold concentration factors can be achieved (Trussell and DeBoer, 1983).

3.3.1.2 Comparison of Extraction Methods

The two extraction techniques discussed above have common advantages. Both are applicable to a wide range of compounds (Kirshen, 1981; Trussell and DeBoer, 1983). Both are accurate (Otson et al., 1979; Trussell et al., 1979; Trussell and DeBoer, 1983), rapid (Al-Dhowalia, 1982; Glaze et al., 1981; Henderson et al., 1976; Kirshen, 1981; Mieure, 1977; Norin and Renberg, 1980; Reding et al., 1979; Richard and Junk, 1977; Trussell et al., 1979; Trussell and DeBoer, 1983), convenient (Al-Dhowalia, 1982; Henderson et al., 1976; Richard and Junk 1977; Trussell et al., 1979), and reproducible (Glaze et al., 1981; Norin and Renberg, 1980; Trussell and DeBoer, 1983).

The purge and trap technique is also sensitive (Al-Dhowalia, 1982; Trussell and DeBoer, 1983), and requires

only a small sample (Trussell and DeBoer, 1983). However, liquid-liquid extraction is simple (Kirshen, 1981; Norin and Renberg, 1980; Otson et al., 1979; Richard and Junk, 1977; Trussell et al., 1979; Trussell and DeBoer, 1983), does not involve complex manipulations (Richard and Junk, 1977; Trussell and DeBoer 1983), requires only conventional injection in the gas chromatograph (Trussell and DeBoer, 1983), and is easily automated (Reding et al., 1979; Trussell et al., 1979). The extract obtained by liquid-liquid extraction allows repetition of the test with only one sample being extracted (Dressman et al., 1979; Norin and Renberg, 1980).

The purge and trap is inexpensive to operate (Trussell and DeBoer, 1983), but requires expensive specialized equipment or instrument modifications (Dressman et al., 1979; Kirshen, 1981; Mieure, 1977; Trussell and DeBoer, 1983; Varma et al., 1979). On the other hand, liquid-liquid extraction requires minimal instrumentation (Henderson et al., 1976; Kirshen, 1981; Mieure, 1977; Richard and Junk, 1977; Trussell et al., 1979; Trussell and DeBoer, 1983), but can be costly in terms of expendable materials (Trussell and DeBoer, 1983). While many trials may be needed to find the appropriate volume of water to be purged, in purge and trap, the extract of liquid-liquid extraction can be diluted if the concentrations are too high (Inoko et al., 1984). Numerous liquid-liquid extractions can be done without dupli-

cating equipment as would be necessary for the purge and trap technique (Trussell and DeBoer, 1983).

The purge and trap also requires transfer of the sample from the original container to a stripping vessel, with the associated possibility of losses, while the liquid-liquid extraction can be done in the original sample container (Trussell and DeBoer, 1983); but even in liquid-liquid extraction, organics losses may occur during concentration (Al-Dhowalia, 1982). Sample preparation time is longer for liquid-liquid extraction than for purge and trap (Reding et al., 1979).

One major problem of liquid-liquid extraction is interference, which may come from impurities in the solvent (Dressman et al., 1979; Trussell et al., 1979; Trussell and DeBoer, 1983; U.S. EPA, 1979) or from the solvent peak itself interfering with component peaks (Al-Dhowalia, 1982; Inoko et al., 1984; Trussell and DeBoer, 1983). Interference is favoured because the solvents used are not selective for purgeable organohalides alone (Reding et al., 1979; Trussell et al., 1979). Another problem of liquid-liquid extraction is its limited sensitivity due to the small amount of solvent that can be injected (Al-Dhowalia, 1982); Trussell et al. (1979) also state that its extraction efficiency may be erratic.

Field sample tests showed the precision of both techniques to be comparable (Dressman et al., 1979; Otson et al., 1979; Reding et al., 1979).

3.3.1.3 Effect of External Variables

Varma et al. (1979) mention that over the range of concentrations studied (0 to 55 $\mu\text{g/l}$), the recovery of one organic by liquid-liquid extraction or purge and trap was not affected by the presence of other organics. Similarly, for liquid-liquid extraction, Richard and Junk (1977) found that using various background waters (distilled, tap) did not significantly affect extraction efficiency, while large amounts of other organics, such as 20% methanol, only had a slight effect. Glaze et al. (1981) also report that the effect of varying pH, ionic strength, or methanol content of the solution on liquid-liquid extraction efficiency was insignificant. For purge and trap analysis, Mieyre (1980) states that increasing the temperature will increase the vapour phase partitioning coefficient, and thus the recovery, and that increasing ionic strength will produce a salting out effect and thus also increase recovery.

3.3.2 Chromatographic Columns

In a gas chromatograph, once a sample has been injected, it is carried by an inert gas through the chromatographic column, that slows down the movement of some compounds while letting other compounds elute with little resistance. The two most popular types of columns for gas chromatographic analysis of volatile organics are packed columns and capillary columns. In a packed column, the liq-

uid phase (that will slow down the movement of the compounds) is coated on a solid phase "packed" in the column; in a capillary column, the column's internal diameter is very small (capillary), and the liquid phase coats the column walls directly.

Packed columns have a much lower resolution (of peaks) power than capillary columns, making them less convenient for the analysis of complex mixtures, such as wastewaters (Al-Dhowalia, 1982; Trussell and DeBoer, 1983). Packed columns are also less sensitive than capillary columns, and active sites, may appear on them and cause sample losses, while capillary columns are inert (Trussell and DeBoer, 1983). Packed columns have a higher loading capacity than capillary columns, however (Trussell and DeBoer, 1983); because of their small internal area, capillary columns can only accommodate small sample volumes, which will create problems in reproducibility and sensitivity. (Al-Dhowalia, 1982). Capillary columns also require special connection and injection hardware, and considerable experience (Trussell and DeBoer, 1983). There is more general experience in separation with packed columns, and packed columns are also less expensive than capillary columns (Trussell and DeBoer, 1983).

Capillary columns have improved analytical times, a greater selectivity and they can withstand extremely low temperatures (Trussell and DeBoer, 1983). However, they are more difficult to prepare and maintain stable than packed

columns (Al-Dhowalia, 1982; Trussell and DeBoer, 1983), and extremely volatile compounds may cause problems with them (Trussell and DeBoer, 1983).

3.3.3 Compounds Identification and Concentration Measurement

3.3.3.1 Detectors

Once the compounds have been separated in the chromatographic column, the amount of each compound coming out of the column must be known. The detectors are used to transform the mass coming out into an electric signal, for measurement. The two detectors most commonly mentioned in volatile organics analysis papers are the flame ionization detector and the electron capture detector; the electrolytic conductivity detector and the mass spectrometer are also used sometimes.

In the flame ionization detector, organic compounds that can be combusted in a hydrogen flame form ions that alter a baseline electrical current when they impact an electrode inserted in the gas flow (Trussell and DeBoer, 1983). This detector will respond to most carbon containing molecules (Trussell and DeBoer, 1983), but will not respond to common inorganics (H_2O , CO_2 , NH_3 , N_2 , He), allowing a wider selection of carrier gases (Al-Dhowalia, 1982). Its sensitivity will be lower than that of more specific detectors (Trussell and DeBoer, 1983).

In an electron capture detector, organic compounds capable of absorbing electrons decrease the baseline signal

generated by electrons emitted from a radioactive foil as beta radiation. (Trussell and DeBoer, 1983). Being among the most sensitive detectors known to date (Al-Dhowalia, 1982), it can measure with a high degree of precision halogen and oxygen containing compounds (Al-Dhowalia, 1982; Trussell and DeBoer, 1983). It is, however, limited in linear dynamic range (Al-Dhowalia, 1982).

In the electrolytic conductivity detector, the halogens are converted to the ionic form as the organics are combusted in a furnace at 800°C; the combusted gas is then bubbled through a nonconducting fluid where the ions generate a signal by allowing electrical current to pass between the two measuring cells (Trussell and DeBoer, 1983). The advantage of this detector, which can also be an inconvenience, is its selectivity for halogenated compounds (Al-Dhowalia, 1982; Trussell and DeBoer, 1983).

The mass spectrometer is more complex. The organic compounds going through it are bombarded with high energy electrons that charge and fragment the molecules in reproducible patterns; the ions are separated by a magnetic field, as a function of their mass, and the current associated with each mass is measured (Trussell and DeBoer, 1983). Thus qualitative as well as quantitative information on the sample is obtained.

3.3.3.2 Identification and Determination of Concentration

The electric signals generated by the detector will be plotted and recorded by a plotter or integrator as peaks showing the variation of the electric signal as various amounts of different substances go through the detector. The compound to which each peak corresponds can be identified by comparing the retention times of the peaks with the retention times of peaks on chromatograms of standard solutions of known compounds (Al-Dhowalia, 1982; Trussell and DeBoer, 1983). Sometimes, an internal standard, that is a compound easily detected and whose retention time is different from those of the compounds of interest, is added in known amounts to the samples, and the ratio of the retention times of each peak relative to the retention time of the internal standard are compared to identify compounds. For a better identification of components in a sample, retention times can be compared on two or more columns; but mass spectrometry still remains the best method for positive identification of components (Al-Dhowalia, 1982; Trussell and DeBoer, 1983).

To determine concentrations, one common method consists of spiking the sample or solvent with a known amount of an internal standard, and then comparing the ratio of component peak height (or area) to internal standard peak height (or area) for the sample to the corresponding ratio for a standard solution of known component concentration (Al-Dhowalia, 1982). This method was used by Eklund et al. (1978), Glaze

et al. (1981), Henderson et al. (1976) and Trussell et al. (1979), usually using 1,2-dibromoethane as the internal standard. Others compared the samples peak heights to standard solutions peak heights directly (Reding et al., 1979; Richard and Junk, 1977; U.S. EPA, 1979), or compared peak areas (Dressman et al., 1979; Kirshen, 1980; Mieure, 1977; Otson et al., 1979; Otson and Williams, 1981).

Reding et al. (1979) state that both ways of assessing response, that is; peak heights and peak areas methods, gave reproducible results. With respect to the use of an internal standard, Al-Dhowalia (1982) believes that its use reduces errors due to slight changes in flow rate, temperature, or due to detector non-linearity and injection non-reproducibility.

CHAPTER 4

EXPERIMENTAL APPROACH

Eqs. (2.16), (2.19), (2.21), and (2.22) show that experimental determination of mass transfer rate constants, $K_L a$, requires a wide array of data. Some parameters, such as concentration and flow rate, can be measured directly. Other parameters, such as liquid density, can be obtained indirectly by temperature measurement. However, less data is available for Henry's law constants.

The motivation for this study came from the necessity to treat groundwater contaminated by leachate from a landfill site in Gloucester, Ontario. The six contaminants that were selected for this study, present in moderate to high concentration in the contaminated groundwater, represent a wide range of volatility and solubility, as shown in Table 4.1. Most of these contaminants present a health hazard. Thus, in November 1985, the U.S. EPA published standards for eight volatile organic chemicals; trichloroethylene and 1,2-dichloroethane were among the five volatile organic chemicals considered as probable carcinogens, and for which maximum contaminant levels of 5 $\mu\text{g/l}$ were proposed (AWWA, 1985a).

Since no value of Henry's law constant for ether could be found in the literature, and because of the comments of

Table 4.1: Physical properties of volatile organics studied, at 20°C*

Volatile Organic Chemical	Other Common Names	Abbreviation Used	Formula	Density (g/ml)	Vapour Pressure (mm Hg)	Solubility in Water (mg/l)	Gloucester Concentration (ug/l)
Trichloroethylene	Trichloroethene	TCE	CCl_2CHCl	1.4642	60	1400 (25°C)	227
1,1-dichloroethane	Ethylidene chloride	1,1-DCA	CHCl_2CH_3	1.1757	180	5500	492
Toluene	Methylbenzene	Toluene	$\text{C}_6\text{H}_5\text{CH}_3$	0.8669	22	515	11
Chloroform	Trichloromethane	CHCl_3	CHCl_3	1.4832	160	8000	7155
1,2-dichloroethane	Ethylene dichloride	1,2-DCA	$\text{CH}_2\text{ClCH}_2\text{Cl}$	1.2351	61	8690	352
Ether	Ethyl Ether Diethyl Ether	Ether	$\text{C}_2\text{H}_5\text{OC}_2\text{H}_5$	0.71378	442	69000	N.A.

* Unless otherwise stated

** Abbreviations used in text or tables

*** From Weast (1977)

From Verschueren (1977)

!! Average concentration found at well 37M, a widely contaminated well in the Gloucester landfill site, in 1983

!!! Not available

some authors (Section 3.1.2.1), Henry's law constants were also determined experimentally. To determine Henry's law constants, H , as well as to determine K_{La} , the concentration of organic compounds in water must be measured. They were measured as follows.

4.1 Water Analysis for Organics

4.1.1 Analytical Instruments

The organic chemicals were isolated using a Varian Vista 6000 gas chromatograph (Varian Instrument Group) equipped with a flame ionization detector. The detector's electric signals were transformed into concentrations by an HP 3392A integrator (Hewlett-Packard Company). The samples could not be injected directly into the gas chromatograph, because the water could affect the chromatographic column, and because for dilute samples, volumes larger than the column capacity would have to be injected. Samples were concentrated with a Tekmar Liquid Sample Concentrator LSC-2 (Tekmar Company), a purge and trap unit.

These three instruments formed a fully automated network. Once the sample was transferred into the purge vessel, all that had to be done was to push the start button on the concentrator. The sample was purged, and the gas chromatograph and integrator started automatically as soon as the trap desorption stage was reached; at the end of the analysis, the integrator printed the concentrations and the gas chromatograph cooled down, while the concentrator was

ready for another run. The concentrator had a miniature valve for single flow through two, right-angle port options, equipped with a Teflon® female luer connector, which allowed introduction of a 5 ml sample directly into the purge vessel from a syringe with luer lock or luer tip without removing the vessel from the concentrator (Fig. 4.1).

Since the samples to be analysed contained only a few organic chemicals, the resolution power of packed chromatographic columns was considered adequate (Section 3.3.2). The column selected was a 2.44 m (8 ft) long by 3.2 mm (1/8 in.) external diameter stainless steel column packed with 1% SP-1000 on 60/80 Carbopack-B (Supelco, Inc.). The trap of the concentrator was a 304.8 mm (12 in.) long by 3.2 mm (1/8 in.) external diameter trap packed with Tenax®. Table 4.2 gives data on the gases used.

4.1.2. Operating Conditions

The gases flow rates and operating pressures are given in Table 4.2. Table 4.3 lists the other instrument operating conditions.

4.1.3. Instruments Preparation

Whenever the concentrator and gas chromatograph were used after long periods of inactivity, the concentrator's trap was baked and the chromatographic column was conditioned according to manufacturers' instructions, to remove possible contaminants.

Figure 4.1: Purge vessel and valve

Table 4.2: Gas data

Function	Gas Type	Pressure kPa (psi)	Flow rate (ml/min)
carrier gas	UHP* nitrogen	531 (77)	30
purge gas	UHP nitrogen	138 (20)	40
detector gas	zero air	414 (60)	250-300
detector gas	zero hydrogen	276 (40)	30

* UHP = ultra-high purity

Table 4.3: Instrument operating conditions

Operation	Concentrator Duration (min)	Temperature (°C)	Gas chromatograph
purge	11		Injector temp.: 200°C
desorb	4	180	Column temp. program: 45°C for 3 min.; in- crease at 8°C/min.; hold at 200°C for 5.63 min.
bake	7	200	Detector temp.: 220°C
			sensitivity range: 10 ⁻¹¹

Since the detector's sensitivity may change, the instrument must be calibrated regularly. For calibration, a standard solution was prepared in a Teflon® bag closed by a Teflon® faced silicone septum, 9.5 mm (3/8 in.) in diameter by 3.2 mm (1/8 in.) thick, fit in a stainless steel Swagelok® 6.35 mm (1/4 in.) union (Fig. 4.2). Anhydrous calcium chloride (CaCl_2) pellets (Fisher Scientific, chemical No. C-614) were dissolved in tap water to a concentration of 0.64275 g/l, to approximate the ionic strength of the Gloucester groundwater. Approximately 970 ml of this solution, and 32 ml of HPLC (high performance liquid chromatography) grade methanol (CH_3OH ; Fisher Scientific, chemical No. A-452) were poured into the bag, which was weighed before and after each addition to determine the volume added. Before the bag was closed, all air that could be removed was exhausted.

Known amounts of the organics of interest, obtained from the suppliers listed in Table 4.4, were injected into the bag, to achieve concentrations of 5 mg/l (or concentrations of 10 to 35 mg/l for chloroform). All injections and sample collection or preparation, were made with Hamilton Microliter® syringes #701 (10 μl) with fixed needles, or with Hamilton Gastight® syringes #1710 (100 μl), #1001 (1 ml), #1005 (5 ml), or #1010 (10 ml), all with Teflon® luer lock tips (Hamilton Company) to which Hamilton model RF728 (gauge 28) or KF722 (gauge 22) hypodermic needles could be attached. The solution in the bag was mixed on a magnetic

Figure 4.2: Septum-closed bag

Table 4.4: Suppliers of organic chemicals

Compound	Supplier	Grade	Supplier No.
trichloroethylene	Fisher Scientific	A.C.S.	T-341
1,1-dichloroethane	Aldrich Chemical Co., Inc.	-	D6; 155-5
toluene	J.T. Baker	Baker analysed	3-9460
chloroform	J.T. Baker	Baker analysed	3-9180
1,2-dichloroethane	Fisher Scientific	A.C.S.	E-175
ether	Fisher Scientific		E-138 CB

Table 4.5: Compounds retention times

Compound	Approximate retention time (min)	Calibration number
trichloroethylene	17.72	5
1,1-dichloroethane	11.47	1
toluene	24.85	6
chloroform	12.78	3
1,2-dichloroethane	13.47	4
ether	12.43	2

stirrer four hours or more, and stored in a refrigerator at approximately 6°C overnight.

The next morning, or soon thereafter, a known amount of standard solution was injected in a 5 ml syringe containing calcium chloride solution, and the resulting 5 ml of solution were immediately transferred into the purge vessel and analysed. The integrator, that plotted the detector's signals as peaks, was programmed to compute concentrations assuming they were directly proportional to the respective peak areas. The same amount of standard was injected five times, and the average response factors (concentration/peak area) were stored in the integrator's memory. Compounds were identified by peak retention times, and no internal standard was used. Fig. 4.3 shows a typical chromatogram and report; the compounds' retention times, given in Table 4.5, are printed by the integrator at the peak tips.

To be sure that the detector response was linear, i.e., the detector signal was always proportional to the amount of substance going through it, samples obtained by dilution of standard solution in calcium chloride solution were analysed. These samples were made to cover the range of concentrations expected in experimental runs. The amount injected was plotted against the amount detected, the line of best fit obtained by the method of least squares was drawn, and the coefficient of determination, r^2 , was computed.

Calibrated and checked for linearity, the instruments were ready for use. While in use, to check that the detec-

Figure 4.3: Typical integrator printout

tor's sensitivity and instrument operating conditions did not change, known amounts of standard solution were analysed every two to three weeks. Blanks (calcium chloride solution with no organics) were analysed daily to check that the trap and chromatographic column were uncontaminated.

4.2 Henry's Law Constants Determination

A method very similar to that of Munz and Roberts (1982; Section 3.1.2.3) was applied to determine Henry's law constants experimentally. A stock solution of the organics of interest was prepared in a Tedlar® 3.8 l gas sampling bag with septum valve (Cole-Parmer Instrument Company) containing methanol and a calcium chloride solution (0.64275 g/l); the bag was closed by a Teflon® faced silicone septum described previously, fit in a brass Swagelok® 6.35 mm (1/4 in.) union (Section 4.1.3, and Fig. 4.2). The solution was mixed at an approximate frequency of one cycle per second for over two hours on a Fisher Shaking Water Bath, model 127 (Fisher Scientific) on which a platform was fit; it was then stored at approximately 6°C.

The temperature of a Forma Lab environmental room (Forma Scientific) was adjusted to approximately 20°C. One ml of stock solution was injected in a 10 ml syringe containing 9 ml of aqueous calcium chloride solution, yielding a solution of concentrations as shown in Table 4.6. The syringe was closed with a Mininert® Teflon® syringe valve for

Table 4.6: Approximate average organics concentration in stock solution for H₂ determination

Compound	Organics concentration ($\mu\text{g/l}$) for experiments at	
	19.9°C	29.75°C
trichloroethylene	1900	1550
1,1-dichloroethane	1400	1300
toluene	1450	1250
chloroform	7650	7650
1,2-dichloroethane	1500	1400
ether	900	900

Figure 4.4: 10 ml Gastight[®] syringe with valve

luer lock syringe (Fig. 4.4), and shaken approximately 20 minutes at 1 cycle/s on the shaking water bath in the environmental room. Five ml of the resultant solution were then analysed, the plunger of the syringe was pulled back so that 5 ml of air were in contact with the remaining 5 ml of solution, the valve was closed again and the syringe was shaken at 1 cycle/s in the environmental room. After 24 hours of continuous shaking, the 5 ml of air were expelled under a fume hood, and the solution analysed. This procedure was repeated for seven other 10 ml syringes.

It was suspected that there would be some organics, losses by volatilization from the syringe-valve system over the 24 hour period; therefore, the above procedure was repeated for all eight syringes, with the difference that no air was drawn into the syringe after the first 5 ml of solution were transferred in the purge vessel. Thus the change in concentration of the solution was due to losses alone. To assess the effect of temperature on H, the above manipulations for Henry's law constants and losses determination were repeated with the environmental room temperature set around 30°C.

4.3 Mass Transfer Rate Constants Determination

4.3.1 Set Up Description

Fig. 4.5 is a schematic representation of the experimental set up. The main water tank, made up of painted aluminium, had a capacity of 1560 l. A Monarch model BE-33,

Figure 4.5: Experimental set up

type A centrifugal steel pump (Monarch Industries Ltd) pumped the water from the main tank to the painted aluminium constant head tank, installed approximately 2.5 m above ground. All pipes between the two tanks, and the removable drain pipes, were 50.8 mm (2 in.) i.d. PVC pipes.

There were three removable drain pipes, of length 111 mm (4 3/8 in.), 225 mm (8 7/8 in.), and 390 mm (15 3/8 in.), respectively, that could be pressure fit in the flange in the bottom of the constant head tank. Thus by changing the water level, three different liquid flow rates could be obtained. Liquid flow rates were measured by recording the time needed to collect a given weight of water at known temperature.

To bring the flow rates into the desired range, one of the 19.05 mm (3/4 in.) brass gate valves at the exit of the constant head tank was partially closed, and a machine screw was fixed in it so that the valve could afterwards be opened fully and closed back to the same degree of opening. A steel machine screw was used for the first experimental runs, but it corroded in the few months that separated Runs 15 and 16, and was replaced by a brass machine screw for Runs 16 to 42.

The other 19.05 mm brass gate could be fully opened or closed, and was used as a flow cut-off valve. A 19.05 mm (3/4 in.) i.d. Plexiglas® pipe, and Plexiglas® and brass 90° bends brought the water from the constant head tank to the packed column. Brass ports in the pipe allowed removal by

suction of the air trapped at high points at the beginning of the runs.

A concentrated solution of the volatile organics of interest was contained in a 20.3 l Tedlar® gas sampling bag with on/off valve (Cole-Parmer Instrument Company) to which a removable Teflon® resin stopcock for burets was adapted to facilitate closure of the bag (Fig. 4.6). A piston metering pump (FMI Lab Pump model RP-D-OSSV; Fluid Metering, Inc.) was used to pump the organics solution into the influent pipe through 6.35 mm (1/4 in.) i.d. Teflon® tubing; the sintered carbon lining of the steel piston was assumed not to affect the organics solution. The flow rate, adjusted from the metering pump, was metered with a rotameter (Lab Crest Series 100 Century Flowmeter; Fischer and Porter) using meter tube No. 448-225 and a stainless steel float; in the rotameter the solution was in contact with stainless steel, glass, Teflon®, and Viton® O rings. The organics injection apparatus is shown on Fig. 4.7.

To be able to assemble and dismantle the column, the second bend of the influent pipe, was attached to the influent pipe and packed column by sleeves made of 25.4 mm (1 in.) i.d. Tygon® tubing, as shown in Figs. 4.8 and 4.9. The pieces of Plexiglas® pipe extending from the two arms of the bend were always brought as close as possible to the extremity of the influent pipe and to the piece of pipe go-

Figure 4.6: Stopcock closed bag

Figure 4.7: Organics injection apparatus

Figure 4.8: Column details

Figure 4.9: Influent pipe flexible connection

ing into the column, and all of these were usually in contact.

Thus, until it reached the packed column, the only materials suspected of being able to adsorb organics that came into contact with the influent organic solution are Plexiglas® and very small amounts of Tygon® tubing. In the column, the solution was distributed on the packing by a perforated brass cap (Fig. 4.10).

The column was made of 304.8 mm (1 ft) long sections of 101.6 mm (4 in.) i.d. Plexiglas® pipe 6.35 mm (1/4 in.) thick, joined by couplings made of 114.3 mm (4 1/2 in.) i.d. Plexiglas® pipe sections 114.3 mm long (Figs. 4.8 and 4.11). Up to six of these packed sections could be assembled (Fig. 4.12). The influent and effluent sections were shorter, to minimize contact time between liquid and gas outside the packing. Thus the liquid distributor cap was approximately 38 mm (1 1/2 in.) above the top of the packing, while the effluent section was about 152.4 mm (6 in.) long.

Figs. 4.8 and 4.11 also show that a Plexiglas® redistribution ring, extending 12.7 mm (1/2 in.) into the column, and a packing support screen made of 6.35 mm (1/4 in.) galvanized steel screen were fixed in the middle of each coupling. A packing support screen is shown in Fig. 4.13. Viton® O rings 3.2 mm (1/8 in.) in cross section, needed to prevent fluid leaks, were placed over 25 mm away from the coupling's center to minimize contamination of the liquid or adsorption from it.

Figure 4:10: Distributor cap details

Figure 4.12: Packed column

Figure 4.11: Unpacked column section

Figure 4.13: Packing support screen

Figure 4.14: 6.35 mm and 12.7 mm Raschig rings, and 12.7 mm Intalox® saddles

The column was packed with 6.35 mm (1/4 in.) or 12.7 mm (1/2 in.) ceramic Raschig rings, or 12.7 mm (1/2 in.) ceramic Intalox® saddles (Fig. 4.14), all obtained from The Norton Company, Chemical Process Products Division. The choice of packing type was based on availability and wide use in industrial applications. The sizes chosen insured a column-to-packing diameter ratio of at least 8 to 1 (Section 3.2.1.1). Also ceramic was not expected to adsorb organics.

Influent and effluent samples were collected in the 10 ml Hamilton Gastight® syringes closed with Mininert® valves used for Henry's law constants determination (Section 4.2 and Fig. 4.4). The sampling valves were Hamilton miniature inert valves for flow through three ports (Fig. 4.15), designed to have a low dead volume. They were tied to the influent and effluent pipes by short brass fittings, again to minimize dead volume. The Teflon® luer tip of the Mininert® syringe valves could be fit in the Teflon® female luer connector of the sampling valves, to minimize possible volatilization losses when sampling.

A 19.05 mm (3/4 in.) brass gate valve on the effluent liquid pipe (Fig. 4.5) was used to control the effluent flow rate, insuring that a depth of 10 to 30 mm of water always remained at the bottom of the column, below the packing and influent air distributor (Fig. 4.8). This water formed a seal, forcing the gas up through the packing.

The air flow, provided by a Brunner model H-63, two cylinder single stage air compressor (Dunham Bush), was con-

Figure 4.15: Sampling valve

Figure 4.16: Aerated effluent basins

trolled by a gate valve on the compressor's tank and metered using a Gilmont shielded bypass flowmeter no. 5 (Cole-Parmer Instrument Company), a rotameter, with a glass float. A hand level (Keuffel & Esser Canada, Inc.) improved the accuracy of the rotameter readings. The pressure at the rotameter's entrance was measured with a u-tube, open end, manometer containing water, while a mercurial barometer with sliding vernier (Sargent-Welch Scientific Company) was used to determine the atmospheric pressure. Another u-tube manometer, filled either with water or red gauge oil (specific gravity 0.827) gave the pressure drop through the packing.

The effluent gas was returned to the atmosphere via a fume hood. The effluent liquid was pumped into the same fume hood, where it went through four diffused aeration basins in series to remove all remaining volatile organics before sending the water to the sewers (Fig. 4.16).

4.3.2. Experimental Conditions

Table 4.7 summarizes the experimental conditions studied.

Experiments were conducted at each packing depth for each of the three pairs of liquid and gas flow rates. Experiments 28, 29, and 30 were designed to determine the correction for end effects as Roberts et al. (1985) did, using an empty column (Section 2.8); thus only the influent and effluent sections, with no packed sections, were used. A packing layer approximately 10 mm deep was spread on the

Table 4.7: Experimental conditions

Run #'s	7-15	16-21	22-27	28-30	31-36	37-42
Dates (1985)	28/05- 06/06	16/09- 23/09	24/09- 01/10	02/10- 04/10	07/10- 14/10	15/10- 23/10
Packing material	6.35 mm Raschig rings	12.7 mm Raschig rings		6.35 mm Raschig rings	12.7 mm Intalox® saddles	
Packing depths (m)	0.914 1.219 1.829	0.914 1.219	1.524 1.829	0.010	0.914 1.219	1.524 1.829

-----Liquid flow rates, l/min-----
gas l/min

<u>1.3854</u> 103.9	<u>1.4209</u> 184.7	<u>1.3385</u> 184.7	<u>1.3303</u> 184.7
<u>1.5300</u> 114.8	<u>1.6048</u> 153.9	<u>1.5299</u> 153.9	<u>1.5150</u> 153.9
<u>1.8119</u> 135.9	<u>1.8607</u> 123.2	<u>1.7836</u> 123.2	<u>1.8139</u> 123.2

-----Desired influent concentrations (µg/l)-----

TCE	1800	1800	2000	2000	2000	3000
1,1-DCA	1000	1000	2000	2000	2000	3000
toluene	1600	1600	2000	2000	2000	3000
CHCl ₃	7000	7000	7000	7000	7000	7000
1,2-DCA	1000	1000	2000	2000	2000	2000
ether	800	800	2000	2000	2000	2000

screen, in the coupling uniting the two sections, to change the flow characteristics of the distributor cap jets, to reproduce in the effluent section the flow patterns observed in the other experiments.

Liquid flow rates were adjusted and measured before Run 7, and again before Run 16, when the steel machine screw in the gate valve was replaced by a brass machine screw (Section 4.3.1). Flow rates were measured again, with no readjustment, after Runs 30 and 39, and the flow rate values shown in the table were obtained. The way in which these different values were accounted for is discussed in Chapter 5. The gas flow rates, that were adjusted and measured each run, were changed for Runs 16 and following, to cover the widest range of gas to liquid ratios possible while remaining in the gas pressure drop zone of 200 to 400 N/m² per metre of packing for 12.7 mm Raschig rings, as recommended by Treybal (1980; Section 2.4). Fig. 2.4 shows the operating conditions on the generalized gas pressure drop correlation curves, assuming a water temperature of 23°C (close to experimental conditions) and using the flow rate values in Table 4.7.

The actual influent concentration values were usually within 10% of the desired concentrations. The influent concentrations of some compounds had to be increased between Runs 21 and 22, and between Runs 36 and 37 to keep the effluent concentrations above 10 µg/l, believed to be close to the lower limit of detector linearity.

Since there was a packing support screen at each coupling, each section of the packed tower could be packed separately. To insure maximum randomness, each section was packed in a water tank with a depth such that the top of the section was at least 100 mm below the water surface; the packing was slowly dumped at the water surface, as recommended by the manufacturer (Norton Company, 1977; Section 3.2.1.1). Porosity of the bed was obtained by capping one extremity of a packed section of column, weighing it, filling the voids with water at a known temperature and weighing it again to determine the volume of water added. Dividing the volume of water by the total section volume yielded porosity.

4.3.3 Preparation of Experimental Runs

The gas chromatograph, concentrator, and integrator, preparation were discussed in Section 4.1.3. A Fisher Accumet® model 210 pH meter with combination electrode, and a Radiometer Copenhagen type CDM 2e conductivity meter were also used; they were calibrated according to manufacturer's instructions, and their calibration was checked periodically.

The main tank was filled with tap water, and calcium chloride was dissolved in it to yield a 0.64275 g/l solution. The solution was prepared at least one day before any experimental run. Thus, the water temperature equilibrated with ambient temperature, yielding a more constant

water temperature throughout the runs, and the gases dissolved in tap water came out, diminishing the possibility of bubble formation in the influent pipe and associated flow rate variation. The main tank contained enough water for five experimental runs.

The organics solution was prepared in the afternoon of the day preceding the run. One litre of methanol was poured into a 3.8 l Tedlar® gas sampling bag described previously (Section 4.2 and Fig. 4.2), the air was removed and the bag was closed using a Teflon® faced septum. Known amounts of organics were injected into the bag, that was then shaken two hours on the shaking water bath in the environmental room (at 8°C). This solution was then transferred into a 20.3 l Tedlar® gas sampling bag closed by a buret stopcock, described in Sec. 4.3.1 (Fig. 4.6), that already contained 3 l of calcium chloride solution (0.64275 g/l). The air was again removed, and the solution shaken two hours in the environmental room, where it then remained until the next morning.

4.3.4 Experimental Runs

The first step of all experimental runs was to fill the organics injection apparatus (Teflon® tubing, metering pump, and rotameter) with an aqueous calcium chloride solution (0.64275 g/l). This was done to eliminate from the apparatus air bubbles that may cause flow variation. The organics

solution bag was then hooked to the tubing. The air compressor was started.

Then the appropriate removable drain pipe was fit in the constant head tank's flange, and the centrifugal pump started. Air bubbles were removed from the influent pipe by suction provided by a Little Giant model 13154 pressure/vacuum pump, (Gelman Instrument Company), and the gate valve closed to the predetermined setting, where the machine screw stopped it. The air flow rate was adjusted, immediately after the effluent liquid flow rate was adjusted to create a water seal at the bottom of the column. The organics solution metering pump was then started and organics flow rate adjusted. The organics flow rate varied throughout the runs, and was readjusted every 10 minutes, by modifying the length of the course of the metering pump's piston (Section 6.3.1.5).

To allow the system time to reach steady state, the first pair of samples (one influent and one effluent sample) was collected one hour after the metering pump was started. Three pairs of samples were collected in the same manner, at 10 minute intervals, the influent sample always being collected before the effluent sample. Before sampling, liquid was allowed to flow through the sampling valves, to obtain a sample as fresh as possible. The liquid used to flush the valves was collected in Teflon® bags and used to determine the influent and effluent liquid pH and conductivity.

All air bubbles were removed from the 10 ml sampling syringes, that were then stored in a refrigerator, at approximately 6°C, until they could be analysed. Five ml of each of the first, second, and third effluent sample were analysed, in that order, followed by 5 ml of the first, second, and third influent sample. After analysing 5 ml of calcium chloride solution, the remaining 5 ml of samples were analysed, in the same order. Because each analysis lasted approximately 40 minutes, even though the first sample was analysed immediately after it was collected, the last sample was analysed eight hours later.

Besides organics concentrations, data on ambient temperature in the packed column room and compressor room, compressed air temperature, and water temperature in the constant head tank and first aerated effluent basin, were collected. The atmospheric pressure, and readings of the two manometers, were also recorded. To find average values for these parameters, their values were recorded 20 minutes before the first sampling and 20 minutes after the last sampling, and averaged.

CHAPTER 5

RESULTS

5.1 Linearity of Detector

As mentioned in Section 4.1.3, the flame ionization detector was tested for linearity. Twenty-five samples ranging in organics concentration between 5 and 3000 $\mu\text{g/l}$ (between 70 and 6000 $\mu\text{g/l}$ for chloroform) were analysed. The amount of each compound introduced into the concentrator (amount injected) is plotted against the amount detected in Figs. 5.1 to 5.6; the bottom graph is an enlargement of the lower left-hand corner of the top graph. The amount injected was evaluated by multiplying the volume of standard solution used by the standard solution's average concentration.

For each compound, the equation of the best fitting line:

$$y = i + sw \quad (5.1)$$

where i = intercept

s = slope

w = independent variable (amount detected, in this case)

y = dependent variable (amount injected, in this case)

was determined by the method of least squares; thus (Kennedy and Neville, 1976):

LINEARITY DATA FOR
TRICHLOROETHYLENE
(0-3 MILLIGRAMS/LITRE)

(0-100 MICROGRAMS/LITRE)

Figure 5.1: Linearity data for trichloroethylene,
first test

LINEARITY DATA FOR
1,1-DICHLOROETHANE
(0-3 MILLIGRAMS/LITRE)

(0-100 MICROGRAMS/LITRE)

Figure 5.2: Linearity data for 1,1-dichloroethane,
first test

LINEARITY DATA FOR
TOLUENE
(0-3 MILLIGRAMS/LITRE)

Figure 5.3: Linearity data for toluene, first test

LINEARITY DATA FOR
CHLOROFORM

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(0-6 MILLIGRAMS/LITRE)

(0-300 MICROGRAMS/LITRE)

Figure 5.4: Linearity data for chloroform,
first test

LINEARITY DATA FOR
1,2-DICHLOROETHANE
(0-3 MILLIGRAMS/LITRE)

(0-100 MICROGRAMS/LITRE)

Figure 5.5: Linearity data for 1,2-dichloroethane, first test

LINEARITY DATA FOR
ETHER

(0-3 MILLIGRAMS/LITRE)

(0-100 MICROGRAMS/LITRE)

Figure 5.6: Linearity data for ether, first test

$$i = \frac{\sum w^2 \Sigma y - \Sigma w \Sigma wy}{N \Sigma w^2 - (\Sigma w)^2} \quad (5.2)$$

$$s = \frac{N \Sigma wy - \Sigma w \Sigma y}{N \Sigma w^2 - (\Sigma w)^2} \quad (5.3)$$

The coefficient of determination, r^2 , was also computed (Kennedy and Neville, 1976):

$$r^2 = \frac{(N \Sigma wy - \Sigma w \Sigma y)^2}{[N \Sigma w^2 - (\Sigma w)^2][N \Sigma y^2 - (\Sigma y)^2]} \quad (5.4)$$

Since the coefficient of determination is symmetrical with respect to y and w (Kennedy and Neville, 1976), the choice of the independent and dependent variables will affect i and s but not r^2 ; the amount injected was selected as the dependent variable, y , yielding the results in Table 5.1.

To verify if there was any interference between chloroform and ether integration, a new standard solution was prepared that contained all compounds but ether. Twelve samples, ranging in concentration between 10 and 3000 $\mu\text{g/l}$ (between 70 and 5700 $\mu\text{g/l}$ for chloroform), were prepared by dilution of this solution and analysed. Ether was added to the standard solution, and another series of twelve samples in the same concentration range analysed. The results are given in Table 5.2, and the chloroform and ether data are plotted in Figs. 5.7 to 5.9.

Table 5.1: First linearity test results

Compound	i	s	r ²
Trichloroethylene	-2.644	1.0094	0.9995
1,1-dichloroethane	-4.176	1.0132	0.9993
Toluene	-7.847	1.0889	0.9992
Chloroform	-16.120	1.0640	0.9791
1,2-dichloroethane	-4.520	1.0547	0.9994
Ether	-10.457	0.9866	0.9945

Table 5.2: Second linearity test results

Compound	Without Ether			With Ether		
	i	s	r ²	i	s	r ²
Trichloro-ethylene	-6.652	1.0366	0.9999	-3.413	1.0391	0.9998
1,1-dichloro-ethane	-9.753	1.0047	0.9999	-6.241	0.9866	0.9998
Toluene	-16.262	1.1744	0.9997	-11.524	1.1739	0.9997
Chloroform	-83.730	1.0698	0.9998	23.914	1.0634	0.9914
1,2-dichloro-ethane	-13.488	1.0586	0.9997	-7.384	1.0357	0.9997
Ether				-24.173	1.0220	0.9981

LINEARITY DATA FOR
CHLOROFORM
(0-6 MILLIGRAMS/LITRE)

Figure 5.7: Linearity data for chloroform,
without ether, second test

LINEARITY DATA FOR
CHLOROFORM
(0-6 MILLIGRAMS/LITRE)

Figure 5.8: Linearity data for chloroform,
with ether, second test

LINEARITY DATA FOR ETHER

(0-3 MILLIGRAMS/LITRE)

(0-100 MICROGRAMS/LITRE)

Figure 5.9: Linearity data for ether, second test

5.2 Henry's Law Constants

5.2.1 Experimental Determination

As mentioned in Section 4.2, Henry's law constants were determined by a method similar to the closed system method of Munz and Roberts (1982; Section 3.1.2.3). Losses from the syringes over their 24 hour period in the environmental room were assessed by analysing the first 5 ml of solution, which yielded the initial concentrations, C_{L0} . The syringe was then agitated one day in the environmental room, and the remaining 5 ml of solution analysed, to obtain the solute concentration after a day, C_{L1} (Section 3.1.2.3). The procedure was repeated for all eight syringes, and the ratio C_{L1}/C_{L0} computed for each syringe and each compound. Then, when computing Henry's law constants, the initial concentrations, C_{L0} , were multiplied by the C_{L1}/C_{L0} ratio computed for the same syringe, temperature, and compound, yielding the equivalent initial concentration, C_{L1} , once losses of a day were accounted for. From this value and the equilibrium concentration value, C_L^E (concentration after having shaken for one day the syringe containing 5 ml of solution and 5 ml of air), Henry's law constants were determined as:

$$H = \frac{C_{L1}}{C_L^E} - 1 \quad (5.5)$$

This equation is equivalent to Eq. (3.17), and reflects the fact that the liquid and gas volumes, V_L and V_G , respectively, were equal. The experimental results and a sample

calculation can be found in Appendix A; Table 5.3 presents the average and coefficient of variation values for the data at each temperature. The average or mean, $\bar{w}$, of a set of N variables, w , and its standard deviation, S_w , are (Kennedy and Neville, 1976):

$$\bar{w} = \frac{\sum w}{N} \quad (5.6)$$

$$S_w = \left[\frac{N \sum w^2 - (\sum w)^2}{N(N-1)} \right]^{1/2} \quad (5.7)$$

and the coefficient of variation, V_w , is simply:

$$V_w = \frac{S_w}{\bar{w}} \times 100 \quad (5.8)$$

5.2.2 Effect of Methanol

Methanol was used to increase organics solubility both in the Henry's law constants and mass transfer experiments stock solutions (Chapter 4). The effect of methanol on Henry's law constant was evaluated for chloroform, the compound found in highest concentration in the solutions, using the theoretical method of Munz and Roberts (1982; Section 3.1.3.3). The calculations are shown in Appendix B. It was found that methanol decreases chloroform's Henry's law constant by approximately 2%.

5.2.3 Effect of Temperature

The dependence of H on temperature was expressed by the equation:

Table 5.3: Henry's law constants data summary

Temperature (°C)	19.9		29.75	
Compound	Henry's law constant, H (mass conc./mass conc.)			
	Ave.	Coef. of Var.	Ave.	Coef. of Var.
TCE	0.375	17.6	0.453	8.8
1,1-DCA	0.220	17.3	0.268	9.7
Toluene	0.189	63.0	0.375	21.3
CHCl ₃	0.153	23.5	0.185	10.3
1,2-DCA	0.059	61.0	0.080	36.3
Ether	0.047	59.6	0.070	28.6

Table 5.4: Henry's law constants temperature correlation parameters*

Compound	Parameters**		Determination coefficient r^2
	b_0	b_1 (°K)	
Trichloroethylene	5.041	-1768	0.423
1,1-dichloroethane	4.790	-1851	0.403
Toluene	25.742	-8100	0.413
Chloroform	4.457	-1863	0.278
1,2-dichloroethane	11.872	-4384	0.124
Ether	13.708	-4968	0.234

* Parameters for each compound were obtained by correlating nine data points (four H values at 19.9°C and five H values at 29.75°C; see Appendix A).

** Parameters of Eq. (5.9), $\ln H = b_0 + b_1/T$.

$$\ln H = b_0 + \frac{b_1}{T_A} \quad (5.9)$$

where $b_0, b_1 = \text{constants}$

Eq. (5.9) has the same form as Eq. (3.24) of Singley et al. (1980). The nine Henry's law constant values obtained for each compound (Appendix A) were used to find the line of best fit by the method of least squares [Eqs. (5.1) to (5.3)], substituting $\ln H$ for y , b_0 for i , b_1 for s , and $1/T_A$ for w . The resulting values of b_0 , b_1 , and r^2 [Eq. (5.4)] are given in Table 5.4. Tables 5.5 and 5.6 give correlation parameters found by Kavanaugh and Trussell (1980), Singley et al. (1980), and ESE (1981). Kavanaugh and Trussell (1980) fit data from Kruis (1976) to a modified version of Eq. (3.23):

$$\log_{10} H_A = \frac{-\Delta H}{RT_A} + K \quad (5.10)$$

To judge if the values of Table 5.4 were reasonable, for each compound the line representing Eq. (5.9) was plotted on a graph of $\log_{10} H$ against $1/T_A$, along with the correlations presented in Tables 5.5 and 5.6, and literature values of H presented in Tables 5.7 to 5.11. All H values in Tables 5.7 to 5.11 were converted to units of mass concentration/mass concentration. The experimental data, found in Appendix A, was also plotted on these graphs (Figs. 5.10 to 5.15).

Roberts and al. (1982) showed that a change of $\pm 20\%$ in H values had only a small effect on experimentally deter-

Table 5.5: Kavanaugh and Trussell* Henry's law constants temperature correlation parameters

Compound	Parameters**	
	ΔH (kcal/kmole)	K
Trichloroethylene	3410	8.59
1,1-dichloroethane	3780	8.87
Chloroform	4000	9.10

* Kavanaugh and Trussell (1980).

** Parameters of Eq. (5.10): $\log_{10} H_A = (-\Delta H / RT_A) + K$
where $R = 1.987$ kcal/kmole-°K.

Table 5.6: Singley et al. and ESE* Henry's law constants temperature correlation parameters

Compound	Parameters**	
	B_0	B_1 (°K)
Trichloroethylene	14.451	-4489
1,1-dichloroethane	14.270	-4599
Toluene	14.014	-4574
Chloroform	16.499	-5310
1,2-dichloroethane***	4.048	-2361

* Singley et al. (1980); ESE (1981).

** Parameters of Eq. (3.24): $\ln H = B_0 + B_1/T_A$
Values obtained from Singley et al. (1980) except for 1,2-dichloroethane.

*** From ESE (1981):

Table S.7: Literature Henry's law constants for trichloroethylene

H mass conc. mass conc.	Temper- ature (°C)	Source*	Comments	Reference
0.49	25	Comp.		Dilling (1977)
0.40	20	Comp.		Dilling (1977)
0.413	20	Comp.		Kavanaugh and Trussell (1980)
0.371	20	Exp.		Mackay and Shiu (1981)
0.410±0.031	20	Exp.		Munz and Roberts (1982)
0.300±0.053	20	Exp.	Closed system measurement	Munz and Roberts (1982)
0.381	20	Lit. Exp.		Munz and Roberts (1982)
0.42±0.01	20	Exp.	Deionized water	Roberts et al. (1984)
0.51±0.03	20	Exp.	Filtered secondary wastewater effluent	Roberts et al. (1984)
0.41	20	Exp.		Roberts et al. (1985)
0.542	25	Exp.		Singley et al. (1980)
0.495	25	Comp.		Singley et al. (1980)
0.42	20	Comp.		Thomas (1982)

* Source: Comp.: Values computed from solubility and vapour pressure data.

Exp.: Values obtained from experimental measurements.

Lit.: Values found in other literature.

Table 5.8: Literature Henry's law constants for 1,1-dichloroethane

H mass conc. mass conc.	Temper- ature (°C)	Source*	Comments	Reference
0.24	25	Comp.		Dilling (1977)
0.234±0.008	25		Recommended value	Mackay and Shiu (1981)
0.313	25	Exp.		Singley et al. (1980)
0.218	25	Comp.		Singley et al. (1980)

* Source: Comp.: Values computed from solubility and vapour pressure data.
 Exp.: Values obtained from experimental measurements.
 Lit.: Values found in other literature.

Table 5.9: Literature Henry's law constants for toluene

H mass conc. mass conc.	Temper- ature (°C)	Source*	Comments	Reference
0.251	25	Comp.		Kavanaugh and Trussell (1980)
0.271	25	Exp.		Mackay et al. (1979)
0.272	25	Comp.		Mackay et al. (1979)
0.270±0.014	25		Recommended value	Mackay and Shiu (1981)
0.215	20	Comp.		Mackay and Yeun (1983)
0.263	25	Exp.		Singley et al. (1980)
0.240	25	Comp.		Singley et al. (1980)
0.28	20	Comp.		Thomas (1982)

* Source: Comp.: Values computed from solubility and vapour pressure data.
 Exp.: Values obtained from experimental measurements.
 Lit.: Values found in other literature.

Table 5.10: Literature Henry's law constants for chloroform

H mass conc. mass conc.	Temper- ature (°C)	Source*	Comments	Reference
0.16	25	Comp.		Dilling (1977)
0.128	20	Comp.		Kavanaugh and Trussell (1980)
0.136	20	Exp.		Lalezary et al. (1984)
0.116	20	Exp.		Mackay and Shiu (1981)
0.129	25	Exp.		Mackay and Shiu (1981)
0.153±0.012	25		Recommended value	Mackay and Shiu (1981)
0.224±0.031	20	Exp.		Munz and Roberts (1982)
0.111±0.040	20	Exp.	Closed system measurement	Munz and Roberts (1982)
0.106	20	Lit. Exp.		Munz and Roberts (1982)
0.24±0.02	20	Exp.	Deionized water	Roberts et al. (1984)
0.33±0.02	20	Exp.	Filtered secondary wastewater effluent	Roberts et al. (1984)
0.22	20	Exp.		Roberts et al. (1985)
0.267	25	Exp.		Singley et al. (1980)
0.166	25	Comp.		Singley et al. (1980)
0.200	20	Comp.		Thomas (1982)

- * Source: Comp.: Values computed from solubility and vapour pressure data.
 Exp.: Values obtained from experimental measurements.
 Lit.: Values found in other literature.

Table 5.11: Literature Henry's law constants for 1,2-dichloroethane

H mass conc. mass conc.	Temperature (°C)	Source*	Comments	Reference
0.050	25	Comp.		Dilling (1977)
0.046	25	Comp.		Kavanaugh and Trussell (1980)
0.040	25	Exp.		Mackay and Shiu (1981)
0.044±0.004	25		Recommended	Mackay and Shiu (1981)
0.04	-20	Comp.		Thomas (1982)

* Source: Comp.: Values computed from solubility and vapour pressure data.
 Exp.: Values obtained from experimental measurements.
 Lit.: Values found in other literature.

1,1-DICHLOROETHANE

Figure 5.11: 1,1-Dichloroethane Henry's law constant against inverse of temperature

Figure 5.12: Toluene Henry's law constant against inverse of temperature

CHLOROFORM

Figure 5.13: Chloroform Henry's law constant against inverse of temperature

1,2-DICHLOROETHANE

Figure 5.14: 1,2-Dichloroethane Henry's law constant against inverse of temperature

ETHER

Figure 5.15: Ether Henry's law constant against inverse of temperature

mined mass transfer rate constants, K_{La} , for stripping factor values $S > 1.5$. However, the values of the Henry's law constants also affect the K_{La} values predicted by the models of Onda et al. (1968) and Shulman et al. (1955c) [Section 5.4; Eq. (2.7)]. To evaluate this effect, K_{La} values predicted by both models were computed using Henry's law constant values equal to $1.2H$ and $0.8H$, and these predicted K_{La} were divided by the corresponding predicted K_{La} using $1.0H$. For each packing and each model, the highest and lowest K_{La} ratios are presented in Tables 5.12 and 5.13, respectively.

5.3 Packed Tower Air Stripping Experiments

5.3.1 Data Collected

Section 4.3.4 presented a brief list of the data collected. More specifically the following data were recorded in each experimental run:

- Packing media: size, type, porosity of bed, depth of bed
- Liquid flow rate; length of removable drain pipe
- Temperature (2): packed column room, compressor room;
compressed air;
water in constant head tank, water in
effluent tank
- Manometers readings (2): packed column manometer, gas
rotameter manometer
- Atmospheric pressure (2)
- Gas rotameter reading (2)
- Specific gravity of packed column manometer fluid

Table 5.12: Ratio of predicted K_{La} using 1.2H to predicted K_{La} using 1.0H

Model Packings*	Onda et al.		Shulman et al.	
	6.35 mm R.r.	12.7 mm R.r.	12.7 mm I.s.	12.7 mm R.r.
Run #**	15	16	31	16
Trichloroethylene	1.003	1.005	1.010	1.006
1,1-dichloroethane	1.005	1.009	1.016	1.009
Toluene	1.005	1.010	1.020	1.011
Chloroform	1.007	1.013	1.023	1.014
1,2-dichloroethane	1.018	1.033	1.057	1.035
Ether	1.020	1.036	1.062	1.038

* R.r.: Raschig rings; I.s.: Intalox® saddles.

** Experimental run number.

Table 5.13: Ratio of predicted K_{La} using 0.8H to predicted K_{La} using 1.0H

Model	Onda et al.		Shulman et al.	
	5.35 mm R.r.	12.7 mm R.r.	12.7 mm I.s.	12.7 mm R.r.
Run #**	15	16	31	16
Trichloroethylene	0.996	0.992	0.985	0.991
1,1-dichloroethane	0.993	0.987	0.976	0.986
Toluene	0.993	0.986	0.972	0.985
Chloroform	0.990	0.982	0.967	0.980
1,2-dichloroethane	0.974	0.954	0.925	0.952
Ether	0.972	0.951	0.920	0.948

* R.r.: Raschig rings; I.s.: Intalox® saddles.

** Experimental run number.

- Water composition: pH, conductivity of influent and effluent liquid;
concentrations of organics in the influent and effluent liquid

The number two in parentheses, (2), follows the headings of measurements that were recorded twice, ten to twenty minutes before and after sampling (Section 4.3.4). Appendix-D presents computer printouts listing the recorded data and results of the first computations.

5.3.2 Flow Rates

5.3.2.1 Gas Flow Rate

As mentioned in Section 4.3.2, the gas flow rate was adjusted and rotameter read at each experimental run. The rotameter's average reading was converted to a gas flow rate value, in l/min, using a manufacturer supplied plot of flow rate against scale reading. Division by 60 000 converted the flow rate value to units of m³/s.

This flow rate value was converted to the equivalent flow rate value at standard temperature and pressure according to manufacturer's instructions, using the formula:

$$Q_{OC} = Q_{OR} \left[\frac{530 p_F}{T_{CR} 760} \right]^{1/2} \quad (5.11)$$

where p_F = total rotameter's inlet pressure (mm Hg)
 Q_{OC} = gas volumetric flow rate at standard temperature and pressure (m³/s)
 Q_{OR} = gas volumetric flow rate read from rotameter conversion chart (m³/s)
 T_{CR} = compressed air temperature, expressed in °R (°F + 460)

The total flowmeter pressure, p_T , was the sum of the barometric pressure and the gauge pressure head on the flowmeter, p_{ga} , in mm Hg. Since the open end u-tube manometer preceding the rotameter was filled with water, p_{ga} was computed as:

$$p_{ga} = \frac{Z_{Ho} - Z_{Lo}}{13.5694} \quad (5.12)$$

where Z_{Ho} = rotameter's manometer liquid level, low pressure side (mm H₂O)

Z_{Lo} = rotameter's manometer liquid level, high pressure side (mm H₂O)

and 13.5694 is the average specific gravity of mercury. The gas flow rate at ambient conditions was found from the ideal gas law:

$$Q_a = Q_{ac} \left[\frac{760}{p_a} \cdot \frac{T_K}{293.15} \right] \quad (5.13)$$

where p_a = barometric (ambient) pressure (mm Hg)

T_K = absolute temperature in packed column room (°K)

A sample calculation can be found in Appendix C. Table 5.14 lists the values for all experimental runs.

5.3.2.2 Liquid Flow Rate

Because water flow rates were measured by weighing and recording time (Section 4.3.1), they could not be measured during each experimental run. For Runs 7 to 15, only one series of flow rates measurements was performed, before Run 7 (Section 4.3.2); liquid flow rates were assumed constant throughout Runs 7 to 15. For Runs 16 to 42, however, flow

Table 5.14: Experimental gas flow rates

Liquid Flow Rate		Low		Medium		High	
Packing depth (m)	Run No.	Q_0 (m^3/s)		Run No.	Q_0 (m^3/s)	Run No.	Q_0 (m^3/s)
6.35 mm Raschig rings							
0.914	15	176.39×10^{-5}		14	195.33×10^{-5}	13	231.77×10^{-5}
1.219	12	175.56×10^{-5}		11	199.84×10^{-5}	10	235.06×10^{-5}
1.829	9	177.63×10^{-5}		8	196.01×10^{-5}	7	233.42×10^{-5}
Average		176.53×10^{-5}			197.06×10^{-5}		233.42×10^{-5}
Std. Dev.		1.04×10^{-5}			2.43×10^{-5}		1.65×10^{-5}
Coef. Var.		0.6			1.2		0.7
12.7 mm Raschig rings							
0.914	18	314.50×10^{-5}		17	259.96×10^{-5}	16	206.80×10^{-5}
1.219	20	315.67×10^{-5}		21	260.99×10^{-5}	19	208.01×10^{-5}
1.524	24	315.58×10^{-5}		23	260.24×10^{-5}	22	208.61×10^{-5}
1.829	27	316.56×10^{-5}		26	260.19×10^{-5}	25	209.82×10^{-5}
Average		315.58×10^{-5}			260.35×10^{-5}		208.31×10^{-5}
Std. Dev.		0.84×10^{-5}			0.45×10^{-5}		1.26×10^{-5}
Coef. Var.		0.3			0.2		0.6
6.35 mm Raschig rings							
0.010	30	312.84×10^{-5}		29	259.07×10^{-5}	28	208.09×10^{-5}
12.7 mm Intalox® saddles							
0.914	33	312.98×10^{-5}		32	259.42×10^{-5}	31	207.74×10^{-5}
1.219	35	313.38×10^{-5}		36	260.39×10^{-5}	34	208.76×10^{-5}
1.524	39	314.56×10^{-5}		38	262.11×10^{-5}	37	210.48×10^{-5}
1.829	42	314.39×10^{-5}		41	260.52×10^{-5}	40	208.80×10^{-5}
Average		313.83×10^{-5}			260.61×10^{-5}		208.95×10^{-5}
Std. Dev.		0.77×10^{-5}			1.11×10^{-5}		1.14×10^{-5}
Coef. Var.		0.2			0.4		0.5

rates were measured before Run 16, and after Runs 30 and 39 (Section 4.3.2).

For Runs 28 to 30 (empty column experiments), the column was a few mm higher than it should have been, and consequently an air bubble approximately 5 mm thick by 25 mm long was trapped in the influent pipe immediately after the second bend. A bubble this size was liable to affect liquid flow rates; thus, the flow rates recorded after Run 30 were assumed to be the flow rates prevailing for Runs 28 to 30.

For Runs 16 to 27, and 31 to 42, it was assumed that flow rates decreased linearly. Liquid flow rates measured before Run 16 were assumed to be the flow rates at mark 0, and those measured after Run 39 were associated with mark 25. Flow rates for Run 16 to 39 and 40 to 42 were ~~set~~ equal to flow rates associated with marks 1 to 24 and 26 to 28, respectively (Fig. 5.16). Note that Runs 28 to 30 were included and the corresponding flow rates computed.

Table 5.15 lists the values for all experimental runs. The values measured for Runs 28 to 30 are listed in the table.

5.3.3 Water Temperature

The effluent water temperature was measured in the first aerated effluent basin. Since aeration was expected to affect the water temperature, water was pumped from a tank into the aeration basins, at a flow rate close to the experimental liquid flow rates, and aerated at a gas flow

Figure 5.16: Assessment of liquid flow rates decrease

Table 5.15: Experimental liquid flow rates

Liquid Flow Rate		Low		Medium		High
Packing depth (m)	Run No.	Q_L (m^3/s)		Run No.	Q_L (m^3/s)	Run No. Q_L (m^3/s)
6.35 mm Raschig rings						
0.914	15	2.3090×10^{-5}		14	2.5500×10^{-5}	13 3.0198×10^{-5}
1.219	12	2.3090×10^{-5}		11	2.5500×10^{-5}	10 3.0198×10^{-5}
1.829	9	2.3090×10^{-5}		8	2.5500×10^{-5}	7 3.0198×10^{-5}
Average		2.3090×10^{-5}			2.5500×10^{-5}	3.0198×10^{-5}
Std. Dev.		0			0	0
Coef. Var.		0			0	0
12.7 mm Raschig rings						
0.914	18	2.3500×10^{-5}		17	2.6627×10^{-5}	16 3.0980×10^{-5}
1.219	20	2.3380×10^{-5}		21	2.6387×10^{-5}	19 3.0887×10^{-5}
1.524	24	2.3138×10^{-5}		23	2.6268×10^{-5}	22 3.0793×10^{-5}
1.829	27	2.2957×10^{-5}		26	2.6088×10^{-5}	25 3.0700×10^{-5}
Average		2.3244×10^{-5}			2.6343×10^{-5}	3.0840×10^{-5}
Std. Dev.		0.0243×10^{-5}			0.0226×10^{-5}	0.0121×10^{-5}
Coef. Var.		1.0			0.9	0.4
6.35 mm Raschig rings						
0.010	30	2.2308×10^{-5}		29	2.5498×10^{-5}	28 2.9727×10^{-5}
12.7 mm Intalox® saddles						
0.914	33	2.2595×10^{-5}		32	2.5728×10^{-5}	31 3.0512×10^{-5}
1.219	35	2.2473×10^{-5}		36	2.5490×10^{-5}	34 3.0418×10^{-5}
1.524	39	2.2232×10^{-5}		38	2.5370×10^{-5}	37 3.0325×10^{-5}
1.829	42	2.1990×10^{-5}		41	2.5130×10^{-5}	40 3.0200×10^{-5}
Average		2.2323×10^{-5}			2.5430×10^{-5}	3.0364×10^{-5}
Std. Dev.		0.0268×10^{-5}			0.0249×10^{-5}	0.0133×10^{-5}
Coef. Var.		1.2			1.0	0.4

rate similar to the experimental one. The temperature of the water was measured in the tank and the aerated basin, and the maximum temperature difference was observed to be 0.3°C (aerated water was colder). Increasing the effluent water temperature by 0.3°C caused a decrease in the number of transfer units (Section 5.3.5) of less than 0.5%. Therefore, the effluent water temperature read in the aerated basin was used, uncorrected, for all computations.

Both the influent and effluent water temperatures varied randomly, depending on ambient conditions. Table 5.16 shows the variation of the average water temperature (average of constant head tank and effluent tank water temperatures).

5.3.4 pH and Conductivity

The influent and effluent water pH and conductivity were recorded to serve as indicators of the variations in water composition. Table 5.17 lists parameters related to pH and conductivity measurements.

5.3.5 Total Number of Transfer Units

Computation of the total number of transfer units, NTUT, and mass transfer rate constants, $K_L a$, requires knowledge of some parameters that can be computed from the recorded data. The liquid mass flux, L ($\text{kg}/\text{m}^2\text{-s}$), can be computed from the volumetric liquid flow rate, Q_L (m^3/s), and liquid density, ρ_L (kg/m^3):

Table 5.16: Average water temperatures

Liquid		Low		Medium		High	
Flow Rate							
Packing	Run	T	Run	T	Run	T	
depth	No.	(°C)	No.	(°C)	No.	(°C)	
(m)							
6.35 mm Raschig rings							
0.914	15	24.225	14	24.350	13	24.212	
1.219	12	24.325	11	25.275	10	25.375	
1.829	9	24.225	8	25.000	7	26.762	
Average		24.258		24.875		25.450	
Std. Dev.		0.058		0.475		1.277	
Coef. Var.		0.2		1.9		5.0	
12.7 mm Raschig rings							
0.914	18	23.475	17	23.375	16	23.675	
1.219	20	24.287	21	24.087	19	24.037	
1.524	24	23.625	23	24.175	22	24.438	
1.829	27	23.875	26	24.025	25	24.087	
Average		23.816		23.916		24.059	
Std. Dev.		0.355		0.366		0.312	
Coef. Var.		1.5		1.5		1.3	
6.35 mm Raschig rings							
0.010	30	23.125	29	23.575	28	23.975	
12.7 mm Intalox® saddles							
0.914	33	22.688	32	22.475	31	22.487	
1.219	35	22.375	36	22.725	34	23.175	
1.524	39	24.450	38	24.063	37	23.525	
1.829	42	24.250	41	24.375	40	24.912	
Average		23.441		23.410		23.525	
Std. Dev.		1.061		0.949		1.020	
Coef. Var.		4.5		4.0		4.3	

Table 5.17. Parameters related to pH and conductivity

Parameter	pH	Conductivity
minimum value	7.39	1180
maximum value	7.82	1340
average	7.617	1274.6
standard deviation	0.074	27.7
coef. of variation	1.0	2.2

LOSSES IN SYRINGES, 29.75°C

Syringe	Parameter	1,1-DCA	Ether	CHCl ₃	1,2-DCA	TCE	Toluene
1	C _{LO}	1318.1	904.12	7663.7	1403.0	1576.2	1258.8
	C _{L1}	1266.2	906.54	7391.6	1386.6	1366.0	1055.8
	C _{L1/C_{LO}}	0.96063	1.00268*	0.96449	0.98831	0.86664	0.83874
2	C _{LO}	1316.6	908.63	7647.5	1406.6	1586.4	1261.7
	C _{L1}	1270.5	903.30	7403.0	1384.0	1380.0	1076.6
	C _{L1/C_{LO}}	0.96499	0.99413	0.96803	0.98393	0.86989	0.85329
R1	C _{LO}	1344.2	929.85	7807.2	1438.2	1615.6	1288.7
	C _{L1}	1270.8	906.42	7414.3	1388.9	1388.0	1083.5
	C _{L1/C_{LO}}	0.94540	0.97480	0.94967	0.96572	0.85912	0.84077
R2	C _{LO}	1335.1	920.66	7767.7	1435.9	1603.1	1280.3
	C _{L1}	1274.2	906.97	7480.9	1374.4	1391.8	1084.9
	C _{L1/C_{LO}}	0.95439	0.98513	0.96308	0.95717	0.86819	0.84738
3	C _{LO}	1306.0	901.48	7618.0	1400.1	1565.0	1252.0
	C _{L1}	1274.6	910.90	7436.1	1394.2	1371.7	1102.2
	C _{L1/C_{LO}}	0.97596	1.01045*	0.97612	0.99579	0.87649	0.88035
4	C _{LO}	1313.8	909.93	7637.8	1406.0	1576.9	1258.3
	C _{L1}	1277.2	908.97	7440.1	1391.5	1390.6	1096.8
	C _{L1/C_{LO}}	0.97214	0.99894	0.97412	0.98969	0.88186	0.87165
R3	C _{LO}	1317.6	913.87	7665.7	1413.0	1583.6	1263.6
	C _{L1}	1280.1	912.93	7461.7	1397.5	1384.6	1079.2
	C _{L1/C_{LO}}	0.97154	0.99897	0.97339	0.98903	0.87434	0.85407
R4	C _{LO}	1284.6	891.93	7475.0	1378.5	1542.2	1231.5
	C _{L1}	1282.6	913.90	7468.6	1398.0	1378.7	1108.1
	C _{L1/C_{LO}}	0.99844	1.02457*	0.99914	1.01415*	0.89398	0.89980

* A value of C_{L1/C_{LO}} = 1.00000 was used instead of the computed value

HENRY'S LAW CONSTANTS, 29.75°C

Syringe	Parameter	1,1-DCA	Ether	CHCl ₃	1,2-DCA	TCE	Toluene
1	C _{LO}	1316.1	911.89	7709.5	1411.0	1575.4	1256.7
	C _{L1}	1264.3	911.89	7435.7	1394.5	1365.3	1054.0
	C _L ^E	991.84	842.75	6248.7	1272.0	925.06	824.99
	H	0.275	0.082	0.190	0.096	0.476	0.278
2	C _{LO}	1320.3	913.13	7708.2	1411.5	1589.5	1263.6
	C _{L1}	1274.1	907.77	7461.8	1388.8	1382.7	1078.2
	C _L ^E	981.90	829.09	6175.2	1253.7	919.44	722.12
	H	0.298	0.095	0.208	0.108	0.504	0.493
R1	C _{LO}	1301.0	903.31	7625.0	1407.2	1549.3	1241.9
	C _{L1}	1230.0	880.55	7241.2	1359.0	1331.0	1044.2
	C _L ^E	991.46	840.56	6248.6	1270.8	945.88	777.44
	H	0.241	0.048	0.159	0.069	0.407	0.343
R2	C _{LO}	1288.4	892.07	7576.8	1364.2	1545.4	1234.0
	C _{L1}	1229.6	878.80	7297.1	1305.8	1341.7	1045.7
	C _L ^E	990.80	834.73	6218.9	1263.2	921.29	770.71
	H	0.241	0.053	0.173	0.034	0.456	0.357
3	C _{LO}	1293.8	899.45	7562.1	1388.2	1543.9	1234.7
	C _{L1}	1262.7	899.45	7381.5	1382.4	1353.2	1087.0
	C _L ^E	982.91	839.39	6179.7	1265.8	952.87	773.79
	H	0.285	0.072	0.194	0.092	0.420	0.405
4	C _{LO}	1281.2	887.88	7491.2	1371.5	1537.0	1225.4
	C _{L1}	1245.5	886.94	7297.3	1357.4	1355.4	1068.1
	C _L ^E	1020.7	867.22	6394.8	1307.8	958.36	1637.6*
	H	0.220	0.023	0.141	0.038	0.414	-----
R3	C _{LO}	1294.1	896.33	7556.1	1384.9	1554.1	1239.5
	C _{L1}	1257.3	895.41	7355.0	1369.7	1358.8	1058.6
	C _L ^E	1000.8	851.21	6276.3	1284.8	940.42	2198.1*
	H	0.256	0.052	0.172	0.066	0.445	-----
R4	C _{LO}	1270.8	879.40	7496.0	1348.4	1520.3	1217.0
	C _{L1}	1268.8	879.40	7489.6	1348.4	1359.1	1095.1
	C _L ^E	999.64	851.00	6272.8	1283.0	932.12	2252.2*
	H	0.269	0.033	0.194	0.051	0.458	-----

* False result due to a malfunction of the integrator. All results for the syringe concerned were not used in subsequent computations.

APPENDIX B

EFFECT OF METHANOL ON HENRY'S LAW CONSTANTS

The theoretical approach used to evaluate methanol's effect on Henry's law constants is presented briefly in Section 3.1.3.3. The components of the solution considered in this appendix are:

1 = water; 2 = chloroform; 3 = methanol

The flow rate of methanol in the influent liquid was approximately 10 ml/min. The lowest liquid flow rate was approximately 1.32 l/min (including the 10 ml/min of methanol). The average chloroform concentration of the influent liquid was 7 mg/l (Table 4.7). The mole fraction of each component of the solution follows.

Mole fraction of each component, assuming a temperature of 20°C:

Water:

$$\frac{[(1.32 \text{ l/min} - 0.01 \text{ l/min}) \times 998.2 \text{ g/l}]}{18.0152 \text{ g/mole}} = 72.585 \frac{\text{moles}}{\text{min}}$$

Chloroform:

$$\frac{(0.007 \text{ g/l} \times 1.32 \text{ l/min})}{119.38 \text{ g/mole}} = 7.740 \times 10^{-5} \frac{\text{moles}}{\text{min}}$$

Methanol:

$$\frac{(0.01 \text{ l/min} \times 791.4 \text{ g/l})}{32.042 \text{ g/mole}} = 0.247 \frac{\text{moles}}{\text{min}}$$

Total flow rate:

$$72.585 + 7.740 \times 10^{-5} + 0.247 = 72.833 \text{ moles/min}$$

Mole fraction of each component:

$$Y_1 = 72.585 / 72.833 = 0.997$$

$$Y_2 = 7.740 \times 10^{-5} / 72.833 = 1.063 \times 10^{-6}$$

$$Y_3 = 0.247 / 72.833 = 3.391 \times 10^{-3}$$

The values of the activity coefficients, $\gamma_{i,j}^0$, obtained from Table B1 of Munz and Roberts (1982), were used in Eq. (3.28) to compute the empirical coefficients $B_{i,j}$:

$$B_{i,j} = \ln \gamma_{i,j}^0$$

$$\gamma_{21}^0 = 830 \quad ; \quad B_{12} = \ln 830 = 6.721$$

$$\gamma_{23}^0 = 2.00 \quad ; \quad B_{23} = \ln 2.00 = 0.693$$

$$\gamma_{31}^0 = 1.53 \quad ; \quad B_{13} = \ln 1.53 = 0.425$$

$$\text{From Eq. (3.29): } B_{23} = B_{12} + \ln \frac{H_{23}}{H_{21}}$$

$$\ln \frac{H_{23}}{H_{21}} = B_{23} - B_{12} = 0.693 - 6.721 = -6.028$$

Using Eqs. (3.8) and (3.9), Henry's law constant value for chloroform at 19.9°C (Table 5.3) can be expressed in units of atm:

$$H_A = H_B \frac{P_L}{P_A} = (H \cdot R \cdot T_A) \frac{P_L}{M_L} \\ = (0.153 \times 82.057 \times 10^{-4} \text{ atm} \cdot \text{m}^3 \cdot \text{K}^{-1}) \times (998.2 \text{ kg/m}^3 / 18.0152 \times 10^{-3} \text{ kg/mole})$$

$$H_{A1} = 203.9 \text{ atm}$$

From Eq. (3.27):

$$\ln \frac{H_{A2}}{H_{A1}} = (Y_1 + Y_2 - 1) \ln \frac{H_{A2}}{H_{A1}} + Y_3 \ln \frac{H_{A2}}{H_{A1}} - B_{13} Y_1 Y_3 \\ = (0.997 + 3.391 \times 10^{-3} - 1) \ln 203.9 \\ + 3.391 \times 10^{-3} \times (-6.028) - 0.425 \times 0.997 \times 3.391 \times 10^{-3} \\ = -0.0219$$

Therefore

$$\frac{H_{A2}}{H_{A1}} = 0.978$$

APPENDIX C

COMPUTATION OF TOTAL NUMBER OF TRANSFER UNITS

A sample calculation of the steps needed to obtain the total number of transfer units, NTUT, is given below. A listing of the Fortran WATFIV program used to perform the computations for all experimental runs follows the sample calculation.

C.1 Sample Calculation

The calculations for experimental Run 18, and for toluene, are presented in the following sections. Symbols used in the computer program are also used below.

C.2 Recorded Data

The only packing related information needed in the computations is the bed depth, $Z = 0.914$ m.

Table C.1 lists the recorded temperatures and manometer readings. Table C.2 presents the toluene concentrations.

The liquid flow rate, interpolated as described in Section 5.3.2.2, was: $Q_L = Q_{L1} = 2.3500 \times 10^{-3} \text{ m}^3/\text{s}$.

The gas flow rate corresponding to the rotameter's reading was: $Q_{GR} = Q_{GR1} = 308.67 \times 10^{-3} \text{ m}^3/\text{s}$.

Table C.1: Recorded temperatures and pressures

Quantity Measured	Symbol	Values	
Temperature (°C)			
Packed column room	TW	23.80	23.85
Constant head tank water	TI	23.70	24.15
Effluent tank water	TE	22.85	23.20
Compressor room	TG	25.00	25.60
Compressed air	TC	27.00	27.50
Manometer readings (mm)			
Column manometer:			
High level	HPW	538.00	538.00
Low level	LPW	485.50	485.50
Rotameter manometer:			
High level	HPG	697.00	697.00
Low level	LPG	330.00	330.00
Barometric pressure (mm Hg)			
	PB	762.10	762.10

Table C.2: Toluene concentrations

Concentration (µg/l)	
Influent, CI	Effluent, CE
1244.7	104.99
1250.3	103.53
1294.7	101.72
1301.0	99.923
1244.5	100.46
1261.7	97.859

The packed column manometer fluid (red gauge oil) specific gravity was: $RMC = 0.827$.

C.3 Gas Flow Rate

From Eq. (5.12)

$$p_{ra} = P_G = (697 - 330) / 13.5694 = 27.0461 \text{ mm Hg}$$

$$p_r = P_F = 762.10 + 27.0461 = 789.1461 \text{ mm Hg}$$

$$T_{ra} = T_{GR} = 1.8 \times [(27.00 + 27.50) / 2] + 32 + 460$$

$$T_{GR} = 541.05 \text{ } ^\circ\text{R}$$

From Eq. (5.11)

$$Q_{GC} = Q_{GC} = 308.67 \times 10^{-3} \times \left[\frac{530}{541.05} \times \frac{789.1461}{760} \right]^{1/2}$$

$$Q_{GC} = 311.3046 \times 10^{-3} \text{ m}^3/\text{s}$$

$$T_K = T_K = [(23.80 + 23.85) / 2] + 273.15 = 296.975 \text{ } ^\circ\text{K}$$

From Eq. (5.13)

$$Q_G = Q_G = 311.3046 \times 10^{-3} \times \frac{760}{762.10} \times \frac{296.975}{293.15}$$

$$Q_G = 314.50 \times 10^{-3} \text{ m}^3/\text{s}$$

C.4 Liquid Mass Flux

From Eq. (5.15)

$$\rho_L = \rho_L = 1000 \times [1 - 1.9549 \times 10^{-3} \times (23.475 - 4)^{1.68}]$$

$$\rho_L = 997.13 \text{ kg/m}^3$$

From Eq. (5.14)

$$L = L = (2.3500 \times 10^{-3} \times 997.13) / 0.008107$$

$$L = 2.890 \text{ kg/m}^2\cdot\text{s}$$

C.5 Packed Column Pressure Drop

The manometer's fluid density at room temperature was determined first.

From Eq. (5.15)

$$\rho_L = \rho_{LG} = 1000 \left[1 - 1.9549 \times 10^{-5} \times (23.825 - 4)^2 \right]$$

$$\rho_{LG} = 997.05 \text{ kg/m}^3$$

$$\rho_{ra} = \rho_M = 0.827 \times 997.05 = 824.56 \text{ kg/m}^3$$

From Eq. (5.16)

$$\Delta p_{OT} = DPG = [(538.0 - 485.5)/1000] \times 824.56 \times 9.8$$

$$DPG = 424.2 \text{ N/m}^2$$

$$\Delta p_{OT}/Z = DPGZ = 424.2 / 0.914 = 464.1 \text{ N/m}^2/\text{m}$$

C.6 Henry's Law Constant and Stripping Factor

The Henry's law constant value at average water temperature was used.

From Eq. (5.9)

$$H = H^* = \exp[25.742 - (8100 / (23.475 + 273.15))]$$

$$H^* = 0.2090$$

From Eq. (2.21)

$$S = S^* = 0.2090 \times 314.50 \times 10^{-3} / (2.3500 \times 10^{-3})$$

$$S = 27.976$$

C.7 Concentrations Average and Standard Deviation

For influent concentrations:

$$\Sigma W = \Sigma C = 7596.9$$

$$\Sigma W^2 = \Sigma C^2 = 9622044.41$$

From Eq. (5.6): $w = CIA = 7596.976 = 1266.15$

$$\text{From Eq. (5.7): } S_w = CIS = \left[\frac{6 \times 9622044.41 - 7596.976^2}{6 \times (6 - 1)} \right]^{1/2}$$

$$CIS = 25.42$$

In the program, the ratio of the standard deviation to the average was computed instead of the coefficient of variation.

$$CISA = 25.42 / 1266.15 = 0.020$$

Similar computations for effluent concentrations yield:

$$CEA = 101.414$$

$$CES = 2.577$$

$$CESA = 0.025$$

C.8 Number of Transfer Units

From Eq. (2.19)

$$NTUT = NTU = \frac{27.976}{27.976 - 1} \times \ln \left\{ \frac{\left[\frac{1266.15}{101.414} \right] \times (27.976 - 1) + 1}{27.976} \right\}$$

$$NTU = 2.583$$

From Eq. (2.22): $HTU = HTU = 0.914 / 2.583 = 0.354$

From Eq. (2.16):

$$KLa = KLA = 2.890 / (997.13 \times 0.354) = 8.192 \times 10^{-3}$$

C.9 Computer Program

The following WATFIV program was used to print the recorded data and compute H, S, and NTUT from the experimental data.

SJOB

C
C
C

READ AND PRINT DATE, RUN NO., AND PACKING PARAMETERS.

```

1  INTEGER DAY, MONTH, YEAR, RUNNO, POR, MEDIA
2  INTEGER NI, NE, NMI, NINT
3  REAL SIZEMM, SIZEIN, Z, ZF
4  REAL QL, TW(2), TI(2), TF(2), HPVCM(2), LPVCM(2), TGC(2), TC(2), HPGCM(2), L
5  SPGCM(2), PBCM(2), OGR, P4C
6  REAL HPVMM(2), LPVMM(2), HPGMM(2), LPGMM(2), PBM(2)
7  REAL TWA, TIA, TEA, HPWA, LPWA, TSA, TCA, HPGA, LPGA, PPA, P3, PF, TCR, QGC, TA,
8  SRL, QLM, L, RLG, RM, DPG, DPOZ, TK, JO
9  REAL PH(2), CY(2)
10 REAL TAA, BO(6), BI(6), HI(6), S(6), LNT
11 REAL CI(6,6), CE(6,6), CIA(6), CEA(6), CIS(6), CES(6), CTSA(6), CESA(6)
12 REAL NTU(6), HTU(6), KLA(6)
13 READ, DAY, MONTH, YEAR, RUNNO
14 READ, SIZEMM, SIZEIN, MEDIA
15 READ, POR
16 READ, Z, ZF
17 PRINT 10, DAY, MONTH, YEAR, RUNNO
18 10 FORMAT('1', 45X, 'DATE: ', I2, '-', I2, '-', I2, 20X, 'RUN #: ', I2)
19 IF (MEDIA.EQ.1) PRINT 20, SIZEMM, SIZEIN, 'RASCHIG RINGS'
20 IF (MEDIA.EQ.2) PRINT 20, SIZEMM, SIZEIN, 'INTALOX SADDLES'
21 20 FORMAT('1', 38X, 'PACKING: SIZE, TYPE: ', F5.2, ' MM (', F4.2, ' IN.) ',
22 SA15)
23 PRINT 30, POR
30 30 FORMAT('1', 47X, 'POROSITY: ', 2X, I2, ' PERCENT')
40 PRINT 40, Z, ZF
40 40 FORMAT('1', 47X, 'DEPTH: ', 3X, 'ZF = ', F5.3, ' M (', F4.2, ' FT)')

```

C
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C

READ LIQUID AND GAS FLOWRATES, AND RELATED DATA.

```

24 READ, QL
25 READ, TW(1), TW(2), TI(1), TI(2), TE(1), TE(2), HPVCM(1), HPVCM(2), LPVCM(1),
26 LPVCM(2), TGC(1), TGC(2), TC(1), TC(2), HPGCM(1), HPGCM(2), LPGA(1), LPGA(2),
27 PBCM(1), PBCM(2)
28 READ, OGR
29 READ, RMC

```

C
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C

CONVERT PRESSURES FROM CM TO MM.

```

28 DO 50 I=1,2,1
29   HPVMM(I)=10*HPVCM(I)
30   LPVMM(I)=10*LPVCM(I)
31   HPGMM(I)=10*HPGCM(I)
32   LPGMM(I)=10*LPGCM(I)
33   PBM(I)=10*PBCM(I)
34 50 CONTINUE

```

C
C
C

PRINT MISCELLANEOUS DATA.

```

35 PRINT 55, '0'
36 55 FORMAT('1', A1)
37 PRINT 60, 'MISCELLANEOUS DATA'
38 60 FORMAT('1', 54X, A16)
39 PRINT 70, 'READING AFTER'
40 70 FORMAT('0', 95X, A13)
41 PRINT 80, 'QUANTITY MEASURED', 'SYMBOLS AND UNITS', '45 MIN. 95 MIN.'

```

```

42 80 FORMAT(' ',37X,A17,18X,A17,4X,A16)
43 PRINT 90,'DATA RELEVANT TO PACKED COLUMN:'
44 90 FORMAT('0',22X,A31)
45 PRINT 100,TW(1),TW(2),TI(1),TI(2),TE(1),TE(2),HPVMM(1),HPVMM(2),LP
46 SVM(1),LPVMM(2)
100 FORMAT('0',27X,'AMBIENT TEMPERATURE, PACKED COLUMN ROOM',3X,'TW',1
50X,'C',7X,F5.2,4X,F5.2,'/',',',27X,'WATER TEMPERATURE, CONSTANT HEAD
5 TANK',11X,'TI',10X,'C',7X,F5.2,4X,F5.2,'/',',',27X,'WATER TEMPERATU
5 RE, EFFLUENT TANK',16X,'TE',10X,'C',7X,F5.2,4X,F5.2,'/',',',27X,'COL
5 SUMN',5,'MANOMETER READING: HIGH PRESSURE',5X,'HPV',9X,'MM',6X,F6.2,
53X,F6.2,'/',',',55X,'LOW PRESSURE',7X,'LPV',9X,'MM',5X,F6.2,3X,F6.2)
47 PRINT 110,'DATA RELEVANT TO AIR COMPRESSOR:'
48 110 FORMAT('0',22X,A32)
49 PRINT 120,TG(1),TG(2),TC(1),TC(2),HPGMM(1),HPGMM(2),LPGMM(1),LPGMM
50 S(2),PBMM(1),PBMM(2)
120 FORMAT('0',27X,'AMBIENT TEMPERATURE, COMPRESSOR ROOM',12X,'TG',10X
5,'C',7X,F5.2,4X,F5.2,'/',',',27X,'COMPRESSED AIR TEMPERATURE',22X,'T
5C',10X,'C',7X,F5.2,4X,F5.2,'/',',',27X,'FLOWMETER',5,'MANOMETER READI
5NG: HIGH PRESSURE',3X,'HPG',9X,'MM',5X,F5.2,3X,F5.2,'/',',',54X,'LOW
5 PRESSURE',4X,'LPG',9X,'MM',5X,F6.2,3X,F5.2,'/',',',27X,'BAROMETRIC
5 PRESSURE',29X,'PB',9X,'MM',6X,F6.2,3X,F6.2)
C
C COMPUTE GAS FLOWRATE, LIQUID MASS FLUX, AND PRESSURE DROP.
C
51 TVA=(TW(1)+TW(2))/2.
52 TIA=(TI(1)+TI(2))/2.
53 TEA=(TE(1)+TE(2))/2.
54 HPV=(HPVMM(1)+HPVMM(2))/2.
55 LPV=(LPVMM(1)+LPVMM(2))/2.
56 TGA=(TG(1)+TG(2))/2.
57 TCA=(TC(1)+TC(2))/2.
58 HPGA=(HPGMM(1)+HPGMM(2))/2.
59 LPG=(LPGMM(1)+LPGMM(2))/2.
60 PBA=(PBMM(1)+PBMM(2))/2.
C
61 PG=(HPGA-LPGA)/13.5694
62 PF=PG+PBA
63 TCR=(1.5*TCA)+492.
64 QGC=QGR*SQRT((530./TCR)*(PF/760.))
65 TA=(TIA+TEA)/2.
66 RL=1000.*(1.-(1.9549E-5)*((ABS(TA-4.))*1.68))
67 QLM=QL*RL
68 L=QLM/0.008107
69 RLQ=1000.*(1.-(1.9549E-5)*((ABS(TVA-4.))*1.68))
70 RM=RMC*RLQ
71 DPG=(HPV-LPV)*RM*0.0098
72 DPQZ=DPG/Z
73 TK=TVA+273.15
74 QQ=QGC*(760./PBA)*(TK/293.15)
C
C PRINT FLOWRATES, TEMPERATURES, DENSITIES, AND PRESSURE DROP.
C
75 PRINT 125,'0'
76 125 FORMAT('T1,A1)
77 PRINT 130,'VOLUMETRIC FLOWRATES:'
78 130 FORMAT(' ',30X,A21)
79 PRINT 140,QL,QGR,QQ
80 140 FORMAT('0',35X,'LIQUID (WATER):',38X,'QL=',1PE10.4,' M**3/S',/,',',
81 S',35X,'GAS (AIR), AS READ FROM FLOWMETER:',16X,'QGR=',1PE10.2,' M
82 S**3/S',/,',',35X,'GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSUR

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SE=,1X,'QG= ',3PE10.2,' M**3/S')
PRINT 150,L
150 FORMAT(' ',30X,'LIQUID MASS FLUX:',40X,'L= ',F5.3,' KG/(S*M**2)')
151 PRINT 160,TWA,TA
160 FORMAT(' ',30X,'AVERAGE TEMPERATURES:',/,',0',35X,'INFLUENT, PACKED COLUMN ROOM:',22X,'TWA= ',F5.3,' C',/,',',35X,'LIQUID (WATER):',36X,'TA= ',F5.3,' C')
152 PRINT 170,RL,RM
170 FORMAT(' ',30X,'DENSITIES:',/,',0',35X,'LIQUID (WATER):',16X,'RL= ',F6.2,' KG/M**3',/,',',35X,'COLUMN'S MANOMETER LIQUID:',25X,'RM= ',F6.2,' KG/M**3')
153 PRINT 180,DPG,DPOZ
180 FORMAT(' ',30X,'PRESSURE DROP IN PACKED COLUMN:',/,',0',35X,'TOTAL SPRESSURE DROP:',30X,'DPG= ',F5.0,' N/M**2',/,',',35X,'PRESSURE DRO SP PER UNIT DEPTH:',20X,'DPOZ= ',F5.0,' (N/M**2)/M')

READING AND PRINTING WATER QUALITY PARAMETERS.
154 PRINT 15, DAY, MONTH, YEAR, RUNN
155 FORMAT(' ',45X,'DATE: ',I2,'-',I2,'-',I2,20X,'RUN #: ',I2)
156 READ, PH(1), PH(2), CY(1), CY(2)
157 PRINT 190, PH(1), PH(2), CY(1), CY(2)
190 FORMAT(' ',30X,'WATER QUALITY PARAMETERS:',/,',0',45X,'PARAMETERS:',12X,'INFLUENT',12X,'EFFLUENT',/,',0',48X,'PH',12X,'A.2,16X,'A.2,/,',37X,'CONDUCTIVITY (MICROMHDS)',7X,F5.0,15X,F5.0)

COMPUTE AND PRINT ABSOLUTE TEMPERATURE AND HENRY'S LAW CONSTANTS.
158 TAA=TA+273.15
159 B0(1)=4.790
160 BI(1)=-1851.
161 B0(2)=13.708
162 BI(2)=-4968.
163 B0(3)=4.457
164 BI(3)=-1863.
165 B0(4)=11.672
166 BI(4)=-4384.
167 B0(5)=5.041
168 BI(5)=-1768.
169 B0(6)=25.742
170 BI(6)=-8100.

171 DO 200 J=1,6,1
172   H(J)=EXP(B0(J)+(BI(J)/TAA))
173   SI(J)=H(J)*QG/QL
200 CONTINUE
174 PRINT 195,' '
195 FORMAT(' ',/,',T1,A1)
175 PRINT 210,'HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (SI.)'
210 FORMAT(' ',35X,A53)
176 EXECUTE HEADIN
177 PRINT 220,H
220 FORMAT('0',6X,'H',5X,6(7X,F8.4,7X))
178 PRINT 230,S
230 FORMAT(' ',6X,'S',5X,6(7X,F8.3,7X))

READ INFLUENT AND EFFLUENT CONCENTRATIONS, COMPUTE AVERAGES, PRINT
179 READ, NI, NE
180 DO 240 K=1,6,1

```

```

122      READ, (CI(K,KL), KL=1, NI)
123      CALL AVERAG(NI, CI, CIA, CIS, CISA, K)
124      READ, (CE(K,M), M=1, NE)
125      CALL AVERAG(NE, CE, CEA, CES, CESA, K)
126
127      240 CONTINUE
128
129      PRINT 245, '-'
130      245 FORMAT(T1, A1)
131      PRINT 250, 'INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGE
132      $S (AV.), AND STANDARD DEVIATIONS (SDEV).'
133      250 FORMAT(' ', 19X, A95)
134      EXECUTE HEADIN
135      PRINT 260, 'TRIAL'
136      260 FORMAT('0', 4X, A5, T10, 6(1X, 'CI', 4X, 'CE'))
137      PRINT 270, ' '
138      270 FORMAT(T1, A1)
139      NMI=MIN0(NI, NE)
140      DO 280 KK=1, NMI, 1
141          PRINT 290, KK, CI(1, KK), CE(1, KK), CI(2, KK), CE(2, KK), CI(3, KK), CE(3,
142          $, KK), CI(4, KK), CE(4, KK), CI(5, KK), CE(5, KK), CI(6, KK), CE(6, KK)
143          290 FORMAT(' ', 6X, I1, 3X, 6(3X, F7.2, 2X, FA, 3))
144      CONTINUE
145      IF (NI .GT. NE) THEN DO
146          NINT=NE+1
147          DO 300 LL=NINT, NI, 1
148              PRINT 310, LL, CI(1, LL), CI(2, LL), CI(3, LL), CI(4, LL), CI(5, LL),
149              $, CI(6, LL)
150              310 FORMAT(' ', 6X, I1, T2, 6(13X, F7.2))
151          CONTINUE
152      ELSE DO
153          IF (NE .GT. NI) THEN DO
154              NINT=NI+1
155              DO 320 MM=NINT, NE, 1
156                  PRINT 330, MM, CE(1, MM), CE(2, MM), CE(3, MM), CE(4, MM), CE(
157                  $, MM), CE(6, MM)
158                  330 FORMAT(' ', 6X, I1, T12, 6(12X, F8.3))
159              CONTINUE
160          ELSE DO
161              END IF
162          END IF
163          PRINT 340, 'AV.', CIA(1), CEA(1), CIA(2), CEA(2), CIA(3), CEA(3), CIA(4), C
164          $EA(4), CIA(5), CEA(5), CIA(6), CEA(6)
165          340 FORMAT('0', 5X, A3, T12, 6(3X, F7.2, 2X, FA, 3))
166          PRINT 360, 'SDEV', CIS(1), CES(1), CIS(2), CES(2), CIS(3), CES(3), CIS(4),
167          $CES(4), CIS(5), CES(5), CIS(6), CES(6)
168          360 FORMAT(' ', 4X, A4, T12, 6(4X, F5.2, 3X, FA, 3))
169          PRINT 380, 'SDEV/AV.', CISA(1), CESA(1), CISA(2), CESA(2), CISA(3), CESA(
170          $3), CISA(4), CESA(4), CISA(5), CESA(5), CISA(6), CESA(6)
171          380 FORMAT(' ', 2X, A8, T12, 6(5X, F5.3, 5X, FA, 3))
172
173      C
174      C
175      COMPUTE AND PRINT NTU, HTU, AND KLA.
176
177      DO 400 JI=1, 6, 1
178          NTU(JI)=(S(JI)/(S(JI)-1.)) * ALOG((CIA(JI)/CEA(JI)) / (S(JI)-1.)) +
179          $S(JI) / S(JI)
180          HTU(JI)=Z / NTU(JI)
181          KLA(JI)=L / (RL * HTU(JI))
182      400 CONTINUE
183      PRINT 405, '-'
184      405 FORMAT(T1, A1)

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170      PRINT 410, 'NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UN
      SIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA)'.
171      A10 FORMAT(' ', 15X, A10Z)
172      EXECUTE HEADIN
173      PRINT 420, NTU
174      420 FORMAT('0', 5X, 'NTU', T6, 6(16X, F6.3))
175      PRINT 430, HTU
176      430 FORMAT(' ', 5X, 'HTU', T6, 6(15X, F5.3))
177      PRINT 440, KLA
178      440 FORMAT(' ', 5X, 'KLA', T6, 6(11X, 1PE9.3))
179      PRINT 445, A
180      445 FORMAT(T1, A1, /, 5(T1, '- ', /))
181      STOP
      C
      C      REMOTE BLOCK PRINTING TABLE HEADING.
      C
182      REMOTE BLOCK HEADIN
183      PRINT 500, '1,1-DICHLORJETHANE', 'ETHER', 'CHLOROFORM', '1,2-DICHL
      SOROETHANE', 'TRICHLOROETHYLENE', 'TOLUENE'
184      500 FORMAT('0', T14, A16, T41, A5, T58, A10, T74, A15, T95, A17, T120, A7)
185      END BLOCK
186      END
      C
      C      SUBROUTINE COMPUTING CONCENTRATION'S AVERAGE AND STANDARD DEVIATIONS.
      C
187      SUBROUTINE AVERAG (NN, C, CA, CS, CSA, JJI)
188      REAL SC(6), SSC(6), C(6, 6), CA(6), CS(6), CSA(6)
189      INTEGER NN
190      SC(JJI) = SSC(JJI) = 0.
191      DO 510 II = 1, NN, 1
192          SC(JJI) = SC(JJI) + C(JJ, II)
193          SSC(JJI) = SSC(JJI) + (C(JJ, II) ** 2)
194      510 CONTINUE
195      CA(JJI) = SC(JJI) / (FLOAT(NN))
196      CS(JJI) = SORT((SSC(JJI) - ((FLOAT(NN)) * (CA(JJI) ** 2))) / (FLOAT(NN - 1)))
197      CSA(JJI) = CS(JJI) / CA(JJI)
198      RETURN
199      END

```

SENTRY

APPENDIX D

EXPERIMENTAL DATA AND FIRST COMPUTATIONS

The following computer printouts, produced by the computer program at the end of Appendix C, list the experimental data and results of the first computations for Runs 7 to 42. Runs 1 to 6 were trial runs and their results were not used.

DATE: 26- 5-65

RUN #1 7

PACKING: SIZE, TYPE: 6.35 MM (C.25 IN.) RASCHIO PINOS
 POROSITY: 54 PERCENT
 DEPTH: 2M 1.829M 16.00 FT

MISCELLANEOUS DATA

QUANTITY MEASURED
 SYMBOLS AND UNITS
 READING AFTER
 45 MIN. 95 MIN.

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM: 24.85 24.80
 WATER TEMPERATURE, CONSTANT HEAD TANK: 27.50 27.50
 WATER TEMPERATURE, EFFLUENT TANK: 28.00 28.00
 COLUMN'S MANOMETER READING: HIGH PRESSURE: 683.00 680.00
 LOW PRESSURE: 350.00 351.00

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM: 24.80 24.80
 COMPRESSED AIR TEMPERATURE: 26.20 26.20
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE: 783.00 781.00
 LOW PRESSURE: 355.00 357.00
 BAROMETRIC PRESSURE: 755.00 755.00

VOLUMETRIC FLOWRATES:

LIQUID (WATER): OLE 3.0198E-05 M³/S
 GAS (AIR): AS READ FROM FLOWMETER: OGP 226.33E-05 M³/S
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: OGP 233.42E-05 M³/S

LIQUID MASS FLUX:

LE 3.711 KG/(S.M²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM: TWA 24.825 C
 LIQUID (WATER): TAW 26.762 C

DENSITIES:

LIQUID (WATER): EL 998.27 KG/M³
 COLUMN'S MANOMETER LIQUID: FME 996.79 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP: DPGE 3224. N/M²
 PRESSURE DROP PER UNIT DEPTH: DPGZE 1783. (N/M²)/M

DATE: 20-5-85

RUN # 7

WATER QUALITY PARAMETERS

PARAMETERS	INFLUENT	EFFLUENT
PH	7.68	7.65
CONDUCTIVITY (MICROMHOS)	1285	1310

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	0.2511 18.411	0.1729 13.368	0.0842 4.963	0.4257 32.804	0.2820 21.787

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	840.80	5.998	736.03	29.754	6770.60	68.812	1020.70	31.077	1778.80	15.877	1988.80	18.331
2	847.43	6.868	726.17	24.574	6818.50	69.352	1035.60	25.821	1772.20	16.587	1988.10	18.824
3	829.32	7.206	726.13	28.332	6670.40	72.000	1008.60	28.884	1765.00	16.692	1950.20	18.988
4	836.20	6.878	719.09	25.381	6734.80	69.362	1004.30	28.146	1746.30	15.924	1947.50	18.980
5	824.73	6.885	721.00	25.206	6643.00	69.053	988.78	28.002	1748.40	15.441	1938.20	18.280
6	847.34	6.936	717.33	24.621	6623.40	69.516	1003.10	25.484	1772.80	15.550	1968.60	18.216
AV.	837.85	6.795	724.38	26.378	6743.65	69.782	1009.21	27.236	1783.88	15.975	1958.23	18.910
SDEV	9.37	0.411	8.72	2.128	75.39	1.159	7.62	2.247	13.86	0.533	13.07	0.291
SDEV/AV.	0.011	0.060	0.009	0.031	0.011	0.017	0.008	0.083	0.008	0.033	0.008	0.017

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	3.960 0.462 0.085E-03	4.857 0.377 9.693E-03	4.251 0.430 8.857E-03	4.820 0.379 9.817E-03	4.716 0.388 8.805E-03
NTU	5.021				
HTU	0.364				
KLA	1.022E-02				

DATE: 29- 5-85

RUN #: 8

PACKING: SIZE, TYPE: 8.35 MM 10.25 IN.) RASCPIC RINGS
 POROSITY: 54 PERCENT
 DEPTH: 2= 1.829 M (6.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED: SYMBOLES AND UNITS (PENDING AFTER 45 MIN. 85 MIN.

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM TV 24.55 24.50
 WATER TEMPERATURE, CONSTANT HEAD TANK TI 25.40 25.60
 WATER TEMPERATURE, EFFLUENT TANK TE 24.40 24.80
 COLUMN'S MANOMETER READING: HIGH PRESSURE MPV 614.00 614.50
 LOW PRESSURE LPV 417.00 418.50

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM TO 24.80 25.30
 COMPRESSED AIR TEMPERATURE TC 25.80 28.20
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE MPG 690.00 690.00
 LOW PRESSURE LPO 1348.00 1349.00
 BAROMETRIC PRESSURE PB 758.80 758.80

VOLUMETRIC FLOWRATES:

LIQUID (WATER): CLZ 2.9800E-05 M³/S
 GAS (AIR), AS READ FROM FLOWMETER: OCR 191.33E-05 M³/S
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: CGR 196.01E-05 M³/S

LIQUID MASS FLUX:

LX 3.135 KG/(S*M²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM: TVAX 24.525 C
 LIQUID (WATER): TAV 25.000 C

DENSITIES:

LIQUID (WATER): CLZ 998.75 KG/M³
 COLUMN'S MANOMETER LIQUID: RPE 998.87 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP: CPGZ 1829. M/M²
 PRESSURE DROP PER UNIT DEPTH: DPGZ 1055. (A/M²)/M

DATE: 29-5-85

SUM 61

WATER QUALITY PARAMETERS

PARAMETERS

INFLUENT

EFFLUENT

PH

7.69

7.58

CONDUCTIVITY (MICROMHOS)

1275

1285

HENRY'S LAW CONSTANTS (M) AND STRIPPING FACTORS (S).

	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
H	0.2421		0.1657		0.0589		0.4111		0.2404	
S	18.612		12.814		4.527		31.800		18.477	

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	814.34	7.278	723.36	37.969	6454.60	73.613	1009.70	36.501	1728.40	18.342	1471.40	18.531
2	823.95	7.307	715.62	32.614	5518.90	73.448	1009.10	31.878	1723.70	17.053	1417.10	18.988
3	854.65	7.247	740.38	34.350	8751.40	72.853	1042.10	31.103	1822.10	19.333	1547.40	18.468
4	815.73	7.333	721.28	32.310	8431.20	73.034	1010.00	31.463	1735.30	19.877	1475.30	18.448
5	812.66	7.169	713.58	31.455	6432.00	72.505	1001.80	30.813	1710.30	15.783	1458.50	18.503
AV.	824.27	7.267	722.84	33.740	6521.62	73.103	1014.54	32.732	1744.00	18.218	1488.02	18.583
SDEV	17.54	0.064	10.58	2.588	132.70	0.480	15.78	2.256	44.97	0.580	35.11	0.238
SDEV/AV.	0.021	0.009	0.015	0.077	0.020	0.006	0.016	0.069	0.026	0.035	0.024	0.014

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
NTU	4.942		3.722		4.784		4.038		4.798		4.536	
HTU	0.370		0.491		0.382		0.446		0.381		0.389	
KLA	8.499E-03		6.401E-03		8.227E-03		7.049E-03		8.231E-03		8.078E-03	

DATE: 30-5-85

RUN #1 0

RASCIO RINGS

PACKING: SIZE, TYPE: 6.35 MM (C.25 IN.)
 POROSITY: 54 PERCENT
 DEPTH: Z= 1.829 M (6.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED

SYMBOLS AND UNITS

READING AFTER
45 MIN. 95 MIN.

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM
 WATER TEMPERATURE, CONSTANT HEAD TANK
 WATER TEMPERATURE, EFFLUENT TANK
 COLUMN'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE

TV 24.40 24.50
 TI 24.40 24.50
 TE 23.60 24.00
 HPN 580.00 591.50
 LPA 441.50 440.00

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM
 COMPRESSED AIR TEMPERATURE
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE
 BAROMETRIC PRESSURE

IC 24.80 25.50
 TC 25.80 28.20
 HPG 852.00 854.00
 LPG 386.00 388.00
 PB 753.10 752.50

VOLUMETRIC FLOWRATES:

LIQUID (WATER):

GAS (AIR): AS READ FROM FLOWMETER

GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE:

CLF 2.3090E-05 M³/S
 OGR 173.33E-05 M³/S
 CGF 177.63E-05 M³/S

LIQUID MASS FLUX:

L= 2.838 KG/(SM²·S)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:

LIQUID (WATER):

TWA 24.450 C
 TAW 24.225 C

DENSITIES:

LIQUID (WATER):

COLUMN'S MANOMETER LIQUID:

FL 998.94 KG/M³
 FAF 998.88 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:

PRESSURE DROP PER UNIT DEPTH:

CPG 1465. M/M²
 CPGZ 801. (M/M²)/M

DATE: 30-5-85

RUN #1

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT
PH 7.63 7.81
CONDUCTIVITY (MICROMHOS) 1285 1325

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S),
1,1-DICHLOROETHANE CHLOROFORM 1,2-DICHLOROETHANE TRICHLOROETHYLENE TOLUENE
0.2382 0.1840 0.0587 0.4048 0.2239
18.328 12.617 4.360 31.141 17.228

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	933.61	5.845	802.97	34.685	7495.70	59.317	1149.80	32.782	1800.30	13.018
2	928.71	5.689	796.96	28.423	7455.30	59.249	1143.10	29.782	1939.00	13.380
3	963.98	5.728	842.63	31.254	7721.80	58.691	1200.10	31.764	2051.30	12.412
4	965.09	5.677	821.83	29.536	7717.10	59.339	1183.80	30.185	2020.20	12.775
5	886.38	5.135	763.52	26.373	7116.80	52.015	1109.70	27.114	1846.50	10.789
6	902.87	5.205	774.97	26.498	7236.70	53.181	1110.00	27.185	1800.40	11.215
AV.	930.10	5.543	803.82	29.628	7457.23	58.959	1149.25	30.304	1962.95	12.261
SDEV	31.77	0.297	24.99	3.120	246.52	3.408	37.08	2.235	65.80	1.042
SDEV/AV.	0.034	0.054	0.031	0.105	0.033	0.086	0.032	0.107	0.034	0.085

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
NTU	5.359	4.073	5.205	4.390	5.211	5.211	5.211	5.211	5.126	5.126
HTU	0.341	0.449	0.351	0.417	0.351	0.351	0.351	0.351	0.357	0.357
KLA	8.346E-03	6.343E-03	8.108E-03	6.838E-03	8.114E-03	8.114E-03	8.114E-03	8.114E-03	7.882E-03	7.882E-03

DATE: 31- 5-85
 RUN #1 10
 PACKING: SIZE TYPE: 4-35 MM (C-25 IN.) RASCHIO RINGS
 POROSITY: 54 PERCENT
 DEPTH: Z= 1.210 M (4.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
DATA RELEVANT TO PACKED COLUMN:		
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TW	25.00 25.00
WATER TEMPERATURE, CONSTANT-HEAT TANK	TI	25.70 25.30
WATER TEMPERATURE, EFFLUENT TANK	TE	24.80 25.00
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPM	642.00 640.00
LOW PRESSURE	LPN	389.00 381.00
DATA RELEVANT TO AIR COMPRESSOR:		
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TC	26.20 26.80
COMPRESSED AIR TEMPERATURE	TC	27.30 27.70
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPC	745.00 743.00
LOW PRESSURE	LPC	283.00 285.00
BAROMETRIC PRESSURE	PB	745.50 744.80

VOLUMETRIC FLOWRATES:

LIQUID (WATER): AS READ FROM FLOWMETER: GLX 3-0188E-05 M³/S
 GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE: GCR 226.53E-05 M³/S
 LIQUID MASS FLUX: LX 3.712 KG/(S*CM²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM: TWP 25.025 C
 LIQUID (WATER): TAE 25.375 C

DENSITIES:

LIQUID (WATER): FLX 996.65 KG/M³
 COLUMN'S MANOMETER LIQUID: FMR 996.74 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP: CPG 2452. M/M²
 PRESSURE DROP PER UNIT DEPTH: OPG 2011. IN/M*0.217M

DATE: 31- 5-85

RUN #1 10

WATER QUALITY PARAMETERS

EFFLUENT

INFLUENT

PARAMETERS

7.40
1280.7.88
1280.

CONDUCTIVITY (MICROPHOSI)

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

H	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE
	CI	CE	CI	CE	CI	CE	CI	CE	
S	0.2440	18.995	0.0532	4.181	0.1880	13.078	0.0600	4.670	0.2487
									19.381
									32.240
									0.2142

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	926.16	31.493	915.75	89.311	7426.30	303.920	1145.00	80.441	1977.70	70.672	1718.80	71.108
2	932.70	29.694	802.95	72.572	7460.40	289.140	1138.40	77.015	1963.90	68.662	1719.80	67.151
3	933.08	30.365	808.84	76.439	7478.40	293.800	1142.70	78.959	2000.10	68.052	1738.10	68.738
4	902.16	30.430	805.98	72.414	7240.40	283.690	1124.20	77.239	1895.90	67.294	1699.60	68.518
5	889.74	29.262	783.67	72.909	7151.80	284.290	1101.90	77.168	1908.80	65.039	1657.00	68.343
6	905.19	29.122	788.34	70.606	7239.70	281.910	1096.70	75.416	1806.10	63.903	1666.20	65.343
AV.	914.64	30.096	797.59	75.708	7332.91	291.125	1124.82	79.539	1942.08	66.930	1692.25	67.917
SDEV.	16.25	0.871	17.93	6.931	138.75	7.925	21.17	5.538	44.00	2.376	35.15	2.030
SDEV/AV.	0.020	0.028	0.022	0.092	0.018	0.027	0.018	0.070	0.023	0.036	0.021	0.030

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
NTU	3.549	0.343	2.779	0.439	3.411	0.357	3.049	0.395	3.444	0.384	3.337	0.385
HTU	1.084E-02	1.084E-02	4.493E-03	1.042E-02	1.042E-02	1.042E-02	9.438E-03	1.052E-02	1.052E-02	1.052E-02	1.052E-02	1.052E-02
KLA												

DATE: 1- (-05) RUN #1 11

PACKING: SIZE, TYPE: 6.35 MM (C.25 IN.) RASCHIG RINGS
 POROSITY: 54 PERCENT
 DEPTH: Z= 1.219 M (4.00 FT)

MISCELLANEOUS DATA

SYMBOLS AND UNITS
 READING AFTER
 45 MIN. 95 MIN.

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN.	READING AFTER 95 MIN.
DATA RELEVANT TO PACKED COLUMN:			
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	T _A	25.10	25.00
AMBIENT TEMPERATURE, CONSTANT HEAD TANK	T _I	25.80	25.80
WATER TEMPERATURE, EFFLUENT TANK	T _E	24.80	24.80
WATER TEMPERATURE, COLUMN'S MANOMETER READING: HIGH PRESSURE	H _P	572.00	572.50
COLUMN'S MANOMETER READING: LOW PRESSURE	L _P	460.00	459.50
DATA RELEVANT TO AIR COMPRESSOR:			
AMBIENT TEMPERATURE, COMPRESSOR ROOM	T _C	26.50	24.80
COMPRESSED AIR TEMPERATURE	T _C	27.50	27.50
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	H _P	647.00	647.00
LOW PRESSURE	L _P	392.00	392.00
BAROMETRIC PRESSURE	P _B	742.50	742.40

VOLUMETRIC FLOWRATES:

LIQUID (WATER): GL= 2.5500E-05 M³/S
 GAS (AIR): AS READ FROM FLOWMETER: GGR= 183.75E-05 M³/S
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: CG= 137.84E-05 M³/S

LIQUID MASS FLUX:

L= 3.135 KG/(50M²S)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM: T_{WA}= 25.050 C
 LIQUID (WATER): T_{LA}= 25.275 C

DENSITIES:

LIQUID (WATER): FL= 998.67 KG/M³
 COLUMN'S MANOMETER LIQUID: FM= 998.73 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP: CPG= 1099. N/M²
 PRESSURE DROP PER UNIT DEPTH: CPGZ= 501. IN/M²/M

DATE: 1-6-85 RUN 8111

WATER QUALITY PARAMETERS

PARAMETERS	INFLUENT	EFFLUENT
PH	7.86	7.51
CONDUCTIVITY (MICROMHOS)	1235.	1305.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	0.0529	0.1877	0.0597	0.4134	0.2485
H	4.145	13.138	4.678	32.384	18.315

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1	881.11	786.57	7037.50	1108.80	1893.80	1821.20
2	883.23	66.159	7058.10	1106.50	1858.80	1807.10
3	873.64	88.642	6980.90	1118.60	1875.90	1807.30
4	866.36	66.004	6931.20	1080.40	1835.30	1583.30
5	892.17	761.78	7129.00	1118.70	1817.10	1840.30
6	879.18	778.23	7031.30	1098.40	1864.70	1803.80
AV.	879.28	765.22	7029.68	1105.57	1875.27	1810.30
SDEV	8.84	15.01	66.74	14.58	27.86	18.18
SDEV/AV.	0.010	0.019	0.009	0.013	0.015	0.012

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	1,1-DICHLOROETHANE	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
NTU	3.745	2.696	3.600	3.214	3.635	3.537
HTU	0.325	0.421	0.339	0.378	0.335	0.345
KLA	9.564E-03	7.472E-03	9.230E-03	8.292E-03	9.379E-03	9.128E-03

DATE: 07-5-85

RUN 81.12

PACKING: SIZE: 8.59 MM (0.25 IN.) RASCHIG RINGS
POROSITY: 54 PERCENT
DEPTH: Z= 1.219 M (4.00 FT)

MISCELLANEOUS DATA

SYMBOLS AND UNITS READING AFTER 45 MIN. 95 MIN.

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM
WATER TEMPERATURE, CONSTANT HEAD TANK
WATER TEMPERATURE, EFFLUENT TANK
COLUMN'S MANOMETER READING: HIGH PRESSURE
LOW PRESSURE

TM 24.00 24.00
TI 24.50 24.50
TE 23.50 23.50
HPM 567.00 567.00
LPV 484.00 484.00

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM
COMPRESSED AIR TEMPERATURE
FLOWMETER'S MANOMETER READING: HIGH PRESSURE
LOW PRESSURE
BAROMETRIC PRESSURE

C 24.80 24.80
TC 25.50 25.50
PM 828.00 828.00
PM 404.00 404.00
PM 533.70 533.70

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
GAS (AIR): AS READ FROM FLOWMETER:
GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE:

CL= 2.3050E-05 M³/S
GRR= 1.7200E-05 M³/S
CG= 1.7556E-05 M³/S

LIQUID MASS FLUX:

L= 25.839 KG/(SM²·S)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
LIQUID (WATER):

TM= 24.000 C
TA= 24.525 C

DENSITIES:

LIQUID (WATER):
COLUMN'S MANOMETER LIQUID:

RL= 886.92 KG/M³
RM= 997.00 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP: 78
PRESSURE DROP PER UNIT CATCH:

CPG= 1006 N/M²
CPG2= 826 N/M²

DATE: 3- 6-85 RUN 81 12

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT

PH 7.64 7.58

CONDUCTIVITY (MICROMHOS) 1260. 1270.

HENRY'S LAW CONSTANTS (PI) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
H	0.2387	0.1844	0.0570	0.4056	0.2280
S	18.152	12.496	4.331	30.838	17.184

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	932.42	22.124	782.40	76.342	7141.00	210.990	1120.70	75.853	1929.70	47.814	1818.30	48.948
2	924.91	21.470	776.42	63.294	7125.30	207.350	1113.70	65.839	1896.30	46.709	1601.30	46.270
3	969.32	21.825	833.88	67.602	7417.90	208.700	1179.20	58.908	2010.60	47.061	1683.70	46.883
4	974.94	22.607	808.15	66.446	7458.20	218.300	1162.50	89.062	1985.10	48.571	1678.10	48.373
5	931.87	21.731	786.23	65.470	7142.70	207.600	1121.40	67.340	1935.30	46.358	1620.40	46.312
6	933.23	21.948	780.22	63.653	7196.10	210.010	1120.20	68.378	1920.00	46.481	1817.80	46.363
AV.	946.28	21.984	794.55	67.134	7246.86	210.492	1136.24	68.836	1946.17	47.189	1636.95	48.892
SDEV	20.40	0.459	22.30	4.789	150.77	4.073	27.48	3.649	43.04	0.861	35.12	0.881
SDEV/AV.	0.022	0.021	0.028	0.071	0.021	0.019	0.024	0.053	0.022	0.018	0.021	0.018

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
NTU	3.923	3.759	3.327	3.811	3.710
HTU	0.311	0.324	0.366	0.320	0.328
KLA	9.156E-03	6.956E-03	7.772E-03	8.905E-03	8.689E-03

RUN 01 13

DATA: RA- 6-85

PACKING: SIZE TYPE: 6.35 MM (0.25 IN.) RASCHIG RINGS
 POROSITY: 24 PERCENT
 DEPTH: 24 0.914 M (3.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED

SYMBOLS AND UNITS

READING AFTER
45 MIN. 95 MIN.

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM TV
 WATER TEMPERATURE, CONSTANT HEAD TANK TI
 WATER TEMPERATURE, EFFLUENT TANK TE
 COLUMN'S MANOMETER READING: HIGH PRESSURE HPM
 LOW PRESSURE LPM

24.75 24.80
 24.40 24.72
 23.70 24.00
 812.00 812.00
 420.00 420.00

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM TC
 COMPRESSED AIR TEMPERATURE TC
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE MPG
 LOW PRESSURE LPG
 BAROMETRIC PRESSURE PB

26.00 27.00
 27.30 28.00
 714.00 713.00
 325.00 326.00
 759.80 759.90

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR), AS READ FROM FLOWMETER:
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE:

QL = 3.0198E-05 M³/S
 QGR = 226.33E-05 M³/S
 CGR = 231.77E-05 M³/S

LIQUID MASS FLUX:

L = 3.714 KG/(S·M²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TAIR = 24.775 C
 TL = 24.212 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

FLW = 886.85 KG/M³
 FPL = 196.80 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT CROD:

CPGE = 1976. N/M²
 CPGZ = 2052. (N/M²) / M

RUN 81 13

DATE: 4- 6-85

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT
 PH 7.61 7.58
 CONDUCTIVITY (MICROMHCS) 1285. 1300.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	0.0498	0.1840	0.0588	0.4047	0.2237
	3.825	12.584	4.347	31.081	17.168

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	966.38	78.276	824.20	166.880	7819.80	727.900	1152.00	171.340	2002.60	167.910	1755.00	167.840
2	973.98	74.365	826.32	139.220	7676.80	723.260	1153.80	153.080	1930.20	163.610	1755.30	165.120
3	912.83	79.631	779.91	149.750	7208.90	734.800	1046.30	160.730	1910.90	169.190	1666.80	168.580
4	934.40	80.702	793.30	143.670	7371.50	742.940	1108.30	157.530	1916.50	168.680	1687.40	170.080
5	945.45	75.495	806.21	140.020	7454.50	700.010	1123.30	151.840	1922.30	161.160	1724.50	181.420
6	949.18	77.120	800.39	137.330	7462.70	711.190	1120.40	151.000	1932.00	160.640	1715.20	162.390
AV.	947.04	78.331	805.72	146.145	7469.00	723.370	1123.70	157.587	1937.42	165.198	1717.33	166.085
SDEV	22.08	1.720	18.87	11.067	168.33	15.597	26.22	7.833	38.03	3.878	35.88	3.673
SDEV/AV.	0.023	0.022	0.023	0.076	0.023	0.022	0.023	0.048	0.019	0.023	0.021	0.022

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	2.582	2.455	2.265	2.524	2.423
NTU	0.351	0.372	0.404	0.382	0.377
HTU	1.052E-02	1.001E-02	9.231E-03	1.024E-02	9.876E-03
KLA					

DATE: 5-1-83

RUN #1 14

PACKING: SIZE, TYPE: 8.39 IN (0.25 IN.) RASCHIG RINGS
 POROSITY: 54 PERCENT
 DEPTH: 7' 0.914 M (3.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 15 MIN.
DATA RELEVANT TO PACKED COLUMN:		
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TA	24.70
WATER TEMPERATURE, CONSTANT HEAD TANK	TI	24.50
WATER TEMPERATURE, EFFLUENT TANK	TE	23.80
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPH	583.00
LOW PRESSURE	LPH	448.00
DATA RELEVANT TO AIR COMPRESSOR:		
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TC	25.80
COMPRESSED AIR TEMPERATURE	TC	26.70
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPO	857.00
LOW PRESSURE	LPO	382.00
BAROMETRIC PRESSURE	PB	758.00

VOLUMETRIC FLOWRATES:

LIQUID (WATER): QL= 2.5500E-05 M³/S
 GAS (AIR): AS READ FROM FLOWMETER: QGR= 191.33E-05 M³/S
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: QG= 195.33E-05 M³/S

L= 3.136 KG/(S-M³)

LIQUID MASS FLUX:

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM: TWA= 24.675 C
 LIQUID (WATER): TAE= 24.350 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

RL= 996.91 KG/M³
 RME= 998.03 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DPGE= 1319.4 N/M²
 DPGE= 1643.1 N/M²/M

DATE: 5- 8-85

RUN #1 14

WATER QUALITY PARAMETERS

PARAMETERS	INFLUENT	EFFLUENT
PH	7.40	7.58
CONDUCTIVITY (MICROMHOS)	1295	1305

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
H	0.2389	0.1844	0.0970	0.4058	0.2289
S	18.297	12.296	4.369	31.088	17.392

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDV).

TRIAL	CI	CE	CF	CI	CE	CF	CI	CE	CI	CE	CE
1	844.74	63.465	146.960	6877.40	585.870	1053.20	151.130	1802.00	137.800	1548.20	132.390
2	920.01	53.620	122.540	7095.10	531.010	1092.50	134.330	1845.80	128.450	1533.30	130.080
3	932.46	83.239	131.140	7143.40	579.140	1100.50	139.850	1909.20	128.350	1635.10	130.830
4	917.66	84.474	123.840	7064.40	519.240	1079.50	135.970	1845.80	131.300	1593.20	132.030
5	919.05	61.364	125.450	7077.80	561.030	1085.70	134.950	1885.20	125.950	1612.30	128.960
6	918.47	61.804	120.440	7064.10	565.180	1078.70	131.750	1855.90	124.910	1598.80	128.280
AV.	915.48	63.001	124.468	7052.23	576.918	1081.88	137.937	1857.28	129.623	1598.35	129.683
SDV	18.14	1.175	9.763	118.67	11.548	16.25	6.855	38.86	4.825	29.51	2.688
SDV/AV.	0.018	0.019	0.078	0.017	0.020	0.015	0.050	0.020	0.038	0.018	0.021

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
NTU	2.776	2.837	2.381	2.719	2.806
HTU	0.329	0.347	0.384	0.338	0.351
KLA	9.552E-03	9.075E-03	4.195E-03	9.358E-03	8.969E-03

DATE: 4-8-69

RUN #115

RASCIO RING

PACKING: SIZE, TYPE: 6.35 MM (0.25 IN.)
 POROSITY: 14 PERCENT
 DEPTH: 0.914 M (3.00 FT)

MISCELLANEOUS DATA

READING AFTER 45 MIN. 95 MIN.

SYMBOLS AND UNITS

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

SYMBOLS AND UNITS	QUANTITY MEASURED	READING AFTER 45 MIN.	READING AFTER 95 MIN.
TV	AMBIENT TEMPERATURE, PACKED COLUMN ROOM	23.99	24.05
TI	AMBIENT TEMPERATURE, CONSTANT HEAD TANK	24.40	24.90
TE	WATER TEMPERATURE, EFFLUENT TANK	23.60	24.00
HPV	WATER TEMPERATURE, EFFLUENT TANK	589.00	589.00
LPV	COLUMN'S MANOMETER READING, HIGH PRESSURE	482.00	482.00
	COLUMN'S MANOMETER READING, LOW PRESSURE		

DATA RELEVANT TO AIR COMPRESSOR:

SYMBOLS AND UNITS	QUANTITY MEASURED	READING AFTER 45 MIN.	READING AFTER 95 MIN.
YO	AMBIENT TEMPERATURE, COMPRESSOR ROOM	24.80	25.80
TC	COMPRESSED AIR TEMPERATURE	25.90	26.30
HPO	FLOWMETER'S MANOMETER READING, HIGH PRESSURE	829.00	829.00
LPO	FLOWMETER'S MANOMETER READING, LOW PRESSURE	407.00	407.00
PB	BAROMETRIC PRESSURE	757.30	757.70

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR), AS READ FROM FLOWMETER:
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE:

QL= 2.3090E-05 M³/S
 QGR= 173.33E-05 M³/S
 QG= 176.39E-05 M³/S

L= 2.039 KG/(S*M³)

LIQUID MASS FLUX:

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TVA= 24.000 C
 TAW= 24.225 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

RL= 998.94 KG/M³
 RME= 997.00 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DPGE= 1043. M/M³
 DPGZ= 1144. (M/M³)/M

DATE: 8-1-85

RUN: 01 15

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT
 PH 7.55 7.61
 CONDUCTIVITY (MICROHMS) 1300. 1305.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHE	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	0.2382	0.1882	0.0587	0.4048	0.2238
	18.119	12.528	4.330	30.823	17.107

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	914.82	52.008	749.89	126.630	1111.80	136.880	1836.10	110.320	1581.00	105.970
2	833.99	53.215	762.71	107.070	1129.90	123.300	1848.30	106.140	1578.40	108.350
3	904.08	51.902	737.21	112.430	1094.80	126.080	1822.50	108.780	1545.70	104.780
4	902.72	52.945	733.83	106.220	1090.00	122.560	1784.40	103.800	1521.50	105.840
5	915.17	51.861	757.04	108.360	1119.70	122.000	1792.70	106.230	1541.60	104.680
6	924.94	51.243	753.96	104.020	1121.20	118.820	1785.50	100.230	1545.00	102.300
AV.	915.95	52.196	749.13	110.472	1111.25	125.103	1811.25	105.928	1550.03	105.007
SDEV	12.03	0.243	11.39	1.410	15.83	6.108	27.31	3.530	17.49	1.498
SDEV/AV.	0.013	0.014	0.015	0.078	0.014	0.048	0.015	0.034	0.011	0.014

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHE	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	2.975	2.830	2.542	2.302	2.800
NTU	0.307	0.323	0.360	0.315	0.326
HTU	8.271E-03	8.320E-03	7.921E-03	9.043E-03	8.724E-03
KLA					

DATE: 16-9-85

RUN #: 16

PACKING: SIZE, TYPE: 12.70 MM (0.50 IN.) RASCHIG RINGS
 POROSITY: 63 PERCENT
 DEPTH: 2= 0.914 M (3.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
DATA RELEVANT TO PACKED COLUMN:		
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TW C	23.60 23.60
WATER TEMPERATURE, CONSTANT HEAD TANK	TI C	23.90 24.00
WATER TEMPERATURE, EFFLUENT TANK	TE C	23.30 23.50
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPM MM	226.00 226.00
COLUMN'S MANOMETER READING: LOW PRESSURE	LPM MM	497.50 497.50

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM	TG C	25.00 25.30
COMPRESSED AIR TEMPERATURE	TC C	26.10 26.50
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HAG MM	406.00 804.00
FLOWMETER'S MANOMETER READING: LOW PRESSURE	LHG MM	421.00 423.00
BAROMETRIC PRESSURE	PA MM	764.00 763.00

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR): AS READ FROM FLOWMETER:
 GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE:

CL= 3.09E-03 M³/S
 CGP= 204.67E-05 M³/S
 CG= 206.80E-05 M³/S

L= 3.810 KG/(15M³/S)

LIQUID MASS FLUX:

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TAW= 23.800 C
 TAE= 23.675 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

CL= 997.08 KG/M³
 CM= 824.58 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DPCT= 230. N/M²
 DPCZ= 252. (N/M²/M)

DATE: 14- 9-65

RUN #1 16

WATER QUALITY PARAMETERS

EFFLUENT

INFLUENT

PARAMETERS

PH
CONDUCTIVITY (MICROMHOS)

7.48
1250.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
H	0.0484	0.1621	0.0952	0.4004	0.2128
S	3.226	10.822	3.681	26.725	14.213

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	CI	CE	CI	CE	CI	SE	CI	CE	TOLUENE
1	762.43	79.449	666.67	177.500	6579.20	800.630	891.81	173.720	1289.20
2	767.07	80.738	648.68	154.390	6612.30	822.660	883.85	158.690	1287.80
3	746.97	80.753	652.02	164.440	6457.10	817.570	875.61	158.170	1267.00
4	771.14	79.805	651.08	151.640	6651.70	813.350	885.51	156.770	1293.50
5	783.98	78.860	677.50	154.830	6413.40	797.830	918.23	154.840	1286.10
6	764.66	79.265	655.99	150.620	6505.20	806.040	888.03	154.170	1282.10
AV.	767.04	79.818	658.65	154.903	6619.82	809.896	890.47	156.268	1292.77
SDEV	13.87	0.791	11.19	10.344	115.63	9.788	14.67	1.881	23.30
SDEV/AV.	0.018	0.010	0.017	0.065	0.017	0.012	0.016	0.012	0.018

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
NTU	2.354	2.222	1.935	2.310	2.217
HTU	0.388	0.411	0.472	0.386	0.412
KLA	9.841E-03	9.289E-03	8.090E-03	9.856E-03	9.270E-03

RUN #1 17

DATE: 17- 9-85

PACKING: SIZE, TYPE: 12.70 MM (0.50 IN.) RASCHIG RINGS
 POROSITY: 83 PERCENT
 DEPTH: Z= 0.914 M (3.00 FT)

MISCELLANEOUS DATA

SYMBOLS AND UNITS
 45 MIN. 95 MIN.

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM
 WATER TEMPERATURE, CONSTANT HEAD TANK
 WATER TEMPERATURE, EFFLUENT TANK
 COLUMN'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE

TV
 TI
 TE
 HPM
 LPM

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM
 COMPRESSED AIR TEMPERATURE
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE
 BAROMETRIC PRESSURE

TC
 TC
 HPG
 LPG
 PB

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR): AS READ FROM FLOWMETER
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE

CLF 2.8827E-05 M³/S
 GCR 256.33E-05 M³/S
 GCR 259.86E-05 M³/S

LIQUID-MASS FLUX:

L= 3.275 KG/(S*M²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TWA 23.500 C
 TAE 23.375 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

FL 997.18 KG/M³
 FM 1224.62 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DFG 327. N/M²
 DFC 354. (N/M²)/M

DATE: 17- 9-65

RUN #1 17

WATER QUALITY PARAMETERS

PARAMETERS	INFLUENT	EFFLUENT
PH	7.60	7.70
CONDUCTIVITY (MICROMHOS)	1250.	1260.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	0.0475	0.1611	0.0343	0.3980	0.2871
	4.642	15.728	5.305	58.854	28.222

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	650.23	59.688	572.61	126.240	5873.50	598.180	745.78	123.770	1315.80	123.120	1093.50	115.020
2	870.24	61.198	574.72	111.090	5839.80	615.590	755.97	115.880	1332.80	125.090	1117.30	117.910
3	860.62	59.565	591.26	113.190	5918.80	598.880	772.76	115.930	1388.20	122.470	1148.40	114.800
4	687.45	60.403	582.52	108.960	5967.40	612.630	769.38	114.420	1374.40	124.530	1145.00	117.130
5	719.67	59.099	619.28	109.060	6242.30	595.610	812.22	113.340	1460.10	122.730	1208.10	114.470
6	701.51	59.068	595.64	107.390	6089.50	594.630	787.08	112.180	1404.10	120.520	1188.50	113.830
AV.	844.95	59.920	589.34	112.655	5955.21	602.586	773.86	115.922	1378.88	123.047	1148.80	115.493
SDEV	24.20	0.916	17.20	6.353	197.35	9.110	23.58	4.112	52.42	1.898	40.61	1.682
SDEV/AV.	0.035	0.015	0.029	0.062	0.033	0.015	0.030	0.035	0.038	0.014	0.035	0.014

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	1.465	2.383	2.124	2.456	2.387
NTU	0.490	0.383	0.430	0.372	0.386
HTU	6.702E-03	8.565E-03	7.633E-03	8.825E-03	8.505E-03
KLA	9.003E-03				

RUN #1 18

DATE: 18-9-85

PACKING: SIZE: TYPE: 12.70 MM (0.50 IN) PASCHIO RINGS
 POROSITY: 85 PERCENT
 DEPTH: Z= 0.914 M (3.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
DATA RELEVANT TO PACKED COLUMN:		
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	T _A	23.40 23.85
WATER TEMPERATURE, CONSTANT HEAD TANK	T _I	23.70 24.15
WATER TEMPERATURE, EFFLUENT TANK	T _E	22.85 23.20
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPV	538.00 538.00
COLUMN'S MANOMETER READING: LOW PRESSURE	LPV	445.50 445.50
DATA RELEVANT TO AIR COMPRESSOR:		
AMBIENT TEMPERATURE, COMPRESSOR ROOM	T _C	25.00 25.60
COMPRESSED AIR TEMPERATURE	T _C	27.00 27.50
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPQ	697.00 697.00
FLOWMETER'S MANOMETER READING: LOW PRESSURE	LPQ	330.00 330.00
BAROMETRIC PRESSURE	PB	782.10 782.10

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR): AS READ FROM FLOWMETER:
 GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE:

OL= 2.3500E-05 M³/S
 OGR= 308.87E-05 M³/S
 CGR= 314.50E-05 M³/S

L= 2.890 KG/(S*M³2)

LIQUID MASS FLUX:

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

T_{AV}= 23.825 C
 T_{AE}= 23.475 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

FL= 997.13 KG/M³
 RM= 824.56 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DPG= 424. N/M²
 DPGZ= 464. (N/M²2)/M

DATE: 10-9-85

RUN #1 18

WATER QUALITY PARAMETERS

EFFLUENT

INFLUENT

PH 7.83
CONDUCTIVITY (MICROMHOS) 1280.7.80
1245.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	0.2345 31.388	0.1814 21.804	0.0548 7.308	0.3883 53.368	0.2090 21.978

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	745.92	54.105	561.22	110.350	5533.60	545.980	874.81	109.480	1518.30	111.880	1244.70	104.930
2	756.15	53.369	557.09	94.249	6612.20	541.280	876.34	98.059	1510.40	109.960	1250.30	103.530
3	775.47	52.440	681.27	96.335	6803.30	531.160	905.94	98.834	1574.80	108.800	1284.70	101.720
4	787.21	51.733	887.89	90.862	6902.20	524.080	915.05	88.652	1573.90	106.390	1301.00	99.923
5	745.87	51.693	651.78	92.471	6556.10	523.190	863.11	96.767	1512.10	106.260	1244.50	100.440
6	764.08	50.614	671.77	89.451	6719.70	512.230	891.90	94.065	1522.30	104.290	1261.70	97.858
AV.	762.45	52.326	668.50	95.718	6696.28	529.652	888.68	93.152	1535.57	107.930	1266.15	101.414
SDEV	16.58	1.264	14.23	7.632	139.67	12.480	18.63	5.498	31.81	2.783	25.44	2.577
SDEV/AV.	0.022	0.024	0.021	0.080	0.021	0.024	0.021	0.055	0.021	0.028	0.020	0.025

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	CI	CE	CI	CE	CI
NTU	2.133	2.615	2.391	2.889	2.583
HTU	0.428	0.350	0.382	0.340	0.354
KLA	6.766E-03	8.292E-03	7.542E-03	8.525E-03	6.183E-03

RUN #1 19

DATE: 20- 8-65

PACKING: SIZE: 12-70 MM (0.50 IN.) RASCHIG RINGS
 POROSITY: 63 PERCENT
 DEPTH: 2= 1.219 M (4.00 FT)

MISCELLANEOUS DATA

READING AFTER
45 MIN. 95 MIN.

SYMBOLS AND UNITS

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM: TV
 WATER TEMPERATURE, CONSTANT HEAD TANK: TI
 WATER TEMPERATURE, EFFLUENT TANK: TE
 COLUMN'S MANOMETER READING: HIGH PRESSURE: MPV
 LOW PRESSURE: LPV

24.70 24.75
 24.05 24.30
 23.80 24.00
 528.00 528.00
 498.00 498.00

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM: TD
 COMPRESSED AIR TEMPERATURE: TC
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE: HPG
 LOW PRESSURE: LPG

26.50 27.00
 27.80 28.00
 608.50 608.00
 420.00 420.50
 758.80 758.30

BAROMETRIC PRESSURE

PB

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR), AS READ FROM FLOWMETER:
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE:

CL= 3.0847E-05 M³/S
 CGR= 205.00E-05 M³/S
 CG= 208.01E-05 M³/S

LIQUID MASS FLUX:

L= 3.798 KG/(S*CM**2)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TA= 24.725 C
 TL= 24.037 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

FL= 998.93 KG/M**3
 FM= 828.37 KG/M**3

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DPG= 267. N/M**2
 DPGZ= 219. N/M**2/M

DATE: 20- 9-65

RUN #1 19

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT
 PH 7.77 7.61
 CONDUCTIVITY (MICROMHOS) 1310. 1260.

HENRY'S LAW CONSTANTS (P) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
H	0.0494	0.1834	0.0562	0.4035	0.2201
S	3.324	11.002	3.782	27.158	14.625

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	736.64	42.620	647.22	121.190	620.320	434.460	842.89	114.430	1436.80	83.160
2	748.56	42.869	644.75	108.210	630.300	422.390	848.43	107.350	1441.90	81.123
3	756.38	42.371	662.31	111.130	641.60	436.470	862.65	106.400	1481.30	80.134
4	747.48	42.431	640.26	105.460	637.90	437.250	842.08	105.380	1434.80	78.512
5	748.30	41.426	649.02	106.770	637.60	427.720	850.78	103.160	1481.10	78.365
6	756.94	41.502	648.33	103.440	645.60	427.940	852.93	103.310	1451.20	77.199
AV.	749.22	42.220	646.65	109.373	637.25	434.372	849.63	107.338	1451.15	79.748
SDEV	7.40	0.622	7.39	6.340	61.76	5.710	7.64	3.907	17.90	2.174
SDEV/AV.	0.010	0.015	0.011	0.056	0.010	0.013	0.009	0.036	0.012	0.027

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
NTU	3.663	2.660	2.455	2.975	2.849
HTU	0.406	0.426	0.496	0.410	0.428
KLA	9.386E-03	6.937E-03	7.674E-03	8.239E-03	8.808E-03

DATE: 21- 9-65

RUN #: 20

PACKING: SIZE, TYPE: 12.70 MM (0.50 IN.) RASCHIO RINGS
 POROSITY: 83 PERCENT
 DEPTH: ZE 1.213' (4.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 55 MIN.
DATA RELEVANT TO PACKED COLUMN:		
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TV	24.85
WATER TEMPERATURE, CONSTANT-HEAD TANK	VI	24.80
WATER TEMPERATURE, EFFLUENT TANK	TE	23.60
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPH	542.50
LOW PRESSURE	LPH	482.00
DATA RELEVANT TO AIR COMPRESSOR:		
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TC	28.70
COMPRESSED AIR TEMPERATURE	TC	28.00
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPO	698.00
LOW PRESSURE	LPO	327.50
BAROMETRIC PRESSURE	PB	759.50

VOLUMETRIC FLOWRATES:

LIQUID (WATER): QLE 2.3380E-05 M³/S
 GAS (AIR): AS READ FROM FLOWMETER: QGR 308.87E-05 M³/S
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: CGR 315.87E-05 M³/S

L= 2.875 KG/(S*M^{0.2})

LIQUID MASS FLUX:

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TVAE 24.800 C
 TAE 24.287 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

RL= 996.93 KG/M³
 RPL 824.35 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DFGE 459. N/M^{0.2}
 DPCZE 401. (N/M^{0.2})/M

DATE: 21- 9-83

RUN #1 20

WATER QUALITY PARAMETERS

PARAMETERS	INFLUENT	EFFLUENT
PH	7.62	7.68
CONDUCTIVITY (MICROMHOS)	1270.	1280.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	0.0501	0.1642	0.0589	0.4053	0.2252
H	-8.758	22.174	7.677	54.724	38.411
S					

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	768.95	26.952	639.34	62.701	6328.60	253.060	885.90	62.369	1450.90	52.013	1209.10	43.887
2	776.77	26.393	633.25	52.773	6392.70	254.790	881.50	55.520	1443.50	49.597	1211.20	43.808
3	772.67	25.134	640.18	54.557	6359.70	241.340	888.27	55.730	1483.60	48.317	1217.80	47.158
4	786.25	25.699	643.24	51.905	6554.00	247.300	890.86	54.402	1477.60	48.720	1240.40	48.182
5	770.21	24.577	643.64	51.248	6344.00	236.190	890.38	52.145	1457.60	46.598	1213.50	46.234
6	782.17	24.633	643.87	49.759	6437.70	237.410	894.98	52.261	1447.50	46.599	1217.50	46.184
AV.	777.09	25.498	641.59	53.825	6402.78	245.008	891.21	55.571	1456.78	48.641	1218.24	47.877
SDEV	10.27	0.858	5.35	4.833	83.85	7.846	7.80	3.581	12.58	2.037	11.47	1.626
SDEV/AV.	0.013	0.034	0.008	0.086	0.013	0.032	0.008	0.065	0.008	0.042	0.009	0.034

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	2.736	38371	3.041	3.445	3.313
NTU	0.445	0.362	0.401	0.354	0.388
HTU	6.477E-03	7.975E-03	7.194E-03	8.149E-03	7.839E-03
KLA					

RUN #1 21

DATE: 23- 9-85

PACKING: SIZE: TYPE: 12.70 MM (C.50 IN.) RASCHIG RINGS
 POROSITY: 63 PERCENT
 DEPTH: Z= 1.219 M (4.00 FT)

MISCELLANEOUS DATA

PEADING AFTER
 45 MIN. 85 MIN.

SYMBOLS AND UNITS

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM
 WATER TEMPERATURE, CONSTANT HEAD TANK
 WATER TEMPERATURE, EFFLUENT TANK
 COLUMN'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE

TV	C	24.30	24.40
TI	C	24.30	24.65
TE	C	23.80	23.80
HPV	MM	535.50	535.50
LPV	MM	488.00	489.00

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM
 COMPRESSED AIR TEMPERATURE
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE
 BAROMETRIC PRESSURE

TC	C	25.80	26.80
TC	C	27.60	28.00
MPQ	MM	653.00	653.00
LPG	MM	373.00	373.00
PO	MM	780.30	780.30

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR): AS READ FROM FLOWMETER
 GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE:

QL= 2.8387E-05 M³/S
 QGR= 256.67E-05 M³/S
 QGM= 260.99E-05 M³/S

LIQUID MASS FLUX:

L= 3.245 KG/(S.M²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TA= 24.350 C
 TAE= 24.087 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

FL= 998.98 KG/M³
 FPL= 824.45 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DPG= 376.4 N/M²
 DPCZ= 308.1 (N/M²)/M

DATE: 23- 9-85

RUN 81 21

WATER QUALITY PARAMETERS

PARAMETERS	INFLUENT	EFFLUENT
PH	7.80	7.55
CONDUCTIVITY (MICROMHOSI)	1270.	1275.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	1,1-DICHLOROETHANE	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
ETHER					
	0.0495	0.1635	0.0565	0.4037	0.2211
	4.885	16.175	5.568	38.928	21.875

H-S

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	732.85	31.251	662.45	64.597	6243.60	314.220	844.40	77.845	1443.00	83.338	1202.50	82.389
2	765.63	31.651	671.79	75.551	6512.70	320.430	866.25	72.482	1483.60	82.311	1245.40	81.438
3	745.27	30.573	672.91	5341.40	5341.40	309.150	858.23	71.738	1473.00	80.854	1225.10	81.543
4	773.30	30.354	677.27	71.717	6569.90	306.700	874.08	69.036	1488.80	58.186	1257.70	80.863
5	728.42	30.291	649.67	72.780	6209.60	306.250	833.68	68.918	1438.90	58.629	1193.50	80.839
6	742.87	29.708	669.17	71.026	6327.30	300.090	853.81	68.248	1433.90	57.833	1207.20	59.284
AV.	748.06	30.638	667.21	75.245	6367.41	309.547	855.04	71.539	1461.20	60.192	1222.87	81.383
SDEV	17.67	0.703	9.86	4.945	144.80	7.160	14.66	3.480	27.15	2.518	24.31	1.431
SDEV/AV.	0.024	0.023	0.015	0.066	0.023	0.023	0.017	0.048	0.019	0.038	0.020	0.023

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	1,1-DICHLOROETHANE	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
NTU	3.294	2.491	3.153	2.405	3.246	3.088
HTU	0.370	0.489	0.386	0.435	0.375	0.385
KLA	8.795E-03	6.652E-03	6.433E-03	7.469E-03	8.688E-03	8.248E-03

RUN #1 22

DATE: 24- 9-85

PACKING: SIZE, TYPE: 12.70 MM (0.50 IN.) PASCHIG RINGS
 POROSITY: 63 PERCENT
 DEPTH: Z= 1.925 M (5.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
DATA RELEVANT TO PACKED COLUMN:		
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TM	24.55
WATER TEMPERATURE, CONSTANT HEAD TANK	TI	24.80
WATER TEMPERATURE, EFFLUENT TANK	TE	24.35
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPH	531.50
LOW PRESSURE	LPH	433.00
DATA RELEVANT TO AIR COMPRESSOR:		
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TD	28.40
COMPRESSED AIR TEMPERATURE	TC	27.70
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPG	610.00
LOW PRESSURE	LPG	417.00
BAROMETRIC PRESSURE	PB	758.80

VOLUMETRIC FLOWRATES:

LIQUID (WATER): GL= 3.0793E-05 M³/S
 GAS (AIR), AS READ FROM FLOWMETER: QGR= 205.67E-05 M³/S
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: QGX= 208.61E-05 M³/S

LIQUID MASS FLUX: LM= 3.787 MG/(5.00M²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TM= 24.575 C
 TX= 24.438 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

FL= 996.89 KG/M³
 FM= 824.40 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

CPG= 315. N/M²
 CPGZ= 207. (N/M²)/M

DATE: 24- 3-85

RUN #1 22

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT

PH 7.68 7.65
CONDUCTIVITY (MICROMHOS) 1280. 1280.

HENRY'S LAW CONSTANTS (M) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
H	0.0505	0.1847	0.0573	0.4065	0.2283
S	3.420	11.181	3.880	27.540	15.488

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	2033.20	60.251	2043.30	255.710	6784.20	241.880	2040.50	187.780	2043.20	58.688	1858.40	68.323
2	2078.60	62.162	2041.60	228.530	6941.80	254.440	2080.00	158.270	2055.10	59.827	1982.60	71.872
3	2010.60	57.375	2010.90	228.660	6710.30	233.430	2018.90	155.140	2029.20	53.873	1843.00	65.900
4	2069.30	56.287	2030.20	216.690	6907.10	238.880	2048.50	151.650	2048.50	55.074	1978.30	68.998
5	2054.30	57.015	2064.00	220.410	6461.10	233.340	2063.00	151.950	2066.40	52.944	1882.10	65.811
6	2033.30	55.960	1982.70	210.960	6748.50	228.540	2003.00	147.140	1995.70	51.679	1928.80	64.318
AV.	2044.25	58.508	2030.12	226.560	6825.50	238.551	2039.03	155.488	2039.58	55.361	1862.67	67.211
SDEV	27.83	2.300	27.71	15.703	91.91	8.312	23.80	7.246	24.95	3.235	23.12	2.595
SDEV/AV.	0.014	0.039	0.014	0.069	0.013	0.037	0.012	0.047	0.012	0.058	0.012	0.039

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
NTU	3.721	3.565	3.101	3.705	3.338
HTU	0.410	0.425	0.491	0.411	0.431
KLA	9.275E-03	8.834E-03	7.726E-03	9.235E-03	8.818E-03

DATE: 29- 9-85

RUN #1 23

PACKING: SIZE, TYPE: 12.70 MM (0.50 IN.) PASCHIO RINGS
 POROSITY: 63 PERCENT
 DEPTH: Z= 1.524 M (5.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED

PEADING AFTER

45 MIN. 95 MIN.

SYMBOLS AND UNITS

DATA RELEVANT TO PACKED COLUMN:

QUANTITY MEASURED	SYMBOLS AND UNITS	PEADING AFTER
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TV	24.45
WATER TEMPERATURE, CONSTANT HEAD TANK	TI	24.50
WATER TEMPERATURE, EFFLUENT TANK	TE	23.80
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPV	540.00
COLUMN'S MANOMETER READING: LOW PRESSURE	LPV	485.00

DATA RELEVANT TO AIR COMPRESSOR:

QUANTITY MEASURED	SYMBOLS AND UNITS	PEADING AFTER
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TC	25.30
COMPRESSED AIR TEMPERATURE	TC	27.00
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPQ	858.00
FLOWMETER'S MANOMETER READING: LOW PRESSURE	LPQ	370.00
BAROMETRIC PRESSURE	PB	760.10

VOLUMETRIC FLOWRATES:

LIQUID (WATER): CL= 2.6268E-09 M³/S
 GAS (AIR): AS READ FROM FLOWMETER: CCR= 255-50E-05 M³/S
 GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE: CG= 260.24E-05 M³/S

LIQUID MASS FLUX:

L= 3.230 KG/(S·M²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM: TVR 24.400 C
 LIQUID (WATER): TLR 24.175 C

DENSITIES:

LIQUID (WATER): FL= 998.96 KG/M³
 COLUMN'S MANOMETER LIQUID: RPL 824.44 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP: CPGR 444. N/M²
 PRESSURE DROP PER UNIT DEPTH: CPGRZ 292. (N/M²)/M

DATE: 25- 9-85

RUN 01 23

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT
 PH 7.72 7.68
 CONDUCTIVITY (MICROMHOS) 1270. 1245.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
H	0.0497	0.1838	0.0585	0.4044	0.2228
S	4.928	16.232	5.801	40.084	22.085

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	2270.60	51.218	2242.90	184.470	7166.20	191.820	2276.40	123.820	2132.20	48.388	2042.30	58.254
2	2300.00	50.582	2187.30	161.160	7250.10	192.910	2258.40	112.890	2125.00	48.848	2071.40	58.388
3	2330.30	51.745	2324.50	177.680	7341.50	193.790	2349.90	120.050	2196.50	48.322	2121.80	58.521
4	2445.30	51.684	2320.00	166.500	7691.60	196.720	2197.30	116.210	2258.20	46.887	2200.30	57.174
5	2294.40	52.691	2259.60	175.050	7229.90	199.980	2287.00	120.600	2161.40	49.012	2088.50	58.462
6	2306.00	52.599	2166.90	169.040	7270.00	200.720	2263.10	118.340	2133.60	47.521	2079.10	58.180
AV.	2324.53	51.667	2253.63	172.983	7324.88	195.990	2307.18	118.653	2187.82	47.828	2103.96	57.193
SDEV.	62.26	0.835	60.84	9.631	188.37	3.755	55.25	3.793	51.80	0.882	51.51	0.931
SDEV/AV.	0.027	0.016	0.027	0.056	0.026	0.019	0.024	0.032	0.024	0.018	0.024	0.016

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
NTU	3.931	3.782	3.387	3.886	3.728
HTU	0.388	0.402	0.420	0.392	0.409
KLA	8.357E-03	6.284E-03	8.084E-03	8.262E-03	7.928E-03

DATE: 26- 9-85

RUN #1 24

PACKING: SIZE, TYPE: 12-70 MM (C-50 IN.) RASCHIG RINGS
 POROSITY: 83 PERCENT
 DEPTH: Z= 1.524 M (5.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED

SYMBOLS AND UNITS

READING AFTER
45 MIN. 95 MIN.

DATA RELEVANT TO PACKED COLUMN:

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TW C	23.85 23-75
WATER TEMPERATURE, CONSTANT HEAD TANK	TI C	24.00 24-30
WATER TEMPERATURE, EFFLUENT TANK	TE C	22.80 23-20
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPA MM	547.50 547-50
LOW PRESSURE	ALPA MM	476.00 476-00

DATA RELEVANT TO AIR COMPRESSOR:

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TG C	25.30 26-00
COMPRESSED AIR TEMPERATURE	YC C	27.00 27-40
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPQ MM	703.00 703-00
LOW PRESSURE	LPQ MM	323.00 323-00
BAROMETRIC PRESSURE	PB MM	757.80 757-10

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR), AS READ FROM FLOWMETER:
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE:

QL= 2.3138E-05 M³/S
 QGR= 308.67E-05 M³/S
 QGW= 315.58E-05 M³/S

LIQUID MASS FLUX:

L= 2.848 KG/(S.M²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TAW= 23.700 C
 TAW= 23.825 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

RL= 987.10 KG/M³
 RPL= 824.58 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DPGM 578. N/M²
 DPGZ 379. (N/M²)/M

DATE 1 26- 9-85

RUN #1 24

WATER QUALITY PARAMETERS

PARAMETERS	INFLUENT	EFFLUENT
PH	7.88	7.80
CONDUCTIVITY (MICROMHOS)	1280.	1265.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S)

	1,1-DICHLOROETHANE	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
H	0.2353	0.0482	0.1813	0.0530	0.4080	0.2119
S	32.088	6.577	22.088	7.504	54.551	28.808

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	2147.30	50.528	1960.20	123.530	4886.80	141.930	2049.90	85.353	1938.10	35.883	1945.30	42.833
2	2198.00	49.539	1973.50	119.680	8808.60	145.670	2114.40	81.887	1952.50	37.973	1972.30	44.114
3	2139.80	45.921	1951.00	112.230	6648.30	141.160	2080.80	78.911	1938.70	35.530	1943.50	42.523
4	2164.60	45.295	1938.00	106.580	6710.40	143.490	2078.80	77.893	1822.20	38.211	1942.80	43.120
5	2223.80	43.044	2034.00	104.750	6908.30	136.410	2166.30	75.618	2005.00	34.590	2015.20	41.325
6	2208.20	42.749	1997.00	102.730	6848.20	137.280	2136.30	74.751	1958.10	34.748	1983.10	41.321
AV.	2180.25	46.179	1975.62	111.593	6763.77	140.992	2111.25	79.538	1952.77	35.835	1967.13	42.538
SDEV	34.59	3.245	35.01	8.489	103.44	3.574	34.92	4.349	28.66	1.229	28.23	1.083
SDEV/AV.	0.016	0.070	0.018	0.076	0.015	0.025	0.017	0.055	0.015	0.034	0.015	0.025

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	1,1-DICHLOROETHANE	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
NTU	3.947	3.208	4.007	3.625	4.054	3.838
HTU	0.386	0.475	0.380	0.420	0.376	0.387
KLA	7.391E-03	6.005E-03	7.504E-03	6.788E-03	7.593E-03	7.310E-03

DATE: 27- 9-85

RUN #1 25

PACKING: SIZE: 12.70 MM (0.50 IN.) RASCHIG RINGS
 POROSITY: 63 PERCENT
 DEPTH: Z= 1.825 M (6.00 FT)

MISCELLANEOUS DATA

SYMBOLS AND UNITS 45 MIN. 95 MIN.
 READING AFTER

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN.	READING AFTER 95 MIN.
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TM	24.25	24.20
WATER TEMPERATURE, CONSTANT HEAD TANK	TI	24.00	24.75
WATER TEMPERATURE, EFFLUENT TANK	TE	23.50	24.10
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPH	534.50	535.00
LOW PRESSURE	LPH	489.00	488.50

DATA RELEVANT TO AIR COMPRESSOR:

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN.	READING AFTER 95 MIN.
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TG	25.80	26.10
COMPRESSED AIR TEMPERATURE	TC	27.00	27.20
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPG	612.00	613.00
LOW PRESSURE	LPG	414.00	413.00
BAROMETRIC PRESSURE	PB	751.20	750.50

VOLUMETRIC FLOWRATES:

LIQUID (WATER): GL= 3.0700E-05 M³/S
 GAS (AIR): AS READ FROM FLOWMETER: QGR= 203.67E-05 M³/S
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: QG= 203.82E-05 M³/S

LIQUID MASS FLUX:

L= 3.775 KG/(50M²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM: TMAE 24.225 C
 LIQUID (WATER): TAE 24.037 C

DENSITIES:

LIQUID (WATER): FL= 998.98 KG/M³
 COLUMN'S MANOMETER LIQUID: FAE 824.47 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP: DPGH 372. M/M²
 PRESSURE DROP PER UNIT DEPTH: DPGZ 203. (M/M²)/M

DATE: 27- 9-85

RUN 81 25

WATER QUALITY PARAMETERS

EFFLUENT

INFLUENT

PARAMETERS

7.58
1285.7.82
1285.

CONDUCTIVITY (MICROMHOS)

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

H	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE
	CI	CE	CI	CE	CI	CE	CI	CE	
0.2376	0.0495	0.0495	0.1635	0.0583	0.4037	0.4037	0.4037	0.4037	0.2211
16.236	3.383	3.383	11.377	3.847	27.580	27.580	27.580	27.580	15.114

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE
	CI	CE	CI	CE	CI	CE	CI	CE	
1	2016.50	41.654	2015.60	204.670	6882.30	161.650	2009.20	127.780	1942.80
2	2042.00	41.773	2003.40	179.310	6755.80	157.000	2012.80	119.180	1951.10
3	1998.80	40.612	1975.90	165.490	6636.20	152.040	1976.50	119.350	1831.10
4	2007.80	41.125	1942.40	178.210	6548.70	155.280	1962.90	117.230	1919.70
5	2031.30	40.995	2017.70	177.520	6721.90	163.920	2015.30	117.670	1958.80
6	2026.50	40.576	1987.20	173.610	6710.30	162.610	1987.10	115.870	1936.20
AV.	2020.48	41.154	1990.37	182.802	6693.20	163.782	1995.63	119.613	1940.08
SDEV	16.10	0.472	28.62	11.432	21.10	2.046	21.54	1.012	14.31
SDEV/AV.	0.008	0.011	0.014	0.063	0.008	0.012	0.011	0.008	0.007

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

NTU	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE
	CI	CE	CI	CE	CI	CE	CI	CE	
4.083	2.946	3.974	3.424	4.051	4.051	4.051	4.051	4.051	3.824
0.448	0.621	0.460	0.534	0.431	0.431	0.431	0.431	0.431	0.466
8.454E-03	6.099E-03	6.226E-03	7.090E-03	8.387E-03	8.387E-03	8.387E-03	8.387E-03	8.387E-03	8.132E-03

DATE: 30- 9-85

RUN #1 26

PACKING: SIZE, TYPE: 12.70 MM 10.50 IN. 1 RASCHIG RINGS
 POROSITY: 83 PERCENT
 DEPTH: Z= 1.029 M 15.00 FT

MISCELLANEOUS DATA

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE: PACKED COLUMN ROOM
 WATER TEMPERATURE: CONSTANT HEAD TANK
 WATER TEMPERATURE: EFFLUENT TANK
 COLUMN'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE: COMPRESSOR ROOM
 COMPRESSED AIR TEMPERATURE
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE

BAROMETRIC PRESSURE

SYMBOLS AND UNITS 45 MIN 85 MIN

24.65 24.60
 24.20 24.40
 23.70 23.80
 544.00 543.50
 480.50 481.00

26.00 26.50
 27.60 27.80
 858.00 857.00
 367.00 368.00
 758.50 758.40

VOLUMETRIC FLOWRATES

LIQUID (WATER):
 GAS (AIR): AS READ FROM FLOWMETER
 GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE

QLE 2.808E-03 M³/S
 QGE 255.17E-05 M³/S
 QCE 260.31E-05 M³/S

L= 3.208 KG/15.0021

LIQUID MASS FLUX:

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TWA 24.825 °C
 TAE 24.025 °C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

SLF 987.00 KG/M³
 FME 824.39 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DPG 2.509 N/M²
 DPGZ 278.1 N/M²/M

DATE: 30- 1-85

RUN #1 28

WATER QUALITY PARAMETERS

INFLUENT EFFLUENT
 PH 7.82 7.60
 CONDUCTIVITY (MICROMHOS) 1280. 1275.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
CI	0.0493	0.1633	0.0561	0.4032	0.2188
CE	4.818	16.289	5.597	40.213	21.930

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	2357.30	24.290	2307.50	123.700	7466.00	86.566	2317.00	75.812	2185.80	23.172	2132.50	27.838
2	2330.20	24.024	2223.80	105.440	7376.80	86.655	2259.10	67.990	2127.80	24.510	2086.00	28.413
3	2314.70	23.721	2238.70	110.450	7326.60	94.585	2261.10	69.555	2155.10	22.572	2088.70	27.286
4	2323.20	24.280	2196.60	105.050	7354.90	87.646	2241.70	67.890	2118.80	23.580	2082.40	28.220
5	2251.20	23.475	2178.00	109.700	7143.10	84.115	2209.70	67.695	2086.20	22.437	2039.10	27.122
6	2253.60	23.185	2155.50	102.470	7149.90	93.160	2183.50	66.028	2051.00	22.278	2020.30	28.825
AV.	2305.07	23.629	2216.68	108.602	7302.88	95.460	2246.35	89.178	2120.75	23.100	2077.17	27.817
SDEV	43.16	0.449	53.75	7.744	129.59	1.760	44.40	3.440	48.00	0.872	41.03	0.637
SDEV/AV.	0.019	0.019	0.024	0.071	0.016	0.018	0.020	0.050	0.023	0.038	0.020	0.023

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
NTU	4.729	4.554	4.006	4.609	4.479
HTU	0.537	0.402	0.457	0.397	0.408
KLA	8.320E-03	6.013E-03	7.048E-03	8.110E-03	7.880E-03

DATE: 1-10-85

RUN #1 27

PACKING: SIZE: 12-70 MM (10-50 IN.) RASCHIG RINGS
 POROSITY: 63 PERCENT
 DEPTH: Z = 1.829 M (6.00 FT)

MISCELLANEOUS DATA

READING AFTER

SYMBOLS AND UNITS

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

DATA RELEVANT TO PACKED COLUMN:	SYMBOLS AND UNITS	READING AFTER
AIR/FLOW TEMPERATURE, PACKED COLUMN ROOM	TV	24.10
WATER TEMPERATURE, CONSTANT HEAD TANK	TI	24.20
WATER TEMPERATURE, EFFLUENT TANK	TE	23.30
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPH	553.00
COLUMN'S MANOMETER READING: LOW PRESSURE	LPH	470.90

DATA RELEVANT TO AIR COMPRESSOR:

DATA RELEVANT TO AIR COMPRESSOR:	SYMBOLS AND UNITS	READING AFTER
AIR/FLOW TEMPERATURE, COMPRESSOR ROOM	TC	26.10
COMPRESSED AIR TEMPERATURE	TC	27.90
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPH	707.50
FLOWMETER'S MANOMETER READING: LOW PRESSURE	LPH	318.00
BAROMETRIC PRESSURE	PB	755.20

VOLUMETRIC FLOWRATES:

LIQUID (WATER): OL = 2.2957E-05 M³/S
 GAS (AIR), AS READ FROM FLOWMETER: OGP = 303.00E-05 M³/S
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: OGP = 318.56E-05 M³/S

LIQUID MASS FLUX:

L = 2.823 KG/(S·M²)

AVERAGE TEMPERATURES:

AIR/FLOW, PACKED COLUMN ROOM:
 LIQUID (WATER):

TVAP = 24.100 C
 TAE = 23.875 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

FL = 997.03 KG/M³
 FME = 824.50 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DPG = 667.4 N/M²
 OPG = 364. (N/M²) / M

DATE: 1-10-85

RUN #1 27

WATER QUALITY PARAMETERS

PARAMETERS
 INFLUENT
 7.81
 1280.
 EFFLUENT
 7.81
 1280.

PH
 CONDUCTIVITY (MICROMHOS)

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
0.2185	0.0489	0.1628	0.0557	0.4020	0.0557	0.4020	0.0557	0.2189	0.0557
32.611	8.744	22.448	7.681	55.428	7.681	55.428	7.681	28.904	7.681

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
2128.30	16.756	6741.30	57.482	2129.60	43.105	1937.30	14.479	1965.20	17.898
2124.00	16.560	6775.00	60.431	2109.60	40.050	1906.20	16.458	1947.60	17.813
2056.00	16.190	6647.00	58.584	2089.70	40.534	1853.80	14.487	1934.20	17.911
2076.20	16.029	6624.50	59.107	2080.90	38.178	1853.80	14.987	1904.40	18.777
2084.30	15.126	6581.00	55.467	2064.70	37.640	1887.00	13.813	1811.80	17.029
2061.30	15.254	6579.90	56.543	2049.80	37.358	1837.40	14.231	1869.80	17.418
2090.01	15.986	6664.78	57.936	2084.05	39.844	1888.82	14.743	1925.85	17.919
29.45	0.869	91.76	1.805	31.19	2.116	37.52	0.921	28.90	0.751
0.014	0.042	0.014	0.031	0.015	0.053	0.020	0.083	0.035	0.042

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
4.995	3.934	4.919	4.398	4.924	4.398	4.924	4.398	4.904	4.398
0.366	0.465	0.372	0.418	0.371	0.418	0.371	0.418	0.381	0.418
7.734E-03	6.035E-03	7.616E-03	6.809E-03	7.623E-03	6.809E-03	7.623E-03	6.809E-03	7.438E-03	6.809E-03

DATE: 2-10-85 RUN #1 28
 PACKING: SIZE, TYPE: 5.35 MM (C.25 IN.) RASCHIG RINGS
 POROSITY: 5% PERCENT
 DEPTH: Z= 0.013 M (C.04 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
DATA RELEVANT TO PACKED COLUMN:		
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TV	23.90 23.90
WATER TEMPERATURE, CONSTANT HEAD TANK	TI	24.40 24.40
WATER TEMPERATURE, EFFLUENT TANK	TE	23.80 23.85
COLUMN'S HANDMETER READING: HIGH PRESSURE	HPV	520.00 520.00
LOW PRESSURE	LPV	503.50 503.50
DATA RELEVANT TO AIR COMPRESSOR:		
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TC	25.80 25.80
COMPRESSED AIR TEMPERATURE	TC	27.00 27.00
FLOWMETER'S HANDMETER READING: HIGH PRESSURE	HPO	601.00 601.00
LOW PRESSURE	LPO	429.00 429.00
BAROMETRIC PRESSURE	PB	760.10 760.10

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR): AS READ FROM FLOWMETER:
 GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE:

QL= 2.9727E-05 M³/S
 QGR= 205.67E-05 M³/S
 QG= 204.09E-05 M³/S

LIQUID MASS FLUX:

L= 3.656 KG/(S.M²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TMA= 23.900 C
 TAV= 23.975 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S HANDMETER LIQUID:

FL= 997.01 KG/M³
 FV= 824.24 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

CPGE= 133. N/M²
 CPGE= 0.000 IN/M²

DATE: 2-10-85

RUN #1 28

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT
 PH 7.62 7.43
 CONDUCTIVITY (MICROMHOS) 1250. 1280.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
CI	1816.00	5135.30	1793.90	1814.00	1772.80
CE	1405.600	4835.598	1558.900	1413.400	1388.000
H	0.2370	0.1631	0.0560	0.4028	0.2189
S	16.590	11.421	3.919	28.185	19.321

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	1817.50	1405.600	5135.30	4835.598	1793.90	1558.900	1814.00	1413.400	1772.80	1388.000
2	1841.30	1423.900	6211.80	4895.102	1784.50	1455.400	1810.80	1388.700	1780.80	1387.000
3	1953.70	1518.000	6574.90	5198.892	1940.10	1591.400	1959.40	1513.700	1902.00	1499.000
4	1989.40	1529.000	6698.10	5237.893	1931.60	1599.300	1970.40	1500.400	1923.20	1498.800
5	2010.10	1541.200	6761.40	5278.801	1974.10	1585.200	2018.90	1541.800	1958.70	1525.800
6	2032.80	1557.000	6843.20	5259.000	1974.30	1563.600	1993.30	1509.600	1958.20	1505.300
AV.	1940.80	1492.150	6537.45	5117.531	1901.42	1552.465	1928.78	1479.215	1882.54	1470.315
SDEV	90.46	60.772	296.14	198.046	84.47	49.516	92.66	59.341	84.47	59.378
SDEV/AV.	0.047	0.041	0.045	0.038	0.045	0.032	0.048	0.040	0.045	0.038

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
NTU	0.265	0.247	0.208	0.267	0.249
HTU	0.049	0.053	0.063	0.049	0.052
KLA	7.469E-02	6.976E-02	5.862E-02	7.516E-02	7.024E-02

DATE: 3-10-65

RUN #: 29

PACKING: SIZE, TYPE: 8.35 MM (0.25 IN.) RASCHIG RINGS
 POROSITY: 54 PERCENT
 DEPTH: Z= 0.013 M (0.04 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
DATA RELEVANT TO PACKED COLUMN:		
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	T _A	23.50
WATER TEMPERATURE, CONSTANT HEAD TANK	T ₁	23.70
WATER TEMPERATURE, EFFLUENT TANK	T ₂	23.05
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPH	524.50
LOW PRESSURE	LPH	433.00
DATA RELEVANT TO AIR COMPRESSOR:		
AMBIENT TEMPERATURE, COMPRESSOR ROOM	T ₀	25.20
COMPRESSED AIR TEMPERATURE	T _C	28.80
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPO	843.00
LOW PRESSURE	LPO	582.00
BAROMETRIC PRESSURE	P _B	752.10

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR), AS READ FROM FLOWMETER:
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE:

QL= 2.5486E-05 M³/S
 QGR= 255.67E-05 M³/S
 QG= 259.07E-05 M³/S

L= 3.136 KG/(50M³/S)

LIQUID MASS FLUX:

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

T_{AE}= 23.500 C
 T_{AL}= 23.575 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

EL= 997.11 KG/M³
 PPE= 824.62 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

CPGE= 202.4 N/M²
 DPCZE= ***** (N/M²)/M

DATE: 3-10-85

RUN 0128

WATER QUALITY PARAMETERS

EFFLUENT

INFLUENT

7.68
1240.7.70
1250.

CONDUCTIVITY (MICROMHOS)

HENRY'S LAW CONSTANTS (K_L) AND STRIPPING FACTORS (S_L)

	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE				
H	0.2350	0.0549	0.398	0.2110
S	23.879	5.978	40.598	21.438

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE				
TRIAL	CI	CE	CI	CE
1	2116.90	1588.400	1861.20	1463.400
2	2101.20	1580.200	1833.40	1450.800
3	2170.10	1625.200	2028.40	1518.100
AV.	2129.40	1591.266	1981.00	1477.888
SDEV	36.26	30.042	47.59	36.493
SDEV/AV.	0.017	0.019	0.024	0.025

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (K_L).

	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE				
NTU	0.293	0.251	0.294	0.276
HTU	0.044	0.052	0.044	0.047
K _L	7.087E-02	5.245E-02	7.115E-02	6.670E-02

RUN #1 30

DATE: 4-10-85

PACKING: SIZE, TYPE: 8-35 MM (C-25 IN-1) RASCHIG RINGS
 POROSITY: 54 PERCENT
 DEPTH: Z= 0.013 M (0.04 FT)

MISCELLANEOUS DATA:

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
DATA RELEVANT TO PACKED COLUMN:		
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TV	23.50
WATER TEMPERATURE, CONSTANT HEAD TANK	TI	23.35
WATER TEMPERATURE, EFFLUENT TANK	TE	22.05
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPV	527.00
LOW PRESSURE	LPV	498.50
DATA RELEVANT TO AIR COMPRESSOR:		
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TO	25.00
COMPRESSED AIR TEMPERATURE	TC	26.80
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPG	688.00
LOW PRESSURE	LPG	337.00
BAROMETRIC PRESSURE	PB	759.10

VOLUMETRIC FLOWRATES:

LIQUID (WATER): GL= 2.2308E-05 M³/S
 GAS (AIR): AS READ FROM FLOWMETER: OGR= 306.67E-05 M³/S
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: OGT= 312.84E-05 M³/S

LIQUID MASS FLUX:

L= 2.744 KG/(SQM²·H)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TV= 23.550 C
 TE= 23.125 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

RL= 997.22 KG/M³
 RPL= 824.61 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

CPG= 246. N/M²
 CPGZ= 0.000 (N/M²·M)

DATE: 4-10-85

RUN #1 30

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT

PH 7.72 7.84
 CONDUCTIVITY (MICROMHOS) 1250. 1270.

HENRY'S LAW CONSTANTS (M) AND STRIPPING FACTORS (S).

	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	0.1602	0.0537	0.3960	0.2024
	22.471	7.925	55.328	28.385

0.2328
 32.647

0.0469
 6.574

0.1602
 22.471

0.0537
 7.925

0.3960
 55.328

0.2024
 28.385

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	1919.80	1375.900	1772.90	1537.200	8066.80	3345.000	1872.40	1375.700	1707.10	1222.100	1739.80	1268.800
2	2089.90	1497.400	1964.10	1550.000	6592.40	4820.199	2056.50	1558.500	1802.30	1325.600	1911.80	1392.800
3	2099.90	1528.500	1959.50	1494.800	6612.90	4902.699	2057.60	1538.800	1874.50	1358.400	1899.20	1406.700
4	2150.00	1575.300	2005.40	1567.500	8775.20	5086.000	2112.70	1608.500	1922.30	1425.600	1863.30	1469.000
5	2166.60	1561.900	2014.00	1544.900	6816.10	5012.602	2119.60	1587.200	1931.80	1387.200	1897.50	1437.800
AV.	2085.24	1507.798	1943.18	1538.880	6572.68	4829.287	2043.76	1537.359	1873.66	1349.780	1894.24	1394.139
SDEV	98.02	79.756	98.22	27.069	299.24	724.290	100.30	84.362	97.71	76.758	90.84	75.803
SDEV/AV.	0.047	0.053	0.051	0.018	0.046	0.156	0.049	0.054	0.052	0.057	0.048	0.054

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	1,1-DICHLOROETHANE	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
NTU	0.326	0.237	0.153	0.290	0.329	0.308
HTU	0.040	0.055	0.037	0.045	0.040	0.042
KLA	6.694E-02	5.021E-02	7.471E-02	6.133E-02	6.960E-02	6.520E-02

DATE: 7-10-85

RUN #1 31

PACKING: SIZE, TYPE: 12.78 MM (0.50 IN.) INTALOX SADDLES
 POROSITY: 74 PERCENT
 DEPTH: Z= 0.91A * (3.00 FT)

MISCELLANEOUS DATA

DATA RELEVANT TO PACKED COLUMN:	QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER NO. MIN. 95 MIN.
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TW	C	22.45
WATER TEMPERATURE, CONSTANT HEAD TANK	TI	C	22.65
WATER TEMPERATURE, EFFLUENT TANK	TE	C	22.15
COLUMN'S MANOMETER READING: HIGH PRESSURE	MPV	MM	521.50
COLUMN'S MANOMETER READING: LOW PRESSURE	LPV	MM	501.00
DATA RELEVANT TO AIR COMPRESSOR:			
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TO	C	24.50
COMPRESSED AIR TEMPERATURE	TC	C	25.80
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	MPG	MM	601.00
FLOWMETER'S MANOMETER READING: LOW PRESSURE	LPB	MM	423.00
BAROMETRIC PRESSURE	PB	MM	758.30

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR): AS READ FROM FLOWMETER:
 GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE:

QL= 2.0512E-05 M³/S
 QGP= 205.47E-05 M³/S
 CGP= 207.74E-05 M³/S

LIQUID MASS FLUX:

L= 3.754 KG/(S*CM²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TWA= 22.475 C
 TAE= 22.487 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

RL= 987.22 KG/M³
 RPL= 824.83 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

CPGE= 166. N/M²
 DPGF= 161. (N/M²)/M

DATE: 7-10-85

RUN 81 31

WATER QUALITY PARAMETERS

PARAMETERS	INFLUENT	EFFLUENT
PH	7.69	7.83
CONDUCTIVITY (MICROMHOS)	1240.	1180.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	0.0452	0.1581	0.0520	0.3908	0.1808
H	3.073	10.763	3.534	26.635	12.882
S					

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE			1,2-DICHLOROETHANE			TRICHLOROETHYLENE			TOLUENE		
	CI	CE	CE	CI	CE	CE	CI	CE	CI	CE	CE	
1	1982.30	155.780	469.450	5762.00	631.016	1964.30	331.170	1978.10	1927.80	178.170		
2	1997.00	157.560	412.430	6821.40	641.086	1979.60	310.170	1963.30	1927.40	177.220		
3	1981.20	160.950	437.560	6751.90	643.720	1955.40	322.810	1988.30	1932.40	181.530		
4	2042.40	162.260	2007.60	6960.70	655.936	2010.30	315.750	2016.00	1970.20	181.800		
5	1943.90	161.510	421.430	6631.80	651.086	1939.50	317.020	1948.80	1825.50	182.140		
6	1998.60	161.680	416.490	6824.80	653.246	1968.50	314.900	1865.40	1828.50	180.880		
AV.	1990.90	159.957	428.128	6792.10	647.010	1968.62	312.720	1975.88	1930.47	179.353		
SDEV	32.10	2.643	21.601	108.24	9.304	24.40	7.253	21.61	23.73	2.586		
SDEV/AV.	0.016	0.017	0.050	0.016	0.014	0.012	0.023	0.011	0.012	0.014		

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	2.628	2.495	2.162	2.612	2.482
NTU	0.346	0.366	0.423	0.430	0.367
HTU	1.083E-02	1.027E-02	8.903E-03	1.078E-02	1.028E-02
KLA					

DATE: 8-10-45

RUN #1 32

PACKING: SIZE: 12.70 MM (0.50 IN.) INTALOX SADDLES
 POROSITY: 74 PERCENT
 DEPTH: Z= 0.914 M (3.00 FT)

MISCELLANEOUS DATA

SYMBOLS AND UNITS

READING AFTER
45 MIN. 95 MIN.

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM
 WATER TEMPERATURE, CONSTANT HEAD TANK
 WATER TEMPERATURE, EFFLUENT TANK
 COLUMN'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE

23.10 23.30
 22.70 23.00
 22.00 22.20
 528.00 528.00
 496.50 498.50

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM
 COMPRESSED AIR TEMPERATURE
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE
 BAROMETRIC PRESSURE

25.00 25.20
 28.50 28.70
 645.00 648.00
 340.00 379.00
 765.70 765.80

VOLUMETRIC FLOWPATES:

LIQUID (WATER):
 GAS (AIR), AS READ FROM FLOWMETER
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE

QL 2.572E-03 M³/S
 QGR 256.67E-03 M³/S
 QCR 299.42E-03 M³/S

LIQUID MASS FLUX:

L= 3.165 KG/(SQM*2)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TWA 23.200 C
 TAE 22.475 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

RL 997.38 KG/M³
 RPL 824.68 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

PPC 238. N/M²
 DPCE 261. (N/M²)/M

DATE: 8-10-85

RUN #1 32

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT

PH 7.60 7.82

CONDUCTIVITY (MICROMHOS) 1245. 1240.

HENRY'S LAW CONSTANTS (K1) AND STRIPPING FACTORS (S1)

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
H	0.0452	0.1580	0.0518	0.3808	0.1908
S	4.556	15.935	5.237	38.405	184218

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV), IS AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	2005.40	144.100	1894.90	372.360	6402.10	534.560	1943.80	276.820	1883.00	1311.500	1822.10	193.420
2	2007.20	148.860	1867.10	328.070	6401.20	552.150	1928.90	255.350	1838.10	135.380	1816.00	197.240
3	2139.00	155.180	2019.50	350.870	6811.40	576.200	2074.70	274.410	1998.20	143.210	1843.80	185.810
4	2139.96	155.330	2049.00	343.760	5898.30	575.750	2113.00	267.420	2023.70	142.390	1881.90	185.720
5	2213.50	159.640	2081.40	357.910	7039.60	593.350	2140.80	276.780	2068.10	146.570	2010.60	170.040
6	2208.90	157.420	2079.40	346.500	7026.00	593.340	2137.30	270.380	2025.80	142.930	1887.80	185.880
AV	2128.65	153.455	1994.55	351.582	6779.77	569.225	2056.58	269.185	1969.48	140.358	1928.02	182.535
SDEV	98.60	3.859	84.25	15.487	304.34	21.753	95.83	7.558	95.18	5.555	87.86	6.084
SDEV/AV	0.046	0.038	0.047	0.044	0.045	0.038	0.047	0.028	0.048	0.040	0.046	0.037

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	NTU	HTU	NTU	HTU	NTU	HTU	NTU	HTU	NTU	HTU	NTU	HTU
1	2.706	1.971	2.540	2.289	2.540	2.289	2.540	2.289	2.540	2.289	2.540	2.289
2	0.338	0.464	0.334	0.399	0.334	0.399	0.334	0.399	0.334	0.399	0.334	0.399
3	9.395E-03	6.643E-03	8.559E-03	7.948E-03	8.559E-03	7.948E-03	8.559E-03	7.948E-03	8.559E-03	7.948E-03	8.559E-03	7.948E-03
4												
5												
6												
AV												
SDEV												
SDEV/AV												

DATE: 9-10-65

PACKING: SIZE, TYPE, 12.70 MM (C.90 IN.) INITIAL SADDLES

POROSITY: 74 PERCENT
DEPTH: 24 0.91 M (3.00 FTE)

MISCELLANEOUS DATA:

SYMBOLS AND UNITS READING AFTER 4.5 MIN. 35 MIN.

DATA RELEVANT TO PACKED COLUMN:
AMBIENT TEMPERATURE, PACKED COLUMN ROOM TV 23.20 23.20
WATER TEMPERATURE, CONSTANT HEAD TANK TC 22.90 23.35
WATER TEMPERATURE, EFFLUENT TANK TE 22.10 22.40
COLUMN'S MANOMETER READING: HIGH PRESSURE HPM 530.50 530.50
LOW PRESSURE LPW 493.00 493.00

DATA RELEVANT TO AIR COMPRESSOR:
AMBIENT TEMPERATURE, COMPRESSOR ROOM TC 23.20 23.60
COMPRESSED AIR TEMPERATURE TC 27.00 27.20
FLOWMETER'S HANDMETER READING: HIGH PRESSURE HPG 887.00 887.00
LOW PRESSURE LPB 337.00 337.00
BAROMETRIC PRESSURE PB 760.60 760.50

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
GAS (AIR): AS READ FROM FLOWMETER: CLE 242.95E-05 M³/S
CORRECTED FOR TEMPERATURE AND PRESSURE: CGR 307.67E-05 M³/S
CORRECTED FOR TEMPERATURE AND PRESSURE: CGP 312.96E-05 M³/S

LIQUID MASS FLUX:

AVERAGE TEMPERATURES:
AMBIENT, PACKED COLUMN ROOM: TPAE 23.200 C
LIQUID (WATER): TLA 22.681 C

DENSITIES:

LIQUID (WATER):
COLUMN'S MANOMETER LIQUID: ELE 997.32 KG/M³
EPE 824.68 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP: CPD 303.4 M³/S
PRESSURE DROP PER UNIT HEIGHT: CPDZ 332. (M³/S²/M)

DATE: 9-10-85

RUN #1 33

WATER QUALITY PARAMETERS

PARAMETERS	INFLUENT	EFFLUENT
PH	7.67	7.62
CONDUCTIVITY (MICROMHOS)	1270.	1245.

HENRY'S LAW CONSTANTS (M) AND STRIPPING FACTORS (S).

	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
ETHER	0.0457	0.0525	0.3825	0.1946
	6.334	7.272	54.366	26.926

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	2118.10	117.600	1823.70	284.770	2088.00	211.710	1948.30	108.250	1843.80	127.570
2	2189.20	118.610	1902.60	252.100	2134.00	194.290	1981.90	109.200	1952.80	128.230
3	2172.10	120.540	2039.20	261.510	2160.30	203.570	2002.80	111.320	1997.60	130.210
4	2205.70	121.720	2006.10	257.820	2154.60	200.430	2000.70	109.970	2009.80	130.740
5	2105.40	119.900	1934.90	252.330	2073.40	199.260	1936.00	110.860	1934.30	130.320
6	2129.00	122.100	1947.20	251.990	2069.10	200.720	1925.30	110.160	1840.00	131.300
AV.	2153.25	120.145	1977.78	259.253	2116.73	202.333	1965.50	109.980	1969.73	129.728
SDEV	41.34	1.866	40.04	13.037	37.61	4.927	33.94	1.124	33.34	1.487
SDEV/AV.	0.019	0.014	0.020	0.050	0.016	0.024	0.017	0.010	0.017	0.011

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
NTU	2.848	2.568	2.920	2.788
HTU	0.310	0.356	0.313	0.228
KLA	6.990E-03	8.624E-03	8.903E-03	8.503E-03

DATE: 10-10-85

RUN #1 34

PACKING: SIZE: TYPE: 12.70 MM (0.50 IN.) INTALOX SMOOLES
 POROSITY: 74 PERCENT
 DEPTH: 2" 1.219 M (4.00 FT)

7 MISCELLANEOUS DATA

QUANTITY MEASURED

SYMBOLS AND UNITS

READING AFTER
45 MIN. 95 MIN.

DATA RELEVANT TO PACKED COLUMN:

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN.	READING AFTER 95 MIN.
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TV	23.40	23.40
WATER TEMPERATURE, CONSTANT HEAD TANK	TI	23.20	23.70
WATER TEMPERATURE, EFFLUENT TANK	TE	22.70	23.10
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPV	523.50	523.50
COLUMN'S MANOMETER READING: LOW PRESSURE	LPV	500.00	500.00

DATA RELEVANT TO AIR COMPRESSOR:

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN.	READING AFTER 95 MIN.
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TC	25.00	25.70
COMPRESSED AIR TEMPERATURE	TC	26.30	26.70
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPG	603.00	603.00
FLOWMETER'S MANOMETER READING: LOW PRESSURE	LPD	422.00	422.00
BAROMETRIC PRESSURE	PB	754.80	754.30

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR): AS READ FROM FLOWMETER:
 GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE

GL= 3.0418E-05 M³/S
 GPR= 205.67E-05 M³/S
 GCR= 208.76E-05 M³/S

LIQUID MASS FLUX:

L= 3.742 KG/(150M²·S)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TVAR 23.400 C
 TAV 23.175 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

RLE 997.21 KG/M³
 RME 822.64 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DPC= 190. N/M²
 DPCZ= 156. N/M²·M

DATE: 10-10-85

RUN 81 34

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT
 PH 7.63 7.80
 CONDUCTIVITY (MICROMHOS) 1250. 1265.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	1,1-DICHLOROETHANE	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
H	0.2330	0.0470	0.1804	0.0538	0.3864	0.2033
S	15.934	3.226	11.009	3.892	27.202	13.855

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	1942.20	83.568	1927.20	318.170	6559.00	337.250	1910.50	210.570	1937.10	81.388	1885.00	95.448
2	1923.20	82.999	1871.90	271.650	6503.90	339.060	1872.20	192.570	1893.40	78.389	1853.00	95.268
3	1951.90	80.312	1971.90	282.950	6574.60	326.010	1911.80	194.640	1959.30	75.798	1899.10	92.280
4	1977.60	80.119	1913.90	285.510	6873.70	327.550	1915.70	188.290	1953.50	75.188	1806.30	92.108
5	1931.50	78.360	1935.80	270.930	6509.80	320.970	1908.20	188.770	1937.80	73.283	1878.00	90.984
6	1908.20	77.134	1853.30	261.110	6421.40	315.400	1856.20	183.460	1879.60	71.918	1840.20	88.526
AV.	1939.10	80.519	1904.29	278.553	6545.40	327.701	1895.74	193.070	1926.75	75.987	1877.53	92.433
SDEV.	24.20	2.433	33.51	20.708	76.67	9.167	25.17	9.410	32.79	3.449	26.28	2.833
SDEV/AV.	0.012	0.030	0.018	0.074	0.012	0.028	0.013	0.048	0.017	0.045	0.014	0.028

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	1,1-DICHLOROETHANE	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
NTU	3.324	2.340	2.194	2.751	3.319	3.184
HTU	0.306	0.521	0.382	0.443	0.367	0.385
KLA	1.024E-02	7.203E-03	9.832E-03	8.466E-03	1.022E-02	9.730E-03

DATE: 11-10-65

RUN #1 35

PACKING: SIZE, TYPE: 12.70 MM (C-50 IN.) INTALOX SADDLES
 POROSITY: 74 PERCENT
 DEPTH: 1.219 M (4.00 FT)

MISCELLANEOUS DATA

1

READING AFTER
45 MIN. 95 MIN.

SYMBOLS AND UNITS

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
TA C	22.75 22.80
TI C	22.80 23.30
TE C	21.50 21.90
HPA MP	523.00 533.50
LPA MP	489.50 499.00

DATA RELEVANT TO AIR COMPRESSOR:

SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
TC C	24.80 25.20
TC MP	24.80 25.20
HPO MP	689.00 691.00
LPO MP	336.00 334.00
BP MP	761.00 761.00

VOLUMETRIC FLOWRATES:

LIQUID (WATER): QL = 2.2473E-05 M³/S
 GAS (AIR): AS READ FROM FLOWMETER: GCPE 308.33E-05 M³/S
 GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE: CG = 313.38E-05 M³/S

LIQUID MASS FLUX:

LM = 2.765 KG/(SQM*2)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM: TMA = 22.775 C
 LIQUID (WATER): TLE = 22.375 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID: RL = 997.40 KG/M³
 RPE = 824.77 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT HEIGHT: DECE 386.1 N/M²
 PCECE 292.1 N/M²

DATE: 11-10-85

RUN #1 35

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT

PH 7.88 7.80

CONDUCTIVITY (MICROMHOS) 1225. 1225.

HENRY'S LAW CONSTANTS (M) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
CI	1938.20	8535.10	2038.20	1893.40	1891.20
CE	52.089	193.000	106.910	48.458	48.428
CI	2042.10	6486.90	2003.20	1809.90	1862.20
CE	51.938	194.980	98.469	48.663	48.509
CI	1988.10	6326.90	1976.90	1791.80	1832.40
CE	53.083	197.990	103.190	48.913	48.049
CI	2034.80	6473.70	1988.00	1801.80	1857.20
CE	52.321	196.370	99.750	48.727	48.415
CI	2067.70	6566.70	2037.60	1870.10	1903.10
CE	51.443	192.650	98.211	47.386	48.398
CI	2049.30	6513.00	2008.40	1813.80	1868.20
CE	51.844	194.570	98.083	47.251	48.562
CI	2040.11	6484.03	2008.72	1823.46	1869.26
CE	52.126	194.927	106.454	48.150	48.130
CI	28.17	84.00	25.30	31.14	25.81
CE	0.545	2.025	3.487	0.684	0.648
CI	0.014	0.013	0.013	0.017	0.014
CE	0.010	0.010	0.035	0.014	0.011

M

S

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	2058.70	52.089	1938.20	159.600	8535.10	193.000	2038.20	106.910	1893.40	48.458	1891.20	48.428
2	2042.10	51.938	1888.10	137.740	6486.90	194.980	2003.20	98.469	1809.90	48.663	1862.20	48.509
3	1988.10	53.083	1878.40	147.720	6326.90	197.990	1976.90	103.190	1791.80	48.913	1832.40	48.049
4	2034.80	52.321	1865.90	138.510	6473.70	196.370	1988.00	99.750	1801.80	48.727	1857.20	48.415
5	2067.70	51.443	1923.10	140.280	6566.70	192.650	2037.60	98.211	1870.10	47.386	1903.10	48.398
6	2049.30	51.844	1887.40	138.670	6513.00	194.570	2008.40	98.083	1813.80	47.251	1868.20	48.562
AV.	2040.11	52.126	1896.28	143.420	6484.03	194.927	2008.72	106.454	1823.46	48.150	1869.26	48.130
SDEV	28.17	0.545	27.48	8.857	84.00	2.025	25.30	3.487	31.14	0.684	25.81	0.648
SDEV/AV.	0.014	0.010	0.014	0.062	0.013	0.010	0.013	0.035	0.017	0.014	0.014	0.011

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
CI	1938.20	8535.10	2038.20	1893.40	1891.20
CE	52.089	193.000	106.910	48.458	48.428
CI	2042.10	6486.90	2003.20	1809.90	1862.20
CE	51.938	194.980	98.469	48.663	48.509
CI	1988.10	6326.90	1976.90	1791.80	1832.40
CE	53.083	197.990	103.190	48.913	48.049
CI	2034.80	6473.70	1988.00	1801.80	1857.20
CE	52.321	196.370	99.750	48.727	48.415
CI	2067.70	6566.70	2037.60	1870.10	1903.10
CE	51.443	192.650	98.211	47.386	48.398
CI	2049.30	6513.00	2008.40	1813.80	1868.20
CE	51.844	194.570	98.083	47.251	48.562
CI	2040.11	6484.03	2008.72	1823.46	1869.26
CE	52.126	194.927	106.454	48.150	48.130
CI	28.17	84.00	25.30	31.14	25.81
CE	0.545	2.025	3.487	0.684	0.648
CI	0.014	0.013	0.013	0.017	0.014
CE	0.010	0.010	0.035	0.014	0.011

NTU

HTU

KLA

DATE: 14-10-85

RUN #1 36

PACKING: SIZE: 12.70 MM (C-50 IN.) INTALOX SADDLES
 POROSITY: 74 PERCENT
 DEPTH: Z= 1.219 M (4.00 FT)

MISCELLANEOUS DATA

SYMBOLS AND UNITS 45 MIN. 95 MIN.

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM TV 22.90 23.10
 WATER TEMPERATURE, CONSTANT HEAD TANK TI 22.90 23.20
 WATER TEMPERATURE, EFFLUENT TANK TE 22.30 22.50
 COLUMN'S MANOMETER READING: HIGH PRESSURE MPV 528.00 528.00
 LOW PRESSURE LPM 494.50 484.50

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM TG 25.00 25.80
 COMPRESSED AIR TEMPERATURE TC 26.80 27.00
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE MPQ 848.00 848.00
 LOW PRESSURE LPO 378.00 376.00
 BAROMETRIC PRESSURE PB 756.50 756.60

VOLUMETRIC FLOWRATES:

LIQUID (WATER): OLE 2.5490E-05 M³/S
 GAS (AIR): AS READ FROM FLOWMETER: COLE 256.33E-05 M³/S
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: COLE 260.33E-05 M³/S

LIQUID MASS FLUX:

L= 3.136 KG/(S*M²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM: TWA= 23.000 C
 LIQUID (WATER): TAW 22.725 C

DENSITIES:

LIQUID (WATER): RLE 997.32 KG/M³
 COLUMN'S MANOMETER LIQUID: RVE 824.73 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP: EPG= 271.4 N/M²
 PRESSURE DROP PER UNIT DEPTH: DPC= 222.4 N/M²/M

DATE: 14-10-85

RUN 81 36

WATER QUALITY PARAMETERS

PARAMETERS	INFLUENT	EFFLUENT
PH	7.69	7.69
CONDUCTIVITY (MICROMHOS)	1260.	1255.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
H	0.0456	0.1589	0.0528	0.3928	0.1923
S	4.681	16.230	5.373	40.124	16.928

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE			1,2-DICHLOROETHANE			TRICHLOROETHYLENE			TOLUENE		
	CI	CE	CF	CI	CE	CF	CI	CE	CF	CI	CE	CF
1	2400.10	71.182	2277.40	256.860	7628.60	275.700	2343.30	2240.10	187.870	2188.30	78.308	
2	2384.40	71.112	2258.80	218.320	7631.80	276.470	2331.20	2208.10	151.390	2172.30	80.032	
3	2310.30	71.378	2173.50	229.050	7351.00	276.900	2242.90	2164.00	157.360	2113.40	78.790	
4	2274.10	70.976	2154.30	216.890	7262.80	275.250	2220.10	2098.30	152.050	2088.20	79.233	
5	2367.00	67.122	2259.90	211.990	7595.00	260.700	2329.60	2231.40	146.980	2182.00	79.315	
AV.	2398.50	67.461	2261.10	208.800	7631.00	261.990	2334.20	2204.10	149.920	2171.70	79.238	
SDEV	2362.30	69.872	2230.50	223.818	7516.87	271.161	2300.22	2191.05	153.928	2149.25	79.186	
SDEV/AV.	53.52	2.008	52.46	17.624	165.51	7.644	53.93	52.87	8.031	48.43	2.272	
	0.023	0.028	0.024	0.079	0.022	0.028	0.023	0.024	0.052	0.023	0.028	

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
NTU	3.633	3.475	3.088	3.600	3.437
HTU	0.336	0.351	0.335	0.339	0.355
KLA	9.370E-03	6.841E-03	7.968E-03	9.288E-03	8.884E-03

DATE: 15-10-45

RUN #1 37

PACKING: SIZE, TYPE 12.70 MM (1/2 IN.) INTALOX SADDLES
 POROSITY: 74 PERCENT
 DEPTH: Z= 1.524 M (5.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
DATA RELEVANT TO PACKED COLUMN:		
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TM	24.80
WATER TEMPERATURE, CONSTANT HEAD TANK	TC	23.50
WATER TEMPERATURE, EFFLUENT TANK	TE	23.50
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPM	524.00
COLUMN'S MANOMETER READING: LOW PRESSURE	LPM	499.50
DATA RELEVANT TO AIR COMPRESSOR:		
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TG	25.50
COMPRESSED AIR TEMPERATURE	YC	26.70
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	HPG	602.00
FLOWMETER'S MANOMETER READING: LOW PRESSURE	LPG	422.00
BAROMETRIC PRESSURE	PB	748.30

VOLUMETRIC FLOWRATES:

LIQUID (WATER): GL= 3.0325E-05 M³/S
 GAS (AIR), AS READ FROM FLOWMETER: OGR= 205.50E-05 M³/S
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: CGR= 210.48E-05 M³/S

LIQUID MASS FLUX:

L= 3.730 KG/(50M²/H)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM: TMA= 24.900 C
 LIQUID (WATER): TLA= 23.525 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

PL= 997.12 KG/M³
 PM= 824.33 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DPCE= 19A. N/M²
 DPGE= 130. (N/M²/M)

DATE: 15-10-75

RUN #1 37

WATER QUALITY PARAMETERS

EFFLUENT

INFLUENT

PARAMETERS

7.60
1325.7.60
1280.PH
CONDUCTIVITY (MICROMHOS)

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
H	0.2348	0.0479	0.1818	0.0547	0.3682	0.0547	0.3682	0.0547	0.2100	0.2100
S	16.295	3.328	11.217	11.217	27.705	3.800	27.705	3.800	14.978	14.978

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	3058.40	55.526	2003.30	263.150	1979.50	121.280	3042.20	54.337	2987.90	67.538
2	3011.20	55.637	1950.60	175.420	1836.70	110.600	2951.90	54.547	2919.10	68.313
3	3170.40	56.847	2062.60	189.210	2045.70	117.660	3165.20	53.837	3104.20	69.503
4	3194.70	58.876	2056.20	179.630	2046.70	114.150	3136.10	50.971	3096.20	68.753
5	3248.70	58.330	2102.20	157.340	2091.80	119.120	3238.90	56.809	3177.50	72.893
6	3194.00	56.717	2067.10	183.050	2056.30	117.010	3123.60	52.857	3095.70	71.587
AV.	3146.30	57.155	2040.33	186.300	2025.95	116.815	3109.81	53.893	3083.88	69.881
SDEV	81.32	1.571	54.29	9.865	57.13	3.484	100.27	1.838	83.30	1.882
SDEV/AV.	0.029	0.027	0.027	0.052	0.028	0.030	0.032	0.038	0.030	0.027

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	1,1-DICHLOROETHANE		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
NTU	4.204	2.966	4.052	4.052	3.485	4.170	4.170	4.170	3.983	3.983
HTU	0.363	0.514	0.376	0.376	0.437	0.385	0.385	0.385	0.383	0.383
KLA	1.032E-02	7.279E-03	9.946E-03	9.946E-03	8.555E-03	1.023E-02	1.023E-02	1.023E-02	9.776E-03	9.776E-03

DATE: 16-10-85

RUN: #1 38

PACKING: SIZE, TYPE: 12.70 MM (C.50 IN.) INTALOX SADOLES
 POROSITY: 74 PERCENT
 DEPTH: Z= 1.524 M (5.00 FT)

MISCELLANEOUS DATA

SYMBOLS AND UNITS 45 MIN. 95 MIN. READING AFTER

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM
 WATER TEMPERATURE, CONSTANT HEAD TANK
 WATER TEMPERATURE, EFFLUENT TANK
 COLUMN'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE

IV C 24.90 25.20
 TI C 24.25 24.75
 TE C 23.45 23.80
 HPV PM 530.00 530.00
 LPV PM 494.50 494.50

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM
 COMPRESSED AIR TEMPERATURE
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE
 BAROMETRIC PRESSURE

TG C 25.30 25.80
 TC C 26.70 26.30
 HPG PM 647.00 646.00
 LPG PM 376.00 377.00
 PB PM 757.00 757.50

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR), AS READ FROM FLOWMETER:
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: CGR 256.33E-03 M³/S
 CGE 256.33E-03 M³/S
 CGF 262.11E-03 M³/S

LIQUID MASS FLUX:

L= 3.120 KG/(S*CM²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TA= 25.050 C
 TL= 24.063 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

FL= 998.20 KG/M³
 RL= 824.30 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT HEIGHT:

CPGE 287. N/M²
 CPCE 182. N/M²

DATE 10-10-85

RUN #1 38

WATER QUALITY PARAMETERS

PARAMETERS

INFLUENT

EFFLUENT

PH 7.80
CONDUCTIVITY (MICROMHOS) 1295.

7.55
1295.

HENRY'S LAW CONSTANTS (M) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	0.2374 24.930	0.1835 16.887	0.0582 5.808	0.4033 41.886	0.2288 22.785

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	3306.50	45.458	2236.70	130.590	7231.00	110.030	2258.50	78.649	3203.80	42.022	3297.80	54.917
2	3324.60	44.085	2202.20	113.780	7279.30	111.090	2244.70	75.287	3172.30	41.601	3286.50	55.523
3	3368.90	46.640	2255.60	124.490	7368.10	116.770	2283.60	78.271	3276.20	38.801	3363.80	56.980
4	3379.50	46.116	2238.60	117.040	7406.90	118.780	2283.30	76.441	3255.40	38.120	3342.10	57.087
5	3419.50	45.841	2291.50	120.050	7486.60	116.410	2328.90	77.748	3213.90	42.178	3400.70	58.728
6	3368.50	44.871	2250.70	115.950	7425.80	114.500	2297.10	75.678	3218.60	41.447	3350.20	55.544
AV.	3364.58	45.505	2245.68	120.310	7385.28	114.255	2283.68	77.019	3235.37	40.685	3340.50	58.050
SDEV	41.95	0.919	29.23	6.264	95.73	3.004	29.77	2.393	50.97	1.764	42.03	1.028
SDEV/AV.	0.012	0.020	0.013	0.052	0.013	0.026	0.013	0.031	0.016	0.043	0.015	0.018

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	4.443 0.343 8.124E-03	4.385 0.349 8.962E-03	3.875 0.353 7.906E-03	4.459 0.342 8.156E-03	4.228 0.380 8.684E-03
NTU					
HTU					
KLA					

RUN #1 39.

DATE: 17-10-85

PACKING: SIZE: 12-70 MP (C-50 IN.) INTALOX SADDLES
 POROSITY: 74 PERCENT
 DEPTH: 7' 1.924 M (5.00 FT)

MISCELLANEOUS DATA

READING AFTER 45 MIN. 95 MIN.

SYMBOLS AND UNITS

QUANTITY MEASURED

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM
 WATER TEMPERATURE, CONSTANT HEAD TANK
 WATER TEMPERATURE, EFFLUENT TANK
 COLUMN'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE

SYMBOL	UNIT	45 MIN.	95 MIN.
TA	C	25.10	25.30
TE	C	24.90	25.50
TE	C	23.50	23.90
HP	MP	535.00	535.00
LP	MP	488.50	488.50

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM
 COMPRESSED AIR TEMPERATURE
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE
 BAROMETRIC PRESSURE

SYMBOL	UNIT	45 MIN.	95 MIN.
TC	C	24.80	25.20
TC	C	26.70	26.80
MP	MP	582.00	683.00
MP	MP	332.00	331.00
MP	MP	769.30	768.40

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR): AS READ FROM FLOWMETER:
 GAS (AIR): CORRECTED FOR TEMPERATURE AND PRESSURE:

CL= 2.2232E-05 M³/S
 CG= 308.87E-05 M³/S
 CG= 314.58E-05 M³/S

LIQUID MASS FLUX:

LE 2.734 KG/(S*M*2)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TA= 25.200 C
 TE= 24.450 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

FL= 996.49 KG/M³
 FM= 824.27 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

DP= 36.1 N/M*2
 DP= 24.1 N/M*2

DATE: 17-10-86

RUN: 81 39

WATER QUALITY PARAMETERS

PARAMETERS INFLUENT EFFLUENT

PH 7.61 7.58
 CONDUCTIVITY (MICROMHOS) 1320 1340

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
H	0.0505	0.1445	0.0573	0.4068	0.2288
S	7.147	23.316	8.108	57.533	39.546

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV), AND STANDARD DEVIATIONS (SDEV).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
TRIAL	CI	CE	CI	CE	CI
1	2997.40	26.742	2036.00	72.850	2897.50
2	2958.00	26.720	2003.70	65.078	2937.70
3	2918.90	27.070	1975.70	71.321	2933.50
4	2965.90	27.065	1942.50	67.573	2943.50
5	3045.70	26.947	2044.80	72.146	3050.60
6	3053.40	27.073	2057.30	65.562	3028.40
AV.	2989.84	26.783	2016.67	66.968	2981.78
SDEV	52.87	0.161	34.27	3.012	50.81
SDEV/AV.	0.018	0.006	0.017	0.045	0.017

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE	CI	CE	CI	CE	CI
NTU	4.822	3.790	4.895	4.260	4.547
HTU	0.316	0.402	0.325	0.358	0.338
KLA	1.677E-03	6.511E-03	8.486E-03	7.655E-03	8.183E-03

DATE: 21-10-85

RUN # 40

PACKING: SIZE: 12-70 MV (0.50 IN.) INTALOX SADDLES
 POROSITY: 74 PERCENT
 DEPTH: 2= 1.829 M (6.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 40 MIN. 95 MIN.
DATA RELEVANT TO PACKED COLUMN:		
AMBIENT TEMPERATURE, PACKED COLUMN ROOM	TV	26.35
WATER TEMPERATURE, CONSTANT HEAD TANK	TI	25.35
WATER TEMPERATURE, EFFLUENT TANK	TE	24.70
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPV	525.50
COLUMN'S MANOMETER READING: LOW PRESSURE	LPA	499.00
		499.00
DATA RELEVANT TO AIR COMPRESSOR:		
AMBIENT TEMPERATURE, COMPRESSOR ROOM	TC	25.00
COMPRESSED AIR TEMPERATURE	TC	26.10
FLOWMETER'S MANOMETER READING: HIGH PRESSURE	MPG	603.00
FLOWMETER'S MANOMETER READING: LOW PRESSURE	LPG	420.00
BAROMETRIC PRESSURE	PB	767.50
		767.80

VOLUMETRIC FLOWPATES:

* LIQUID (WATER): CLW 3.0200F-05 M=375
 GAS (AIR), AS READ FROM FLOWMETER: GGF 205.50E-05 M=375
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: CGM 208.80E-05 M=375

LIQUID MASS FLUX:

LB 3.713 KG/150M=21

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM: TWA 26.250 C
 LIQUID (WATER): TWA 24.932 C

DENSITIES:

LIQUID (WATER): PL 998.77 KG/M=3
 COLUMN'S MANOMETER LIQUID: PML 824.03 KG/M=3

PRESSURE DROP IN EACH COLUMN:

ACTUAL PRESSURE DROP: 32.5 PSI
 PRESSURE DROP PER UNIT DEPTH: 1.78 PSI/FT

DATE 21-10-85

RUN 81 40

WATER QUALITY PARAMETERS

EFFLUENT

INFLUENT

PARAMETERS

PH 7.58
CONDUCTIVITY (MICROMHOS) 1385.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
H	0.0518	0.1564	0.0586	0.4104	0.2385
S	3.584	11.505	4.054	28.374	18.487

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TYPICAL	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	3152.40	22.514	2083.40	114.230	6847.40	64.989	2038.00	66.773	3128.60	22.573	3040.20	29.508
2	3175.70	23.129	2070.10	101.840	6891.50	66.998	2013.50	61.255	3098.00	21.866	3038.20	31.778
3	3236.00	22.105	2108.50	106.230	7025.50	63.872	2076.00	61.836	3220.20	21.874	3128.20	28.089
4	3262.40	22.971	2068.70	103.930	7074.70	66.626	2063.00	61.893	3183.30	23.451	3120.80	30.598
5	3274.00	22.347	2139.70	104.130	7097.80	64.883	2106.40	61.453	3248.50	22.100	3153.60	28.174
6	3251.70	22.813	2076.30	98.825	7050.70	63.341	2068.70	59.154	3175.40	21.918	3111.60	28.773
AV.	3225.37	22.468	2082.89	105.531	6997.95	65.114	2061.47	62.078	3175.33	23.113	3099.25	29.810
SDEV	48.70	0.502	40.15	6.708	103.41	1.458	32.40	2.517	58.26	1.832	49.88	1.145
2DEV/AV.	0.015	0.022	0.019	0.064	0.015	0.022	0.018	0.041	0.018	0.079	0.036	0.038

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
1,1-DICHLOROETHANE					
NTU	5.217	5.024	4.287	5.086	4.871
HTU	0.351	0.384	0.427	0.361	0.375
KLA	1.063E-02	1.023E-02	8.731E-03	1.032E-02	9.935E-03

DATE: 22-10-85

RUN #1 43

PACKING: SIZE, TYPE: 12.70 MM (0.50 IN.) INTALOX SADDLES
 POROSITY: 74 PERCENT
 DEPTH: Z= 1.829 M (6.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED

SYMBOLS AND UNITS

READING AFTER
45 MIN. 95 MIN.

DATA RELEVANT TO PACKED COLUMN:

AMBIENT TEMPERATURE, PACKED COLUMN ROOM
 WATER TEMPERATURE, CONSTANT HEAD TANK
 WATER TEMPERATURE, EFFLUENT TANK
 COLUMN'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE

25.40 25.40
 24.80 25.00
 23.80 23.90
 530.50 530.50
 493.00 493.00

DATA RELEVANT TO AIR COMPRESSOR:

AMBIENT TEMPERATURE, COMPRESSOR ROOM
 COMPRESSED AIR TEMPERATURE
 FLOWMETER'S MANOMETER READING: HIGH PRESSURE
 LOW PRESSURE
 BAROMETRIC PRESSURE

25.30 26.00
 27.00 27.50
 648.00 648.00
 375.00 375.00
 785.20 785.20

VOLUMETRIC FLOWRATES:

LIQUID (WATER):
 GAS (AIR), AS READ FROM FLOWMETER:
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE:

GLF 2.5130E-05 M³/S
 GDF 256.00E-05 M³/S
 GCR 260.52E-05 M³/S

LIQUID MASS FLUX:

L= 3.090 KG/(S*M²)

AVERAGE TEMPERATURES:

AMBIENT, PACKED COLUMN ROOM:
 LIQUID (WATER):

TYA= 25.400 C
 TAE= 24.375 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID:

FLF 996.81 KG/M³
 RPF 824.22 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP:
 PRESSURE DROP PER UNIT DEPTH:

CPGF 303. N/M²
 CPGZ 166. (N/M²)/M

DATE: 22-10-85

RUN 81 41

WATER QUALITY PARAMETERS

EFFLUENT

INFLUENT

 PH
 CONDUCTIVITY (MICROMHOS)

 7.58
 1285.

 7.40
 1320.

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	1,1-DICHLOROETHANE	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
H	0.2390	0.0503	0.1845	0.0571	0.4080	0.2270
S	24.776	5.214	17.057	5.820	42.081	23.537

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

TRIAL	1,1-DICHLOROETHANE			ETHER			CHLOROFORM			1,2-DICHLOROETHANE			TRICHLOROETHYLENE			TOLUENE		
	CI	CF	CI	CI	CE	CF	CI	CE	CI	CE	CI	CE	CI	CE	CI	CI	CE	CE
1	3450.80	16.830	2371.90	73.079	73.079	73.079	73.079	73.079	48.767	2385.30	42.613	42.613	3365.10	17.438	3417.10	3417.10	23.238	23.238
2	3419.90	17.645	2245.90	65.913	65.913	65.913	65.913	65.913	48.478	2330.20	40.263	40.263	3292.70	21.074	3377.10	3377.10	23.529	23.529
3	3312.80	17.240	2211.80	68.222	68.222	68.222	68.222	68.222	48.200	2273.10	40.820	40.820	3238.20	17.888	3308.20	3308.20	23.687	23.687
4	3289.90	17.874	2186.40	66.898	66.898	66.898	66.898	66.898	50.204	2245.60	40.891	40.891	3165.80	18.339	3256.10	3256.10	25.114	25.114
5	3407.30	17.471	2335.20	66.349	66.349	66.349	66.349	66.349	48.461	2387.30	40.310	40.310	3382.80	17.805	3439.70	3439.70	23.954	23.954
6	3460.90	17.971	2276.90	66.654	66.654	66.654	66.654	66.654	50.031	2362.60	40.811	40.811	3325.20	18.667	3408.10	3408.10	24.488	24.488
AV.	3400.26	17.505	2278.18	67.852	67.852	67.852	67.852	67.852	48.481	2332.35	40.951	40.951	3256.63	18.701	3367.51	3367.51	24.281	24.281
SDEV	78.73	0.425	70.02	2.679	2.679	2.679	2.679	2.679	1.302	61.63	0.859	0.859	84.10	1.350	71.08	71.08	0.824	0.824
SDEV/AV.	0.023	0.024	0.031	0.039	0.039	0.039	0.039	0.039	0.027	0.026	0.021	0.021	0.026	0.072	0.021	0.021	0.038	0.038

NUMBER OF TRANSFER UNITS (NTU), WEIGHT OF A TRANSFER UNIT (MTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	1,1-DICHLOROETHANE	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
NTU	5.448	4.093	5.276	4.646	5.273	5.107
MTU	0.336	0.447	0.347	0.394	0.347	0.358
KLA	9.233E-03	6.937E-03	8.942E-03	7.673E-03	8.537E-03	8.655E-03

RUN #1 42

DATE: 23-10-85

PACKING: SIZE: 12.70 MM (0.50 IN.) INTALOX SADDLES
 POROSITY: 74 PERCENT
 DEPTH: 2" 1.825 M (8.00 FT)

MISCELLANEOUS DATA

QUANTITY MEASURED	SYMBOLS AND UNITS	READING AFTER 45 MIN. 95 MIN.
DATA RELEVANT TO PACKED COLUMN:		
AIR FLOW TEMPERATURE, PACKED COLUMN ROOM	TA	24.90
WATER TEMPERATURE, CONSTANT HEAD TANK	TC	25.20
WATER TEMPERATURE, EFFLUENT TANK	TE	23.80
COLUMN'S MANOMETER READING: HIGH PRESSURE	HPM	536.50
COLUMN'S MANOMETER READING: LOW PRESSURE	LPV	488.00
DATA RELEVANT TO AIR COMPRESSOR:		
AIR FLOW TEMPERATURE, COMPRESSOR ROOM	TA	28.10
WATER TEMPERATURE, COMPRESSOR ROOM	TC	27.80
COMPRESSED AIR TEMPERATURE	TC	27.30
FLO-METER'S MANOMETER READING: HIGH PRESSURE	HPO	692.00
FLO-METER'S MANOMETER READING: LOW PRESSURE	LPG	331.00
DAROMETRIC PRESSURE	PD	764.10

VOLUMETRIC FLOWRATES:

LIQUID (WATER): CLX 2.1990E-05 M³/S
 GAS (AIR): A READ FROM FLOWMETER: QGR 308.00E-05 M³/S
 GAS (AIR), CORRECTED FOR TEMPERATURE AND PRESSURE: QCM 314.58E-05 M³/S

LIQUID MASS FLUX:

L = 2.704 KG/(S*CM²)

AVERAGE TEMPERATURES:

AIR FLOW, PACKED COLUMN ROOM: TAA 24.950 C
 LIQUID (WATER): TAE 24.250 C

DENSITIES:

LIQUID (WATER):
 COLUMN'S MANOMETER LIQUID: FLE 995.94 KG/M³
 FVE 924.32 KG/M³

PRESSURE DROP IN PACKED COLUMN:

TOTAL PRESSURE DROP: CPGE 332. N/M²
 PRESSURE DROP PER UNIT DEPTH: CPGZ 214. (N/M²)/M

DATE: 23-10-85

RUN 81 42

WATER QUALITY PARAMETERS

EFFLUENT

INFLUENT

PARAMETERS

7.39
1285.7.60
1280.

CONDUCTIVITY (MICROMHOS)

PH

HENRY'S LAW CONSTANTS (H) AND STRIPPING FACTORS (S).

	1,1-DICHLOROETHANE	ETHEP	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
H	9.2384	0.0489	0.1641	0.0569	0.4050	0.2245
S	34.080	7.141	23.481	8.114	97.804	32.092

INFLUENT (CI) AND EFFLUENT (CE) CONCENTRATIONS, AVERAGES (AV.), AND STANDARD DEVIATIONS (SDEV).

	1,1-DICHLOROETHANE		ETHER		CHLOROFORM		1,2-DICHLOROETHANE		TRICHLOROETHYLENE		TOLUENE	
TRIAL	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE	CI	CE
1	2973.20	10.786	1970.30	38.910	6599.10	29.297	2073.80	24.424	2968.70	12.428	2983.00	14.975
2	2957.90	11.134	1922.10	34.727	6565.40	30.714	2040.00	22.613	2906.70	14.995	2923.40	16.906
3	3145.60	10.571	2118.30	35.046	6972.10	28.930	2213.90	22.359	3152.90	11.772	3141.60	14.445
4	3105.30	11.060	2032.90	34.187	6886.00	30.856	2153.00	22.235	3053.30	13.117	3069.20	15.711
5	3083.70	10.660	2101.80	34.319	6839.70	29.322	2166.00	22.235	3086.40	11.282	3078.50	14.729
6	3054.60	10.672	2035.00	33.522	6775.40	29.540	2123.90	21.669	2997.70	12.211	3016.90	14.857
AV.	3053.38	10.417	2025.08	35.118	6773.35	29.742	2131.90	22.647	3027.62	12.634	3031.77	15.204
SOEV	74.45	0.235	75.73	1.928	161.75	0.755	65.85	6.904	88.11	1.312	80.24	0.785
SOEV/AV.	0.024	0.022	0.037	0.055	0.024	0.025	0.031	0.040	0.028	0.104	0.026	0.050

NUMBER OF TRANSFER UNITS (NTU), HEIGHT OF A TRANSFER UNIT (HTU), AND MASS TRANSFER COEFFICIENTS (KLA).

	1,1-DICHLOROETHANE	ETHER	CHLOROFORM	1,2-DICHLOROETHANE	TRICHLOROETHYLENE	TOLUENE
NTU	5.783	4.543	5.625	5.035	5.558	5.433
MTU	0.316	0.403	0.323	0.163	0.329	0.337
KLA	8.576E-03	6.737E-03	8.341E-03	7.466E-03	8.242E-03	8.058E-03

APPENDIX E

COMPUTATION OF CORRECTIONS FOR END EFFECTS

A sample calculation of the gas pressure drop correction for end effects, Δp_{ec} , and of the NTU correction for end effects, NTUC, is given below. A listing of the Fortran WATFIV program used to perform the computations for all experimental runs follows the sample calculation.

E.1 Sample Calculation

The calculations for experimental Runs 18, 20, 24, and 27, and for trichloroethylene are presented in the following sections. Symbols used in the computer program are also used below.

E.2 Input Data

The necessary data are listed in Table E.1.

Table E.1: Input data

Run #	Packing Depth Z (m)	Liquid Mass Flux L (kg/m ² -s)	Liquid Density $\rho_L = \rho_L$ (kg/m ³)	Pressure Drop $\Delta p_{ec} = DP$ (N/m ²)	Total NTU NTUT=NT
18	0.914	2.890	997.13	424	2.688
20	1.219	2.875	996.93	489	3.445
24	1.524	2.846	997.10	578	4.054
27	1.829	2.823	997.03	667	4.924

E.3 Equation of Best Fit Line Through Pressure Drop Data

$$\Sigma w = \Sigma MZ = 5.486$$

$$\Sigma w^2 = \Sigma MZ^2 = 7.9892$$

$$\Sigma y = \Sigma MP = 2158$$

$$\Sigma y^2 = \Sigma MP^2 = 1197870$$

$$\Sigma yw = \Sigma MZP = 3084.442$$

From Eq. (5.2)

$$i = AP = \frac{(7.9892 \times 2158) - (5.486 \times 3084.442)}{4 \times 7.9892 - (5.486)^2} = 172$$

From Eq. (5.3)

$$s = BP = \frac{(4 \times 3084.442) - (5.486 \times 2158)}{4 \times 7.9892 - (5.486)^2} = 268$$

From Eq. (5.4)

$$r^2 = R^2P = \frac{[(4 \times 3084.442) - (5.486 \times 2158)]^2}{[(4 \times 7.9892) - (5.486)^2] \times [(4 \times 1197870) - (2158)^2]}$$

$$R^2P = 0.9948$$

E.4 Pressure Drop per Unit Depth

$$\Delta p_{oc} = i = AP = 172 \text{ N/m}^2$$

For Run 18, from Eq. (5.23): $\Delta p_o = CP = 424 - 172 = 252 \text{ N/m}^2$

$$\Delta p_o / Z = PZ = 252 / 0.914 = 276 \text{ N/m}^2/\text{m}$$

Results for other runs are presented in Table E.2.

Table E.2: Pressure drop per unit depth

Run #	$\Delta p_o = CP$ (N/m ²)	$\Delta p_o / Z = PZ$ (N/m ² /m)
18	252	275.7
20	317	260.0
24	406	266.4
27	495	270.6

$$\Sigma w = \text{SUMPZ} = 1072.7$$

$$\Sigma w^2 = \text{SUMPZ}^2 = 287803.81$$

$$\text{From Eq. (5.6): } \bar{w} = \text{PZAV} = 1072.7 / 4 = 268$$

$$\text{From Eq. (5.7)}$$

$$S_w = \text{PZSD} = \left[\frac{4 \times 287803.81 - (1072.7)^2}{4 \times 3} \right]^{1/2} = 6.645$$

$$\text{From Eq. (5.8): } V_w = 100 \times \text{PZSA} = \frac{6.645}{268} \times 100 = 2.5$$

E.5 Equation of Best Fit Line Through NTU Data

$$\Sigma y = \text{SUMNT} = 15.1110$$

$$\Sigma y^2 = \text{SUMNT}^2 = 59.7741$$

$$\Sigma yw = \text{SUMZNT} = 21.8406$$

$$\Sigma w = \text{SUMZ} = 5.486; \Sigma w^2 = \text{SUMZ}^2 = 7.9892 \text{ as in Section E.3}$$

$$\text{From Eq. (5.2):}$$

$$i = \text{ANT} = \frac{7.9892 \times 15.111 - 5.486 \times 21.8406}{4 \times 7.9892 - (5.486)^2} = 0.488$$

$$\text{From Eq. (5.3):}$$

$$s = \text{BNT} = \frac{4 \times 21.8406 - 5.486 \times 15.111}{4 \times 7.9892 - (5.486)^2} = 2.399$$

$$\text{From Eq. (5.4):}$$

$$r^2 = R^2_{\text{NT}} = \frac{(4 \times 21.8406 - 5.486 \times 15.111)^2}{[(4 \times 7.9892) - (5.486)^2] \times [(4 \times 59.7741) - (15.111)^2]}$$

$$R^2_{\text{NT}} = 0.9956$$

E.6 Confidence Limits for NTU vs Z Line

For Run 18 and trichloroethylene:

From Eq. (5.19):

$$res_1 = RES = 2.688 - (0.488 + 2.399 \times 0.914) = 0.007314$$

Residuals for the other runs are given in Table E.3.

Table E.3: Residuals of NTU vs Z line

Run #	res ₁ = RES
18	0.007314
20	0.032619
24	-0.090076
27	0.048229

$$\Sigma res^2 = \Sigma MRS^2 = 0.011557$$

From Eq. (5.18): $S_{vw}^2 = VARNT = 0.011557 / (4 - 2) = 0.005779$

$$\Sigma w = \Sigma MZ = 5.486; \Sigma w^2 = \Sigma MZ^2 = 7.9892 \text{ as in Section E.3.}$$

From Eq. (5.21): $\Sigma (w - \bar{w})^2 = 7.9892 - (5.486)^2 / 4 = 0.4652$

From Eq. (5.6): $\bar{w} = ZAV = 5.486 / 4 = 1.3715$

At Z = 0 m:

From Eq. (5.20):

$$S_v^2 = VARMN = 0.005779 \times \left[\frac{1}{4} + \frac{(0 - 1.3715)^2}{0.4652} \right] = 0.0248$$

The t statistic for N-2 = 2 degrees of freedom and the 95% confidence interval is:

$$t = T = 4.303$$

From Eq. (5.22), the confidence interval is equal to

$$0.488 \pm 4.303 \times (0.0248)^{1/2} = 0.488 \pm 0.678$$

To plot the NTUT vs Z graphs, these limits were also computed at depths (Z) of 0.457, 1.914, 1.372 and 1.829 m, respectively.

E.7 Mass Transfer Rate Constants

The mass transfer rate constants, their average, standard deviation and coefficient of variation were computed using the extrapolated NTUC value. But the computation was repeated with the empty column NTUC as shown in Appendix G.

E.8 Computer Program

The following WATFIV program was used to compute Δp_{ac} , $\Delta p_{ac}/Z$, NTUC, and the limits of confidence interval values.

```

3J08
C THIS PROGRAM COMPUTES NTUC, KLA VALUES, AND THE 95 % CONFIDENCE
C INTERVAL LIMITS (SEE LINES 100-102) FOR THE NTUT VS Z PLOTS.
C DEFINITION OF SETS OF VARIABLES.
C
1  INTEGER RUNO(4)
2  REAL Z(4),L(4),RL(4),DP(4),NT(6,4)
3  REAL SUMNT(6),SUMNT2(6),SUMZNT(6)
4  REAL NMAP,NMBP
5  REAL CP(4),PZ(4)
6  REAL DENNT(6),NMANT(6),NMBNT(6),ANT(6),BNT(6),R2NT(6)
7  REAL RES(6,4),SUMRS2(6),VARNT(6)
8  REAL NEWZ(5),VARMN(6,5),NNT(6,5),UPLM(6,5),LOLM(6,5)
9  REAL NTN(6,4),KLA(6,4),SUMKA(6),SUMKA2(6)
10 REAL KLAAB(6),KLAAD(6),KLASA(6)

C READ AND PRINT INPUT DATA.
C
11 READ,N
12 DO 10 I=1,N,1
13   READ,RUNO(I),Z(I),L(I),RL(I),DP(I)
14   READ,(NT(J,I),J=1,6)
15 10 CONTINUE
16 PRINT 20,'THE INPUT DATA FOLLOWS:'
17 20 FORMAT('1',10X,A23)
18 PRINT 30,'RUN =',PACKING DEPTH',PRESSURE DROP',NUMBER OF TRANSF
SER UNITS, NTUT'
19 30 FORMAT('1',T03,A05,T10,A13,T25,A13,T53,A30)
20 PRINT 40,'Z (M)',DP (IN/M**2)',TCE',1,1-OCA',TOLUENE',CHCL3',
S1,2-OCA',ETHER'
21 40 FORMAT(T14,A05,T26,A11,T42,A03,T50,A07,T60,A07,T71,A05,T90,A07,T91
S,A05,/,')
22 DO 50 K=1,N,1
23   PRINT 60,RUNO(K),Z(K),DP(K),NT(NN,K),NN=1,6)
24   60 FORMAT(T05,I2,T14,F5.3,T29,F5.0,T40,6(F6.3,4X))
25 50 CONTINUE

C COMPUTE SUM AND SUM OF SQUARES OF DEPTH, PRESSURE DROP, AND NTU.
C
26 SUMZ=SUMZ2=SUMP=SUMP2=SUMZP=0
27 DO 65 LN=1,6,1
28   SUMNT(LN)=SUMNT2(LN)=SUMZNT(LN)=0
29 65 CONTINUE
30 DO 70 M=1,N,1
31   SUMZ=SUMZ+Z(M)
32   SUMZ2=SUMZ2+(Z(M)**2)
33   SUMP=SUMP+DP(M)
34   SUMP2=SUMP2+(DP(M)**2)
35   SUMZP=SUMZP+(Z(M)*DP(M))
36 DO 80 II=1,6,1
37   SUMNT(II)=SUMNT(II)+NT(II,M)
38   SUMNT2(II)=SUMNT2(II)+(NT(II,M)**2)
39   SUMZNT(II)=SUMZNT(II)+(Z(M)*NT(II,M))
40 80 CONTINUE
41 70 CONTINUE

C COMPUTE COEFFICIENTS OF BEST FIT LINE THROUGH PRESSURE DROP DATA.
C

```

```

42      DENZ=(N*SUMZ2)-(SUMZ**2)
43      DENP=(N*SUMP2)-(SUMP**2)
44      NMAP=(SUMZ2*SUMP)-(SUMZ*SUMP)
45      NMBP=(N*SUMP2)-(SUMZ*SUMP)
46      AP=NMAP/DENZ
47      BP=NMBP/DENZ
48      R2P=(NMBP/SQRT(DENZ*DENP))**2

C
C COMPUTE PRESSURE DROPS PER UNIT DEPTH, THEIR AVERAGE AND STANDARD DEV.
C
49      SUMPZ=SUMPZ2=0
50      DO 90 IJ=1,N,1
51          CP(IJ)=DP(IJ)-AP
52          PZ(IJ)=CP(IJ)/Z(IJ)
53          SUMPZ=SUMPZ+PZ(IJ)
54          SUMPZ2=SUMPZ2+(PZ(IJ)**2)
55      90 CONTINUE
56      PZAV=SUMPZ/N
57      PZSD=SQRT(((N*SUMPZ2)-(SUMPZ**2))/(N*(N-1)))
58      PZSA=PZSD/PZAV

C
C PRINT PRESSURE DROP RESULTS.
C
59      PRINT 100, 'THE EQUATION OF THE BEST FIT LINE THROUGH PRESSURE DROP
      $ DATA IS:'
60      FORMAT('---',/,',-',T05,A84)
61      PRINT 110,AP,BP
62      FORMAT('0',T10,'DELTA PG= ',F5.0,' + ',F5.0,'*Z')
63      PRINT 120,R2P
64      FORMAT('0',T10,'COEFFICIENT OF DETERMINATION R**2= ',F7.4)
65      PRINT 130, 'THE PRESSURE DROP PER UNIT DEPTH IS:'
66      FORMAT('---',T05,A37)
67      PRINT 140, 'RUN #', 'PACKING DEPTH', 'PRESSURE DROP PER'
68      FORMAT('0',T03,A05,T10,A13,T27,A17)
69      PRINT 150, 'Z (M)', 'UNIT DEPTH (N/M**2/M)'
70      FORMAT(T14,A05,T25,A21)
71      DO 160 IK=1,N,1
72          PRINT 170,RUND(IK),Z(IK),PZ(IK)
73          FORMAT(T05,I2,T14,F5.3,T33,F5.0)
74      CONTINUE
75      PRINT 180, 'AVERAGE', PZAV
76      FORMAT('0',T03,A07,T33,F5.0)
77      PRINT 190, 'STANDARD DEVIATION', PZSD
78      FORMAT(T03,A18,T32,F7.3)
79      PRINT 200, 'STANDARD DEVIATION/AVERAGE', PZSA
80      FORMAT(T03,A26,T33,F6.3)

C
C COMPUTE COEFFICIENTS OF BEST FIT LINE THROUGH NTU DATA, AND PRINT.
C
81      DO 210 IL=1,8,1
82          DENNT(IL)=(N*SUMNT2(IL))-(SUMNT(IL)**2)
83          NMANT(IL)=(SUMZ2*SUMNT(IL))-(SUMZ*SUMZNT(IL))
84          NMBNT(IL)=(N*SUMZNT(IL))-(SUMZ*SUMNT(IL))
85          ANT(IL)=NMANT(IL)/DENZ
86          BNT(IL)=NMBNT(IL)/DENZ
87          R2NT(IL)=(NMBNT(IL)/SQRT(DENZ*DENNT(IL)))**2
88      210 CONTINUE
89      PRINT 220, 'THE COEFFICIENTS OF NTUT = (1/HTU)*Z + NTUC ARE:'
90      FORMAT('---',/,',-',T03,A50)
91      PRINT 230, 'TCE', '1,1-DCA', 'TOLUENE', 'CHCL3', '1,2-DCA', 'ETHER'

```

```

92      230 FORMAT('0',T27,A03,T35,A07,T45,A07,T55,A05,T65,A07,T76,A05)
93      PRINT 240,'NTUC',(ANT(IM),IM=1,6)
94      240 FORMAT(T03,A04,T25,6(F6.3,4X))
95      PRINT 250,'1/HTU',(BNT(IN),IN=1,6)
96      250 FORMAT(T03,A05,T25,6(F6.3,4X))
97      PRINT 280,'COEFF. OF DET., R=2',(R2NT(JI),JI=1,6)
98      280 FORMAT(T03,A20,T25,6(F6.4,4X))

C
C COMPUTE LIMITS OF CONFIDENCE INTERVAL FOR NTUT VS Z PLOTS.
C
99      ZAV=SUMZ/N
100     LC=95
101     IF (N.EQ.3) T=12.706
102     IF (N.EQ.4) T=4.303
103     DO 265 MI=1,6,1
104         SUMRS2(MI)=0
105     265 CONTINUE
106     DO 270 JJ=1,6,1
107         DO 280 JK=1,N,1
108             RES(JJ,JK)=NT(JJ,JK)-(ANT(JJ)+(BNT(JJ)*Z(JK)))
109             SUMRS2(JJ)=SUMRS2(JJ)+(RES(JJ,JK)**2)
110     280 CONTINUE
111     VARNT(JJ)=SUMRS2(JJ)/(N-2)
112     DO 290 JL=1,5,1
113         NEVZ(JL)=0.45725*(JL-1)
114         VARMN(JJ,JL)=VARNT(JJ)*((1./N)+(((NEVZ(JL)-ZAV)**2)/(SUMZ
115             S2-((SUMZ**2)/N))))
116         NNT(JJ,JL)=ANT(JJ)+(BNT(JJ)*NEVZ(JL))
117         UPLM(JJ,JL)=NNT(JJ,JL)+(T*SQR(VARMN(JJ,JL)))
118         LOLM(JJ,JL)=NNT(JJ,JL)-(T*SQR(VARMN(JJ,JL)))
119     290 CONTINUE
120     270 CONTINUE

C
C PRINT LIMITS OF CONFIDENCE INTERVAL FOR NTUT VS Z PLOTS.
C
120     PRINT 300,'NTUT VALUES ALONG THE BEST FIT LINES ARE PRESENTED BELO
121     SW:'
122     300 FORMAT('0',/,',',',',T03,A57)
123     EXECUTE HEADIN
124     DO 310 JM=1,5,1
125         PRINT 320,NEVZ(JM),(NNT(JM,JM),JM=1,6)
126     310 CONTINUE
127     320 FORMAT(T05,F5.3,T15,6(F6.3,4X))
128     PRINT 330,'THE ',LC,' X CONFIDENCE INTERVAL UPPER LIMITS ARE:'
129     330 FORMAT('0',T03,A04,I2,A40)
130     EXECUTE HEADIN
131     DO 340 KI=1,5,1
132         PRINT 320,NEVZ(KI),(UPLM(KI,KI),KI=1,6)
133     340 CONTINUE
134     PRINT 330,'THE ',LC,' X CONFIDENCE INTERVAL LOWER LIMITS ARE:'
135     EXECUTE HEADIN
136     DO 350 KK=1,5,1
137         PRINT 320,NEVZ(KK),(LOLM(KK,KK),KK=1,6)
138     350 CONTINUE

C
C COMPUTE AND PRINT KLA'S, THEIR AVERAGES AND STANDARD DEVIATIONS.
C
138     DO 355 MJ=1,6,1
139         SUMKA(MJ)=SUMKA2(MJ)=0
140     355 CONTINUE

```


$$L = \frac{Q_L \rho_L}{0.008107} \quad (5.14)$$

in which 0.008107 represents the cross sectional area of the packed column, in m^2 . The liquid was assumed to have the density of water, which was determined using the correlation formula of Heggen (1983):

$$\rho_L = (1 - 1.9549 \times 10^{-5}(T - 4)^{1.40}) \times 1000 \quad (5.15)$$

The average of the influent and effluent water temperatures was used as T .

The pressure drop computation requires the knowledge of the packed column manometer's fluid density, ρ_m (kg/m^3). For Runs 7 to 15, the fluid was water, which was replaced by red gauge oil (specific gravity 0.827) for Runs 16 to 42. The fluid density, ρ_m , was obtained by multiplying water's density (Eq. 5.15) at packed column room temperature by the fluid's specific gravity. The total pressure drop, measured by the manometer, was computed as:

$$\Delta p_{OT} = \left[\frac{Z_{HL} - Z_{LL}}{1000} \right] \rho_m \times 9.8 \quad (5.16)$$

where Z_{HL} = column's manometer liquid level, low pressure side (mm)

Z_{LL} = column's manometer liquid level, high pressure side (mm)

Δp_{OT} = total measured pressure drop (N/m^2)

The values of Henry's law constants for each compound at average water temperature, were needed to compute the stripping factor. The correlations developed in this work (Eq. (5.9), Table 5.4) were used to compute H , and the values obtained, were substituted in Eq. (2.21) to yield the

stripping factor, S , value for each compound. The total number of transfer units was computed by Eq. (2.19), using the average influent and effluent concentrations. Eq. (2.22) was used to determine HTU, and from it Eq. (2.16) yielded $K_L a$.

Sample calculations can be found in Appendix C, which also includes a listing of the computer program used for the computations. Appendix D presents computer printouts listing the recorded data and results of the above computations.

5.3.6 NTU Correction for End Effects

The total number of transfer units, NTUT, values computed from experimental data include the removal above and below the packing. Two ways to account for these end effects (Section 2.8) were applied to the experimental data.

5.3.6.1 Empty Column Method

Roberts et al. (1982; 1985) suggested that the NTU observed in the column without packing should be used as the correction for end effects, NTUC, at the same flow conditions, and substituted in Eq. (2.50) to yield the net NTU, NTUN.

Experimental Runs 28 to 30 were made with an empty column at flow conditions similar to those of Runs 16 to 27 and 31 to 42 (12.7 mm Raschig rings and 12.7 mm Intalox® saddles). However, due to an air bubble in the influent pipe, liquid flow rates for Runs 28 to 30 were slightly lower than

they should have been (Section 5.3.2.2). To obtain NTUC values as close as possible to NTUC at flow conditions of Runs 16 to 27 and 31 to 42, the three NTUC - Q_L pairs available for each compound were used to find the values of the constants in quadratic equations similar to the equation Roberts et al. (1982) derived:

$$NTUC = B_1 + B_2 Q_L + B_3 Q_L^2 \quad (5.17)$$

where B_1 , B_2 , B_3 = compound dependent constants

From these equations, the NTUC values at the Q_L values obtained by interpolation for Runs 28 to 30 (Section 5.3.2.2) were computed. Table 5.18 presents the recorded and corrected NTUC values, and the values of the constants of Eq. (5.17) for each compound.

5.3.6.2 Extrapolation Method

Ball et al. (1984) and Umphres et al. (1983) measured NTUT at different packing depths, Z , and found by extrapolation the value of NTUC at depth $Z = 0$.

In this work, NTUT values were available at 3 (Runs 7 to 15), or 4 depths (Runs 16 to 42) and a line of best fit was determined for each data set by the method of least squares [Eqs. (5.1) to (5.3)]. The coefficient of determination, r^2 [Eq. (5.4)], for each line is given in Table 5.19. Table 5.20 lists the extrapolated NTUC values [the "i" value of Eq. (5.1)] as well as the corresponding NTUC values obtained from empty column tests.

Table 5.18: Empty column NTUC values

Run No. or Constant	Q_L (l/min)	TCE	1,1-DCA	Toluene	CHCl_3	1,2-DCA	Ether
Initial NTUC values							
28	1.7836	0.267	0.265	0.249	0.247	0.208	0.167
29	1.5299	0.294	0.293	0.276	0.276	0.251	0.217
30	1.3385	0.329	0.326	0.308	0.353	0.290	0.237
Constants of Eq. (5.17)							
B_3		0.925	0.842	0.811	2.216	0.720	-0.049
B_4		-0.675	-0.572	-0.559	-2.258	-0.425	0.492
B_5		0.172	0.139	0.137	0.647	0.077	-0.208
Corrected NTUC values							
28	1.8364	0.264	0.261	0.246	0.251	0.200	0.153
29	1.5545	0.290	0.289	0.273	0.270	0.246	0.213
30	1.3665	0.323	0.321	0.303	0.339	0.284	0.235

Table 5.19: Coefficients of determination, r^2 , for NTUT vs Z lines

Liquid flow rate	TCE	1,1-DCA	Toluene	CHCl_3	1,2-DCA	Ether
6.35 mm Raschig rings						
Low	0.9954	0.9948	0.9958	0.9958	0.9893	0.9947
Medium	0.9853	0.9833	0.9839	0.9830	0.9705	0.9680
High	0.9942	0.9949	0.9946	0.9947	0.9915	0.9940
12.7 mm Raschig rings						
Low	0.9957	0.9768	0.9959	0.9951	0.9968	0.9933
Medium	0.9985	0.9981	0.9992	0.9986	0.9990	0.9971
High	0.9804	0.9833	0.9872	0.9865	0.9851	0.9845
12.7 mm Intalox® saddles						
Low	0.9969	0.9972	0.9976	0.9971	0.9978	0.9962
Medium	0.9993	0.9984	0.9996	1.0000	0.9999	0.9998
High	0.9972	0.9934	0.9962	0.9948	0.9955	0.9936

Table 5.20: Extrapolated and empty column NTUC values

Packing*	TCE	1,1-DCA	Toluene	CHCl ₃	1,2-DCA	Ether
Low liquid flow						
6.35 mm	0.685	0.692	0.563	0.546	0.805	0.509
R.r.	+2.961	+3.259	+2.862	+2.918	+3.591	+2.507
12.7 mm	0.488	0.542	0.383	0.334	0.394	0.363
R.r.	+0.677	+1.570	+0.660	+0.742	+0.528	+0.681
12.7 mm	0.196	0.022	0.064	-0.062	0.037	-0.154
I.s.	+0.705	+0.714	+0.620	+0.723	+0.555	+0.683
Empty column	0.323	0.321	0.303	0.339	0.284	0.235
Medium liquid flow						
6.35 mm	0.786	0.771	0.669	0.651	0.832	0.642
R.r.	+4.738	+5.249	+4.980	+5.256	+5.532	+5.440
12.7 mm	0.357	0.328	0.278	0.258	0.280	0.272
R.r.	+0.391	+0.442	+0.282	+0.377	+0.274	+0.410
12.7 mm	0.127	-0.006	0.036	-0.113	-0.059	-0.167
I.s.	+0.319	+0.504	+0.246	+0.062	+0.088	+0.138
Empty column	0.290	0.289	0.273	0.270	0.246	0.213
High liquid flow						
6.35 mm	0.330	0.245	0.229	0.155	0.385	0.099
R.r.	+3.287	+3.272	+3.180	+3.301	+3.443	+2.883
12.7 mm	0.583	0.635	0.519	0.471	0.430	0.395
R.r.	+1.189	+1.085	+0.932	+0.986	+0.886	+0.773
12.7 mm	0.099	-0.041	0.045	-0.106	-0.026	-0.121
I.s.	+0.612	+0.992	+0.695	+0.863	+0.678	+0.710
Empty column	0.264	0.261	0.246	0.251	0.200	0.153

* R.r.: Raschig rings; I.s.: Intalox® saddles

For the extrapolated NTUC values, the 95% confidence interval limits are also given. To compute the confidence limits for a mean estimated value of y_i (y estimated using Eq. (5.1)), the variance of y must be computed (Kennedy and Neville, 1976):

$$S_{yw}^2 = \frac{\sum \text{res}^2}{N-2} \quad (5.18)$$

where S_{yw} = variance of y , estimated by the regression line
 res = residual

and

$$\text{res}_i = y_i - (i + sw_i) \quad (5.19)$$

The variance of the mean estimated value of y_i , S_y^2 , can then be computed as (Kennedy and Neville, 1976):

$$S_y^2 = S_{yw}^2 \left[\frac{1}{N} + \frac{(w_i - \bar{w})^2}{\sum (w - \bar{w})^2} \right] \quad (5.20)$$

in which one can substitute:

$$\sum (w_i - \bar{w})^2 = \sum w^2 - \frac{(\sum w)^2}{N} \quad (5.21)$$

The confidence interval of the mean estimated value of y_i is then (Kennedy and Neville, 1976):

$$\text{confidence interval} = y_i \pm t S_y \quad (5.22)$$

where t = Student's t statistic

A sample calculation can be found in Appendix E, which also presents a listing of the computer program used for the computations.

NTUT values, best fit line, and limits of confidence intervals were plotted on NTU vs Z graphs for each packing,

flow condition, and compound. Data for 12.7 mm Raschig rings and 12.7 mm Intalox® saddles, for each compound and flow condition, were plotted on the same graph, along with the corresponding empty column NTUC value, facilitating comparison of results. Typical plots are presented in Figs. 5.17 and 5.18; all plots can be found in Appendix F.

5.3.7 Pressure Drop Correction for End Effects

The total pressure drop values, Δp_{or} , computed from experimental data also include the pressure drop above and below the packing. The pressure drop correction for end effects, Δp_{ec} (N/m^2), can be found by measurement in an empty column, or by extrapolation to $Z = 0$ of data for Δp_{or} at 3 or 4 packing depths. The pressure drop in the packing is then:

$$\Delta p_{\text{p}} = \Delta p_{\text{or}} - \Delta p_{\text{ec}} \quad (5.23)$$

The empty column Δp_{ec} values were not corrected for the difference in liquid flow rate observed between Runs 28 to 30 and Runs 16 to 27 and 31 to 42. The empty column and the extrapolated values of Δp_{ec} are presented in Table 5.21, while Table 5.22 lists the coefficients of determination for each line. A sample calculation can be found in Appendix E, along with a listing of the computer program used for the computations.

Pressure drop data was plotted against depth for each flow condition and packing, and the best fit line drawn in; these plots are presented in Figs. 5.19 to 5.27.

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Figure 5.17: Typical NTUT vs Z plot for 6.35 mm Raschig rings

Figure 5.18: Typical NTUT vs Z plot for 12.7 mm Raschig rings and 12.7 mm Intalox® saddles

Table 5.21: Extrapolated and empty column Δp_{ac} values

Packing*	Liquid flow rate		
	Low	Medium	High
6.35 mm R.r.	510**	438	611
12.7 mm R.r.	172	138	83
12.7 mm I.s.	229	180	124
Empty column	246	202	133

* R.r.: Raschig rings; I.s.: Intalox® saddles

** Δp_{ac} , in N/m²Table 5.22: Coefficients of determination, r^2 , for Δp_{ac} vs Z lines.

Packing*	Liquid flow rate		
	Low	Medium	High
6.35 mm R.r.	0.8410	0.6885	0.9887
12.7 mm R.r.	0.9949	0.9954	0.9912
12.7 mm I.s.	0.9173	0.9625	0.9626

* R.r.: Raschig rings; I.s.: Intalox® saddles

Figure 5.19: Δp_{GT} vs Z plot for 6.35 mm Raschig rings; at low liquid flow rate

Figure 5.20: Δp_{GT} vs Z plot for 6.35 mm Raschig rings, at medium liquid flow rate

Figure 5.21: Δp_{GT} vs Z plot for 6.35 mm Raschig rings, at high liquid flow rate

Figure 5.22: Δp_{GT} vs Z plot for 12.7 mm Raschig rings, at low liquid flow rate

Figure 5.23: Δp_{GT} vs Z plot for 12.7 mm Raschig rings, at medium liquid flow rate

Figure 5.24: Δp_{GT} vs Z plot for 12.7 mm Raschig rings, at high liquid flow rate

Figure 5.25: Δp_{GT} vs Z plot for 12.7 mm Intalox[®] saddles, at low liquid flow rate

Figure 5.26: Δp_{GT} vs Z plot for 12.7 mm Intalox[®] saddles, at medium liquid flow rate

Figure 5.27: Δp_{GT} vs Z plot for 12.7 mm Intalox[®] saddles, at high liquid flow rate

5.3.8 Pressure Drop per Unit Depth

The net packing gas pressure drop, Δp_g [Eq. (5.23)], divided by the corresponding packing depth, Z , yields the gas pressure drop per unit depth, $\Delta p_g/Z$ ($N/m^2/m$), which should be constant for a given packing and flow condition.

Thus, for each packing and flow condition, the average, standard deviation, and coefficient of correlation of $\Delta p_g/Z$ data were computed [Eqs. (5.6) to (5.8)] and are presented in Table 5.23. The extrapolated Δp_{gc} value was used to compute Δp_g . Appendix E presents a sample calculation.

5.3.9 Mass Transfer Rate Constants

The HTU and $K_L a$ values of the computer printouts (Appendix D) were computed using the NTUT values (Appendix C). HTU and $K_L a$ should be computed from Eqs. (2.22) and (2.16) using NTUN [Eq. (2.50)] as the NTU.

In this work, the empty column NTUC was used to compute NTUN, whenever available. Tables 5.24 to 5.26 present the resulting $K_L a$ values. A sample calculation is presented in Appendix G, which also shows a listing of the computer programs used for the computations.

Table 5.23: Average pressure drop per unit depth, $\Delta p_0/Z$

Parameter	Liquid flow rate		
	Low	Medium	High
6.35 mm Raschig rings			
Average	504	774	1441
Std. dev.	90.4	213.9	64.0
Coef. var.	17.9	27.6	4.4
12.7 mm Raschig rings			
Average	268	201	156
Std. dev.	6.7	4.8	4.7
Coef. var.	2.5	2.4	3.0
12.7 mm Intalox® saddles			
Average	91	69	50
Std. dev.	9.6	4.7	3.4
Coef. var.	10.6	6.8	6.8

Table 5.24: Experimental mass transfer rate constants, $K_L(s^{-1})$,
for 6.35 mm Rasching rings

RUN #	ICE	1,1-DCA	TOLUENE	CHLOROFORM	1,2-DCA	ETHER
13	6.941E-03	7.524E-03	8.941E-03	9.373E-03	7.662E-03	7.686E-03
10	9.518E-03	1.010E-02	9.497E-03	9.949E-03	8.263E-03	8.189E-03
7	9.144E-03	9.727E-03	9.138E-03	9.578E-03	7.673E-03	7.863E-03
AVERAGE *	9.200E-03	9.742E-03	9.192E-03	9.633E-03	7.933E-03	7.913E-03
STD. DEV. **	0.291E-03	0.290E-03	0.282E-03	0.292E-03	0.305E-03	0.255E-03
COEFF. VAR.	3.2	3.0	3.1	3.0	3.8	3.2
14	6.652E-03	6.900E-03	5.658E-03	6.875E-03	5.331E-03	5.014E-03
11	7.351E-03	7.674E-03	7.400E-03	7.609E-03	5.146E-03	5.816E-03
8	6.900E-03	7.173E-03	5.925E-03	7.104E-03	5.618E-03	5.297E-03
AVERAGE	6.968E-03	7.248E-03	5.997E-03	7.184E-03	5.690E-03	5.376E-03
STD. DEV.	0.355E-03	0.392E-03	0.372E-03	0.393E-03	0.414E-03	0.407E-03
COEFF. VAR.	5.1	5.4	5.3	5.5	7.3	7.6
15	6.908E-03	7.114E-03	6.971E-03	7.117E-03	5.413E-03	5.631E-03
12	7.304E-03	7.549E-03	7.353E-03	7.507E-03	5.893E-03	5.766E-03
9	7.048E-03	7.268E-03	7.106E-03	7.255E-03	5.583E-03	5.550E-03
AVERAGE	7.087E-03	7.310E-03	7.143E-03	7.293E-03	5.629E-03	5.583E-03
STD. DEV.	0.200E-03	0.221E-03	0.194E-03	0.194E-03	0.253E-03	0.170E-03
COEFF. VAR.	2.8	3.0	2.7	2.7	4.3	3.0

* Standard deviation

** Coefficient of variation

Table 5.25: Experimental mass transfer rate constants, $K_L a(s^{-1})$,
for 12.7 mm Raschig rings

RUN #	TCE	1,1-DCA	TOLUENE	CHLOROFORM	1,2-DCA	ETHER
16	8.554E-03	8.751E-03	8.241E-03	8.241E-03	7.254E-03	6.351E-03
19	8.473E-03	8.570E-03	8.136E-03	8.136E-03	7.048E-03	6.191E-03
22	8.576E-03	8.623E-03	8.207E-03	8.309E-03	7.230E-03	6.283E-03
25	7.841E-03	7.913E-03	7.615E-03	7.708E-03	6.675E-03	5.783E-03
AVERAGE	8.361E-03	8.484E-03	8.030E-03	8.109E-03	7.052E-03	6.192E-03
STD. DEV.	0.350E-03	0.375E-03	0.293E-03	0.271E-03	0.267E-03	0.255E-03
COEFF. VAR.	4.2	4.4	3.6	3.3	3.8	4.1
17	7.783E-03	7.963E-03	7.525E-03	7.593E-03	6.749E-03	5.936E-03
21	7.893E-03	8.024E-03	7.515E-03	7.711E-03	6.833E-03	6.082E-03
23	7.645E-03	7.743E-03	7.348E-03	7.490E-03	6.678E-03	5.840E-03
26	7.599E-03	7.812E-03	7.400E-03	7.537E-03	6.615E-03	5.808E-03
AVERAGE	7.730E-03	7.815E-03	7.447E-03	7.583E-03	6.719E-03	5.917E-03
STD. DEV.	0.134E-03	0.130E-03	0.073E-03	0.952E-04	0.934E-04	0.123E-03
COEFF. VAR.	1.7	1.6	1.2	1.3	1.4	2.1
18	7.501E-03	7.559E-03	7.231E-03	7.218E-03	6.682E-03	6.019E-03
20	7.386E-03	7.511E-03	7.121E-03	7.173E-03	6.523E-03	5.922E-03
24	6.987E-03	6.791E-03	6.104E-03	5.569E-03	5.257E-03	5.564E-03
27	7.123E-03	7.238E-03	6.959E-03	7.091E-03	6.369E-03	5.727E-03
AVERAGE	7.249E-03	7.300E-03	7.031E-03	7.082E-03	6.458E-03	5.808E-03
STD. DEV.	0.235E-03	0.382E-03	0.145E-03	0.155E-03	0.185E-03	0.203E-03
COEFF. VAR.	3.2	5.2	2.6	2.2	2.9	3.5

* Standard deviation

** Coefficient of variation

Table 5.26: Experimental mass transfer rate constants, $K_L a (s^{-1})$, for 12.7 mm Intalox® saddles

RUN #	TCE	1,1-DCA	TOLUENE	CHLOROFORM	1,2-DCA	ETHER
31	9.669E-03	9.751E-03	9.249E-03	9.240E-03	8.079E-03	6.868E-03
34	9.403E-03	9.440E-03	8.994E-03	9.059E-03	7.852E-03	6.732E-03
37	9.587E-03	9.679E-03	9.172E-03	9.329E-03	8.065E-03	6.904E-03
40	9.780E-03	1.009E-02	9.434E-03	9.721E-03	8.924E-03	7.245E-03
AVERAGE	9.610E-03	9.741E-03	9.212E-03	9.337E-03	8.080E-03	6.937E-03
STD. DEV.	0.159E-03	0.270E-03	0.142E-03	0.280E-03	0.193E-03	0.218E-03
COEF. VAR.	1.7	2.8	2.0	3.0	2.4	3.1
32	8.316E-03	8.392E-03	7.930E-03	9.021E-03	7.094E-03	6.104E-03
36	8.538E-03	8.625E-03	8.161E-03	8.267E-03	7.330E-03	6.291E-03
38	8.561E-03	8.530E-03	8.123E-03	8.409E-03	7.452E-03	6.513E-03
41	8.445E-03	8.743E-03	8.193E-03	8.444E-03	7.457E-03	6.578E-03
AVERAGE	8.465E-03	8.573E-03	8.102E-03	8.295E-03	7.333E-03	6.371E-03
STD. DEV.	0.111E-03	0.149E-03	0.111E-03	0.204E-03	0.170E-03	0.216E-03
COEF. VAR.	1.3	1.7	1.5	2.5	2.3	3.4
33	7.919E-03	8.011E-03	7.578E-03	7.590E-03	6.965E-03	6.108E-03
35	7.643E-03	7.807E-03	7.385E-03	7.470E-03	6.879E-03	6.019E-03
39	7.914E-03	8.099E-03	7.637E-03	7.438E-03	7.155E-03	6.397E-03
42	7.764E-03	8.100E-03	7.604E-03	7.439E-03	7.046E-03	6.389E-03
AVERAGE	7.810E-03	8.004E-03	7.552E-03	7.684E-03	7.011E-03	6.228E-03
STD. DEV.	0.133E-03	0.134E-03	0.113E-03	0.185E-03	0.117E-03	0.194E-03
COEF. VAR.	1.7	1.7	1.5	2.4	1.7	3.1

* Standard deviation

** Coefficient of variation

5.4 Mass Transfer Rate Constant Models

5.4.1 Application of Models

The equations and parameters needed to compute the mass transfer rate constant, K_{La} , values using the models presented in Chapter 2 are given in the following sections.

5.4.1.1 Mass Transfer Rate Constant Correlation Formulae

Essentially, the formulae presented in Table 2.2 were used to compute K_{La} values, isolating the k_{La} , k_L , or k_o term as required. For the models of Onda et al. (1968) and Shulman et al. (1955c), the k_L , k_o , and a_w or a terms were combined using Eq. (2.7) to yield K_{La} values. Since Sherwood and Holloway (1940) assumed gas phase mass transfer resistance was negligible (Section 2.6.2), $K_{La} = k_{La}$ for that model.

The only equation of Table 2.2 that was changed is Eq. (2.39). Since the packing size was below 15 mm, a value of 2.0 was substituted for 5.23 in that equation, as suggested by Onda et al. (1968; Section 2.6.4).

The following sections give values of constants and formulae to compute parameters needed to apply the models. The K_{La} predicted by the model(s) were computed at the flow and temperature conditions of each experimental run.

5.4.1.2 Known Constants

Values of packing related constants are given in Table 5.27. The values of some constants, such as α and n for the model of Sherwood and Holloway (1940) and d_0 , d , q , and h for the model of Shulman et al. (1955c), were available only for 12.7 mm Raschig rings, and these models could be applied only to that packing.

For Onda et al.'s (1968) model, the values of σ_c depend only on the material from which the packing is made; since all packings were made of ceramic, $\sigma_c = 61 \times 10^{-3}$ N/m (Perry et al., 1984). For Shulman et al.'s (1955c) model, the experimentally determined values of f_0 were used.

5.4.1.3 Mass Fluxes

The liquid mass flux, L , was computed from Eq. (5.14). The gas mass flux, G (kg/m²·s), was obtained from a similar equation:

$$G = \frac{Q_0 \rho_0}{0.008107} \quad (5.24)$$

5.4.1.4 Densities, Viscosities, and Surface Tensions

Density, viscosity, and surface tension are temperature dependent properties. The correlation formulae of Heggen (1983) were used to determine the liquid properties at experimental average water temperature. The liquid density, ρ_L , was determined by Eq. (5.15). The liquid viscosity, μ_L , was computed as:

Table 5.27: Constants for K_La models

Constant	Packing* material			Reference
	6.35 mm R.r.	12.7 mm R.r.	12.7 mm I.s.	
Onda et al. (1968)				
a_c (m^2/m^3)	764	407	623	Ludwig (1979)
d_R (m)	0.00635	0.0127	0.0127	
Sherwood and Holloway (1940)				
α		280		Sherwood and Holloway (1940)
n		0.35		Sherwood and Holloway (1940)
Shulman et al. (1955c)				
d_g (m)		0.01774		Treybal (1980)
d		14.69		Treybal (1980)
q		(0.01114L + 0.148)		Treybal (1980)
h		-0.111		Treybal (1980)
ϵ_o lit	0.62	0.64	0.71	Ludwig (1979)
ϵ_o exp**	0.54	0.63	0.74	

* R.r.: Raschig rings; I.s.: Intalox® saddles

** Experimentally determined ε_o

$$\mu_L = \left\{ 0.20319 + 1.5883 \exp \left[\frac{-T^{0.7}}{22} \right] \right\} \times 10^{-3} \quad (5.25)$$

and the liquid surface tension, σ_L , as:

$$\sigma_L = (20987 - 92.613T)^{0.4348} \times 10^{-3} \quad (5.26)$$

where T = average water temperature ($^{\circ}\text{C}$)

Since the relative humidity of the air was not known, the air was assumed to be dry. The density of dry air was computed as (Weast, 1977):

$$\rho_a = \frac{1.293}{1 + 0.00367T} \times \frac{p_a}{760} \quad (5.27)$$

where T = packed column room temperature ($^{\circ}\text{C}$)

No correlation could be found for air viscosity, μ_a . Therefore, a curve was fit to air viscosity data at standard atmospheric pressure, at 10, 20, 30, and 40 $^{\circ}\text{C}$, obtained from Daugherty and Franzini (1977), yielding:

$$\mu_a = (1.71 + 0.005T) \times 10^{-4} \quad (5.28)$$

where T = packed column room temperature ($^{\circ}\text{C}$)

5.4.1.5 Diffusion Coefficients

Tucker and Nelken (1982) reviewed the equations available to estimate diffusion coefficients in gases and liquids. The equation of Hayduk and Laudie (1974) was used to compute diffusion coefficients in liquids:

$$D_L = \left[\frac{13.26 \times 10^{-6}}{(1000\mu_L)^{1.14} (V_D)^{0.009}} \right] \times 10^{-4} \quad (5.29)$$

where V_D = molar volume of solute, estimated by LeBas incremental method (cm^3/mole)

To estimate D_o , the method of Fuller, Schettler, and Giddings (1966), recommended by Tucker and Nelken (1982), was used:

$$D_o = \left[\frac{10^{-3} T_A^{1.75} M_A^{1/2}}{p_T (V_A^{1/3} + V_o^{1/3})^2} \right] \times 10^{-4} \quad (5.30)$$

where T_A = absolute packed column room temperature ($^{\circ}\text{K}$)
 V_A = molar volume of air ($20.1 \text{ cm}^3/\text{mole}$)
 V_o = molar volume of solute, estimated by the incremental method used by Fuller, Schettler, and Giddings (1966) (cm^3/mole)

and

$$M_R = \frac{M_A + M_o}{M_A \times M_o} \quad (5.31)$$

where M_A = molar weight of air (28.97 g/mole)
 M_o = molar weight of solute (g/mole)

The values of M_A and V_A given above were obtained from Tucker and Nelken (1982), who also list the volume increments that may be added to obtain V_A or V_o . The increments used are presented in Table 5.28, while Table 5.29 lists the resulting values of V_A , V_o , and the values of M_o , that were used to compute D_L and D_o .

5.4.1.6 Predicted K_{La}

A sample calculation, and listings of the computer programs used to compute the predicted K_{La} at all experimental conditions, can be found in Appendix G. Tables 5.30 to 5.34 present the predicted K_{La} values, computed by the program presented in Appendix G.

Table 5.28: Volume increments*

Atom	Volume increments (cm ³ /mole)	
	V_{D}	V_{O}
C	14.8	16.5
H	3.7	1.98
O (no esters or ethers)	7.4	5.48
Cl	24.6	19.5
6-membered ring	-15.0	
Rings		-20.2

* From Tucker and Nelken (1982)

Table 5.29: Molar weights and volumes

Compound	V_{D} (cm ³ /mole)	V_{O} (cm ³ /mole)	M_{O} (g/mole)
Trichloroethylene	107.1	93.48	131.39
1,1-dichloroethane	93.6	79.92	98.96
Toluene	118.2	111.14	92.15
Chloroform	92.3	76.98	119.38
1,2-dichloroethane	93.6	79.92	98.96
Ether	106.1	91.28	74.12

Table 5.30: Mass transfer rate constants, $K_L(s^{-1})$, for 6.35 mm Raschig rings, predicted by the model of Onda et al. (1968)

PUN #	TCE	1,1-DCA	TOLUENE	CHLOROFORM	1,2-DCA	ETHER
13	1.009E-02	1.039E-02	9.675E-03	1.031E-02	9.592E-03	9.144E-03
10	1.048E-02	1.080E-02	1.008E-02	1.071E-02	1.001E-02	9.552E-03
7	1.097E-02	1.129E-02	1.057E-02	1.120E-02	1.049E-02	1.002E-02
AVERAGE *	1.051E-02	1.082E-02	1.011E-02	1.074E-02	1.003E-02	9.574E-03
STD. DEV. **	0.442E-03	0.454E-03	0.447E-03	0.449E-03	0.450E-03	0.441E-03
COEFF. VAR.	4.2	4.2	4.4	4.2	4.5	4.6
14	8.800E-03	9.140E-03	8.515E-03	9.055E-03	8.417E-03	8.021E-03
11	9.159E-03	9.429E-03	8.802E-03	9.353E-03	8.718E-03	8.318E-03
8	9.074E-03	9.339E-03	8.713E-03	9.262E-03	8.614E-03	8.214E-03
AVERAGE *	9.038E-03	9.303E-03	8.677E-03	9.227E-03	8.582E-03	8.184E-03
STD. DEV.	0.143E-03	0.148E-03	0.146E-03	0.147E-03	0.152E-03	0.149E-03
COEFF. VAR.	1.6	1.6	1.7	1.6	1.8	1.8
15	8.183E-03	8.420E-03	7.843E-03	8.344E-03	7.735E-03	7.368E-03
12	8.210E-03	8.448E-03	7.870E-03	8.375E-03	7.761E-03	7.394E-03
9	8.184E-03	8.422E-03	7.845E-03	8.351E-03	7.741E-03	7.375E-03
AVERAGE *	8.192E-03	8.430E-03	7.853E-03	8.354E-03	7.746E-03	7.379E-03
STD. DEV.	0.153E-04	0.139E-04	0.153E-04	0.139E-04	0.125E-04	0.125E-04
COEFF. VAR.	0.2	0.2	0.2	0.2	0.2	0.2

* Standard deviation

** Coefficient of deviation

Table 5.31: Mass transfer rate constants, $K_L a(s^{-1})$, for 12.7 mm Raschig rings, predicted by the model of Onda et al. (1968)

RUN #	TCE	1,1-DCA	TOLUENE	CHLOROFORM	1,2-DCA	ETHER
16	8.753E-03	8.917E-03	8.271E-03	8.742E-03	7.614E-03	7.183E-03
19	8.841E-03	9.004E-03	8.367E-03	8.832E-03	7.713E-03	7.261E-03
22	8.939E-03	9.104E-03	8.473E-03	8.930E-03	7.814E-03	7.362E-03
25	8.817E-03	8.985E-03	8.349E-03	8.813E-03	7.707E-03	7.276E-03
AVERAGE	8.837E-03	9.005E-03	8.355E-03	8.829E-03	7.712E-03	7.281E-03
STD. DEV.	0.767E-04	0.785E-04	0.833E-04	0.769E-04	0.816E-04	0.816E-04
COEF. VAR.	0.9	0.9	1.0	0.9	1.1	1.1
17	7.764E-03	7.943E-03	7.369E-03	7.824E-03	5.975E-03	5.602E-03
21	7.896E-03	8.079E-03	7.513E-03	7.959E-03	7.120E-03	6.746E-03
23	7.892E-03	8.075E-03	7.511E-03	7.954E-03	7.119E-03	6.746E-03
26	7.812E-03	7.994E-03	7.432E-03	7.875E-03	7.047E-03	6.677E-03
AVERAGE	7.841E-03	8.023E-03	7.458E-03	7.903E-03	7.065E-03	6.693E-03
STD. DEV.	0.643E-04	0.659E-04	0.694E-04	0.652E-04	0.689E-04	0.688E-04
COEF. VAR.	0.8	0.8	0.9	0.8	1.0	1.0
18	7.106E-03	7.290E-03	5.773E-03	7.204E-03	5.938E-03	5.203E-03
20	7.273E-03	7.462E-03	5.948E-03	7.374E-03	6.713E-03	6.378E-03
24	7.058E-03	7.243E-03	5.731E-03	7.158E-03	6.505E-03	6.176E-03
27	7.075E-03	7.261E-03	5.753E-03	7.176E-03	6.531E-03	6.203E-03
AVERAGE	7.128E-03	7.314E-03	5.801E-03	7.228E-03	6.572E-03	6.241E-03
STD. DEV.	0.986E-04	0.101E-03	0.991E-04	0.991E-04	0.951E-04	0.926E-04
COEF. VAR.	1.4	1.4	1.5	1.4	1.4	1.5

* Standard deviation

** Coefficient of deviation

Table 5.32: Mass transfer rate constants, $K_L(s^{-1})$, for 12.7 mm Raschig rings, predicted by the model of Sherwood and Holloway (1940)

Run #	TCE	1,1-DCA	TOLUENE	CHLOROFORM	1,2-DCA	ETHEP
16	9.095E-03	9.463E-03	8.834E-03	9.502E-03	9.463E-03	9.120E-03
19	9.132E-03	9.502E-03	8.871E-03	9.541E-03	9.502E-03	9.157E-03
22	9.175E-03	9.546E-03	8.912E-03	9.585E-03	9.546E-03	9.200E-03
25	9.104E-03	9.472E-03	8.843E-03	9.511E-03	9.472E-03	9.129E-03
AVERAGE	9.126E-03	9.496E-03	8.865E-03	9.535E-03	9.496E-03	9.152E-03
STD. DEV.	0.350E-04	0.366E-04	0.347E-04	0.369E-04	0.366E-04	0.355E-04
COEF. VAR.	0.4	0.4	0.4	0.4	0.4	0.4
17	8.201E-03	8.533E-03	7.986E-03	8.568E-03	8.533E-03	8.224E-03
21	8.250E-03	8.544E-03	8.014E-03	8.620E-03	8.564E-03	8.273E-03
23	8.238E-03	8.572E-03	8.002E-03	8.607E-03	8.572E-03	8.261E-03
26	8.161E-03	8.512E-03	7.947E-03	8.547E-03	8.512E-03	8.204E-03
AVERAGE	8.210E-03	8.550E-03	7.982E-03	8.586E-03	8.550E-03	8.240E-03
STD. DEV.	0.318E-04	0.333E-04	0.311E-04	0.335E-04	0.333E-04	0.315E-04
COEF. VAR.	0.4	0.4	0.4	0.4	0.4	0.4
18	7.574E-03	7.881E-03	7.357E-03	7.913E-03	7.881E-03	7.595E-03
20	7.652E-03	7.962E-03	7.433E-03	7.994E-03	7.962E-03	7.673E-03
24	7.517E-03	7.821E-03	7.302E-03	7.853E-03	7.821E-03	7.538E-03
27	7.510E-03	7.814E-03	7.296E-03	7.846E-03	7.814E-03	7.531E-03
AVERAGE	7.563E-03	7.869E-03	7.347E-03	7.902E-03	7.869E-03	7.584E-03
STD. DEV.	0.656E-04	0.680E-04	0.634E-04	0.644E-04	0.680E-04	0.659E-04
COEF. VAR.	0.9	0.9	0.9	0.9	0.9	0.9

* Standard deviation

** Coefficient of deviation

Table 5.33: Mass transfer rate constants, $K_L(s^{-1})$, for 12.7 mm Raschig rings, predicted by the model of Shulman et al. (1955)

RUN #	TCE	1,1-DCA	TOLUENE	CHLOROFORM	1,2-DCA	ETHER
16	9.782E-03	9.950E-03	9.224E-03	9.737E-03	8.403E-03	7.916E-03
19	9.814E-03	9.985E-03	9.271E-03	9.775E-03	8.465E-03	7.982E-03
22	9.853E-03	1.003E-02	9.325E-03	9.816E-03	8.527E-03	8.047E-03
25	9.798E-03	9.971E-03	9.261E-03	9.764E-03	8.470E-03	7.989E-03
AVERAGE	9.812E-03	9.983E-03	9.270E-03	9.773E-03	8.486E-03	7.964E-03
STD. DEV.	0.285E-04	0.302E-04	0.434E-04	0.321E-04	0.506E-04	0.538E-04
COEF. VAR.	0.3	0.3	0.4	0.3	0.6	0.7
17	9.412E-03	9.512E-03	8.912E-03	9.450E-03	8.338E-03	7.879E-03
21	9.452E-03	9.657E-03	8.977E-03	9.497E-03	8.422E-03	7.970E-03
23	9.434E-03	9.638E-03	8.953E-03	9.479E-03	8.411E-03	7.960E-03
26	9.380E-03	9.583E-03	8.907E-03	9.425E-03	8.360E-03	7.910E-03
AVERAGE	9.420E-03	9.523E-03	8.940E-03	9.463E-03	8.383E-03	7.930E-03
STD. DEV.	0.308E-04	0.299E-04	0.347E-04	0.295E-04	0.392E-04	0.425E-04
COEF. VAR.	0.3	0.3	0.4	0.3	0.5	0.5
18	9.165E-03	9.388E-03	8.716E-03	9.280E-03	8.319E-03	7.883E-03
20	9.235E-03	9.461E-03	8.806E-03	9.334E-03	8.426E-03	7.996E-03
24	9.111E-03	9.334E-03	8.671E-03	9.208E-03	8.287E-03	7.858E-03
27	9.105E-03	9.329E-03	8.673E-03	9.205E-03	8.300E-03	7.872E-03
AVERAGE	9.154E-03	9.374E-03	8.717E-03	9.252E-03	8.333E-03	7.902E-03
STD. DEV.	0.594E-04	0.607E-04	0.635E-04	0.599E-04	0.629E-04	0.631E-04
COEF. VAR.	0.6	0.6	0.7	0.6	0.8	0.8

* Standard deviation

** Coefficient of deviation

Table 5.34: Mass transfer rate constants, $K_L(a(s^{-1}))$, for 12.7 mm Intalox® saddles, predicted by the model of Onda et al. (1968)

RUN #	TCE	1,1-DCA	TOLUENE	CHLOROFORM	1,2-DCA	ETHER
31	1.060E-02	1.060E-02	9.645E-03	1.019E-02	7.958E-03	7.379E-03
34	1.082E-02	1.073E-02	9.847E-03	1.040E-02	8.182E-03	7.803E-03
37	1.093E-02	1.094E-02	1.008E-02	1.052E-02	8.310E-03	7.731E-03
40	1.140E-02	1.140E-02	1.061E-02	1.095E-02	8.724E-03	8.145E-03
AVERAGE	1.094E-02	1.094E-02	1.008E-02	1.051E-02	8.293E-03	7.715E-03
STD. DEV.	0.337E-03	0.335E-03	0.344E-03	0.320E-03	0.322E-03	0.322E-03
COEF. VAR.	3.1	3.1	3.4	3.0	3.9	4.2
32	9.403E-03	9.476E-03	8.592E-03	9.181E-03	7.467E-03	6.963E-03
36	9.419E-03	9.494E-03	8.725E-03	9.201E-03	7.507E-03	7.006E-03
39	9.816E-03	9.895E-03	9.159E-03	9.588E-03	7.901E-03	7.399E-03
41	9.843E-03	9.921E-03	9.210E-03	9.612E-03	7.933E-03	7.434E-03
AVERAGE	9.620E-03	9.697E-03	8.949E-03	9.396E-03	7.702E-03	7.200E-03
STD. DEV.	0.242E-03	0.244E-03	0.279E-03	0.236E-03	0.249E-03	0.250E-03
COEF. VAR.	2.5	2.5	3.1	2.5	3.2	3.5
33	8.637E-03	8.750E-03	8.058E-03	8.526E-03	7.149E-03	6.699E-03
35	8.512E-03	8.624E-03	7.929E-03	8.404E-03	7.038E-03	6.590E-03
39	9.048E-03	9.166E-03	8.520E-03	8.930E-03	7.571E-03	7.121E-03
42	8.915E-03	9.032E-03	8.341E-03	8.802E-03	7.461E-03	7.016E-03
AVERAGE	8.778E-03	8.893E-03	8.224E-03	8.665E-03	7.305E-03	6.856E-03
STD. DEV.	0.247E-03	0.249E-03	0.276E-03	0.242E-03	0.252E-03	0.253E-03
COEF. VAR.	2.8	2.8	3.4	2.8	3.5	3.7

* Standard deviation

** Coefficient of deviation

5.4.2 Comparison of Experimental and Predicted K_{La}

For each packing, and for each model applicable to it, a plot of the logarithm (base 10) of the K_{La} values predicted by the model at all experimental conditions studied against the logarithm of the corresponding experimental (or observed) K_{La} values was produced (Figs. 5.28 to 5.32).

For each set of data plotted, the coefficients of the equation of the line of best fit (on the logarithmic plot) and the corresponding coefficient of determination were computed using Eqs. (5.2) to (5.4). The line of best fit was not plotted on Figs. 5.28 to 5.32, but its equation and the values of r^2 are given in Table 5.35. Since there were doubts concerning the accuracy of the chloroform and ether data, values of i , s , and r^2 were also computed using the data related to the other four compounds only; results are again presented in Table 5.35.

The goodness of fit of the best fit line to the data is indicated by r^2 . To estimate the amount of error involved in a prediction situation, the standard error of estimate, SEE, was computed as shown by Roscoe (1969); for this specific case:

$$SEE = \left[\frac{\sum (\log_{10} K_{La_{pred}} - \log_{10} K_{La_{obsd}})^2}{N - 2} \right]^{1/2} \quad (5.32)$$

Resulting SEE values are also given in Table 5.35. A sample calculation, and listings of the computer programs used to compute r^2 and SEE, are presented in Appendix G. The values

Figure 5.28: Logarithmic plot of $K_L a$ predicted by the model of Onda et al. (1968) against experimental $K_L a$, 6.35 mm Raschig rings.

Figure 5.29: Logarithmic plot of K_L predicted by the model of Onda et al. (1968) against experimental K_L , 12.7 mm Raschig rings

Figure 5.30: Logarithmic plot of $K_L a$ predicted by the model of Sherwood and Holloway (1940) against experimental $K_L a$, 12.7 mm Raschig rings

Figure 5.31: Logarithmic plot of $K_L a$ predicted by the model of Shulman et al. (1955) against experimental $K_L a$, 12.7 mm Raschig rings

Figure 5.32: Logarithmic plot of $K_L a$ predicted by the model of Onda et al. (1968) against experimental $K_L a$, 12.7 mm Intalox® saddles

Table 5.35: Comparison of mass transfer rate constant prediction models

Packing*	Model**	No. of comp.	Regression equation'''			SEE
			i	s	r ²	
6.35 mm R.r.	Onda	6	-0.9007	0.5360	0.7245	0.1041
12.7 mm R.r.	Onda	6	-0.4247	0.7929	0.7609	0.0317
12.7 mm R.r.	Sher.	6	-1.4127	0.3093	0.1841	0.0835
12.7 mm R.r.	Shul.	6	-0.7377	0.6114	0.8664	0.0993
12.7 mm I.s.	Onda	6	0.1945	1.0720	0.9450	0.0466
6.35 mm R.r.	Onda	4	-0.8978	0.5376	0.6767	0.1002
12.7 mm R.r.	Onda	4	-0.0012	0.9928	0.7919	0.0224
12.7 mm R.r.	Sher.	4	-1.0229	0.4940	0.2644	0.0640
12.7 mm R.r.	Shul.	4	-0.7398	0.6108	0.7762	0.0911
12.7 mm I.s.	Onda	4	0.4744	1.2081	0.9288	0.0446

* R.r.: Raschig rings; I.s.: Intalox® saddles

** Onda: Onda et al. (1968)

Sher.: Sherwood and Holloway (1940)

Shul.: Shulman et al. (1955c)

6: all compounds; 4: chloroform and ether excluded

''' Coefficients of Eq.: $\log_{10} K_{La, pred} = i + s \log_{10} K_{La, obs}$

obtained by Roberts et al. (1985) for 12.7 mm Berl saddles experiments are presented in Table 5.36.

The average K_{La} values (observed or predicted) at each flow condition (Tables 5.24 to 5.26, and 5.30 to 5.34) were also plotted against the average gas flow rate and liquid flow rate (Tables 5.14 and 5.15) on logarithmic axes. A typical plot is shown in Fig. 5.33. The plots for all compounds, packings, and flow rates, are in Appendix H.

5.4.3 Effect of Model on Packed Depth

Using a modification of the design procedure given in Table 2.1, the depth of packing required to achieve a given removal of 1,2-dichloroethane, chloroform, and trichloroethylene under the conditions of Run 18 was computed, with the experimental (observed) mass transfer rate constant as well as with the predicted constants. Details of the calculations are shown in Appendix I. Table 5.37 gives the ratio of the packing depth computed from the predicted K_{La} value to the packing depth computed from the observed K_{La} value.

Table 5.36: Literature* results - mass transfer rate constant prediction models

Model**	Regression equation [†]			SEE
	i	s	r ²	
Onda	0.274	1.108	0.951	0.0845
Sher.	-0.118	0.936	0.865	0.125
Shul.	0.893	1.377	0.909	0.198

* Results of Roberts et al. (1985), for 12.7 mm (1/2 in.) Berl saddles

** Onda: Onda et al. (1968)
 Sher.: Sherwood and Holloway (1940)
 Shul.: Shulman et al. (1955c)

† Coefficients of Eq.: $\log_{10} K_{La, pred} = i + s \log_{10} K_{La, obs}$

Table 5.37: Packing depth ratio of experimental and predicted K_{La}

Model	Ratio Z_{pred}/Z_{obs}		
	TCE	CHCl ₃	1,2-DCA
Onda et al. (1968)	1.056	1.002	1.022
Sherwood and Holloway (1940)	0.990	0.912	0.848
Shulman et al. (1955c)	0.818	0.779	0.803

Figure 5.33: Typical logarithmic plot of average gas and liquid flow rates against average observed and predicted mass transfer rate constants

CHAPTER 6

DISCUSSION

6.1 Water Analysis for Organics

6.1.1 Method of Analysis

As described in Section 4.1.1, the concentrator, gas chromatograph, and integrator formed a fully automated network. Errors in the volume of sample to be purged were probably the main source of discrepancy in analysis results; even sample manipulation was minimized by the purge vessel's valve with female luer connector.

No internal standard was used to identify and quantify the chemicals (Sections 4.1.3 and 3.3.3.2), but it was felt that the separation of the peaks (Fig. 4.3) and full automation of the system insured proper identification. For quantification, the computation of both Henry's law constants and mass transfer constants required only relative concentration values (influent/effluent concentration, initial/equilibrium concentration), and only a very sudden, and thus noticeable, sensitivity change would affect the value of this ratio.

The long analysis time (approximately 40 minutes) implies that the last sample of any experimental run is not

analysed until 8 hours after the first one (Section 4.3.4). Volatile organics losses from the syringes in the refrigerator were measured and accounted for in Henry's law constants measurement experiments (Section 5.2.1), and some losses can be expected to occur over an 8 hour period. Since other factors, such as the order of analysis of the samples, will affect the losses, they will be discussed later. Organics losses from the septum closed bags containing standard solutions may also have occurred, but no significant difference could be observed between samples analysed within a few days; these losses were thus assumed negligible.

6.1.2 Linearity of Detector

Results of the first linearity test are presented in Figs 5.1 to 5.6 and Table 5.1. The coefficient of determination, r^2 , values for 1,1-dichloroethane, toluene, trichloroethylene, and 1,2-dichloroethane were all above 0.999, showing the goodness of fit of the straight lines to the data. Figs 5.1 to 5.3, and 5.5 show the data points to always be close to the line of best fit. The fact that most data points below 100 $\mu\text{g/l}$ are above the best fit line while above the 100 $\mu\text{g/l}$ mark, the data points are mostly below the line, is thought to be due to the use of different syringes for the injection of standard solution in calcium chloride (10 and 100 μl syringes for amounts below 100 $\mu\text{g/l}$, 1 and 5 ml syringes for larger amounts). This hypothesis is supported by the fact that the points show no tendency to

deviate away from the line, in one direction or another. Thus; the detector is considered linear for these four compounds.

However, for ether and chloroform, the values of r^2 dropped. Fig. 5.4 even shows that for chloroform the data points are well below the line until the 1 mg/l mark, and then go far above the line of best fit. Deviations from the best fit line are also greater for ether (Fig. 5.6) than for the other compounds. It appeared that the ether and chloroform peaks may have been too close to each other (Fig. 4.3) and that the integration of one may have interfered with the integration of the other.

Results of the second linearity test (Figs 5.7 to 5.9, and Table 5.2) confirm this. In the test without ether, all r^2 values including that of chloroform were above 0.999 (Table 5.2). The chloroform data was also above the line until the 200 μ g/l mark, and then mostly below the line, as for the other compounds. When ether was added, r^2 values of chloroform and ether dropped below 0.999, and the chloroform plot changed appearance (Fig. 5.8), while r^2 values of other compounds remained above 0.999.

Because of this interference, the experimental data for chloroform and ether should be used and interpreted with caution.

6.2 Henry's Law Constants

6.2.1 Experimental Determination

Henry's law constants were determined experimentally because no value of H could be found for ether in the literature, and because the various factors (solute concentrations, water composition) affecting H were thus accounted for (Section 3.1.2.1). The closed system measurement method of Munz and Roberts (1982) was selected because the syringes and valves required were available and affordable.

Munz and Roberts (1982) blamed the short contact time, little amount of shaking, and volatilization during sample transfer for liquid-liquid extraction for the apparently low H values obtained by this method (Section 3.1.2.3). The valve of the purge vessel, in these experiments, reduced the possibilities of volatilization during sample transfer; and the syringes were agitated all day long. With respect to the effects of temperature, the environmental room's temperature varied by less than 0.2°C over the experimental period.

The syringes used were totally inert (glass and Teflon®) and reputed "gas tight", but volatilization losses nevertheless occurred over a day. As mentioned in Section 5.2.1, losses computed once for each syringe, compound, and temperature, were then used to compute the equivalent initial concentration after one day, C_{L1} . The plunger may not have fit the same way in the syringe barrel when at the 5 ml

mark (during losses determination) and at the 10 ml mark (during H determination, with 5 ml of liquid and 5 ml of gas); at the 10 ml mark only a short length of barrel remained to guide the plunger. Also the valves had to be removed from the syringes after each run, to allow injection of the standard solution in the calcium chloride solution contained in the syringes. Although care was taken to always use the same valve on each syringe, both of the above factors may have made the losses computed different from the losses occurring during H determination. Because of the small volume of the syringes (10 ml), the relative effect of any slight measurement error or dead volume may have been significant. These factors may have caused the wide variation of the data, reflected by high coefficient of variation values in Table 5.3.

Problems were experienced with the integrator during these experiments, and consequently some data had to be rejected (Appendix A). For the least volatile compounds (ether and 1,2-dichloroethane), losses were so small and equilibrium concentrations so close to initial concentrations that some samples were observed to gain volatiles, while negative H values were observed in other cases. Where there was a negative loss, or gain, of volatiles it was assumed that no losses occurred ($C_{L1}/C_{L0} = 1.0$). All results for any syringe for which negative H values were observed have been rejected. According to Chauvenet's criterion

(Kennedy and Neville, 1976), none of the remaining values could be considered to be outliers.

Solute concentrations possibly affect H values. Since there is no agreement in the literature with respect to this question (Section 3.1.3.2), and because the solute concentrations for H determination tests (Table 4.6) were in the range of the packed column influent concentrations (Table 4.7), solute concentration effect was assumed negligible.

6.2.2 Effect of Methanol

It was evaluated that methanol addition decreases chloroform's Henry's law constant by slightly more than 2%. In view of the accuracy of H determination (Table 5.3), and since approximately the same amount of methanol will be present in packed column influent liquid, this decrease was considered insignificant.

6.2.3 Effect of Temperature

Of the two forms of correlation equations used to relate Henry's law constants to temperature, Kavanaugh and Trussell's (1980) equation is fundamentally correct, H_a being the true expression of activity ratio in a vapour-liquid system (Section 3.1.3.1). From Eqs. (3.8) and (3.9):

$$\ln H_a = \ln H + \ln RT_a \frac{p_L}{M_L} \quad (6.1)$$

Thus for Eq. (5.9) and the equation of Singley et al. [1980; Eq. (3.24)] to accurately represent the theoretically pre-

dicted temperature dependence of H , the $\ln RT_0(P_L/M_L)$ term should be included. It was, however, felt safe to neglect the term, in view of the small range of absolute temperatures examined, and Eq. (5.9) was used to correlate the experimental data. The straight line appearance of the Kavanaugh and Trussell (1980) correlation, plotted on Figs. 5.10, 5.11, and 5.13, illustrates the insignificance of the logarithmic term in that range of temperature.

Because of the scatter of experimental H values (Appendix A), reflected by the large coefficients of variation in Table 5.3, and because of the fact that H was determined at only two temperatures, the coefficients of determination associated with the derived correlations were very low (Table 5.4). Tables 5.7 to 5.11 show that the literature values of Henry's law constants at a given temperature vary significantly from one source to another; these variations are sometimes explained by differences in background water (e.g., Roberts et al., 1984), but often could not be explained. The correlations of Kavanaugh and Trussell (1980) and Singley et al. (1980) also gave different results at the same temperatures, as shown on Figs. 5.10, 5.11, and 5.13.

Figs. 5.10 to 5.14 show that, in the 20 to 25°C range, the experimental data correlations of this work were within the range of literature data and correlations for chloroform and 1,1-dichloroethane, and slightly outside of it for toluene around 20°C and for 1,2-dichloroethane and tri-

chloroethylene around 25°C. Thus, it was felt that the correlations of this work could be used, since they were close to the widely ranging data, and should be used, since they were derived under this work's specific experimental conditions (water composition, solutes concentrations).

The correlations of this work could be refined. However, Roberts et al. (1982) found that a change of + 20% in H values had only a small effect on experimentally determined mass transfer rate constants K_La for stripping factor values, $S > 1.5$. Since the lowest stripping factor value was above 3 in this work, the correlations can be safely applied to compute experimental K_La . The effect of H on K_La values predicted using Onda et al.'s (1968) or Shulman et al.'s (1955c) models was more important, especially for 1,2-dichloroethane and ether, as shown in Tables 5.12 and 5.13, but still the correlations of this work were applied to compute predicted K_La values.

6.3 Packed Tower Air Stripping Experiments

6.3.1 Experimental Set Up and Conditions

6.3.1.1 Manometers

Liquid levels in the u-tube manometers could be read on millimetric scales fixed behind the u-tubes. The accuracy of the readings, neglecting the parallax effect, was ± 0.5 mm. This accuracy was considered suitable for the pressure measurement before the rotameter, since the measured pres-

sure was added to the much greater barometric pressure to correct the measured flow (Section 5.3.2.1); the error caused by a 0.5 mm inaccuracy, relative to ambient pressure (~760 mm of mercury), appears to be insignificant. The packed column's gas pressure drop measurement was an interesting but not essential measurement, that could be used as an indicator of flow conditions. An accuracy of ± 0.5 mm was acceptable.

6.3.1.2 Adsorbent Material

It was mentioned in Section 4.3.1 that the organics solution came in contact with Plexiglas®, short sections of Tygon® tubing, and Viton® O rings, all of which may have adsorbed some of the organics. Since the same parts were used throughout all runs, it was assumed that the exposure of the above materials to the organics solution during the first six experimental runs, which were trial runs whose results were not used in further computations, was sufficient to saturate any adsorption capacity.

6.3.1.3 Samples Collection and Storage

As described in Chapter 4, the influent and effluent liquid samples were collected in 10 ml Gastight® syringes equipped with Mininert® Teflon® syringe valves (Fig. 4.4). Samples were drawn from the miniature inert sampling valves, previously flushed, through female luer connectors (Fig. 4.15). The sampling syringes were also used to transfer 5

ml samples in the purging vessel, through the miniature valve equipped with a female luer connector (Fig. 4.1).

Thus, there was almost no dead volume, and sample manipulations were reduced to a minimum. The only open air sample manipulations occurred immediately after sampling, when the small air bubbles sometimes drawn into the syringe during sampling were removed, and the sample volume was adjusted to 10 ml, under the fume hood; however, this task was accomplished in less than one minute.

Samples were then stored in a refrigerator, some of them for up to 8 hours, before being analysed (Section 4.3.4); volatilization of organics may have occurred during that period. As mentioned in Section 4.3.4, the contents of each syringe were analysed once before the contents of any syringe were analysed a second time, so that losses would not be much more important for the last syringes analysed than for the first ones. Losses were not quantified here, but the syringes having been stored only 8 hours or less in a refrigerator at 6°C, they were expected to have much smaller losses than the losses observed during the Henry's law constants determination (Appendix A).

Some tiny gas bubbles, being too small to be removed, remained in the syringes until sample analysis. In light of their small volume relative to the volume of liquid, possible concentration changes due to the liquid and gas establishing equilibrium were considered negligible. Similarly, errors that may have been caused by inaccurate sample vol-

umes, as measured by the syringes, were neglected, since the syringes were accurate to 0.1 ml (Chromatographic Specialties Limited, 1985; Supelco Canada Ltd/Ltee, 1985).

The low coefficients of variation for influent and effluent concentrations (usually the coefficient of variation was below 3% for influent concentrations, and below 5% for effluent concentrations; see Appendix D) were interpreted as an indication that losses were small and that sample collection and storage procedures were adequate.

6.3.1.4 Flow Patterns

As mentioned in Section 4.3.1, there was a packing support screen at each coupling, allowing for each column section to be packed separately. As sections were assembled, the packing settled slightly, and this settling combined with space taken by the support screen and redistributor ring, resulted in a gap (< 25 mm) in the packing at each coupling. Although the flow pattern in the gaps was different from that in the packing, the gaps were small compared to the total packing depth, and their effect on the results is believed to be small.

The gaps, however, allowed visual observation of channeling in the column. Packing depths in this study ranged from 0.914 to 1.829 m; they were selected so that end effects would be small compared to removal in the packing. Effectively, NTUC values were below 15% of NTUT values for 12.7 mm Raschig rings and Intalox® saddles, and below 40% of

NTUT for 6.35 mm Raschig rings (Section 5.3.6 and Appendix D). Roberts et al. (1982) mention that packed heights greater than 1.5 m are typical of full scale applications; packing depths in this study were in that range. However, for higher towers, the probability of channeling increases.

Even though the column to packing diameter ratio was at least 8 to 1, and redistributor rings were placed at spaces equivalent to 3 column diameters, as suggested by Treybal (1980), channeling was significant, as shown on Figs. 6.1 and 6.2. The portion of flow channeled was not measured, but visual observation in the gaps at each coupling gave the impression that up to 25 to 50% of the flow was channeled for 12.7 mm Raschig rings; visual observation also showed that channeling appeared to be less important for 12.7 mm Intalox® saddles and 6.35 mm Raschig rings. The redistribution rings appeared to temporarily reduce the channeling, and a better redistribution ring design may have helped, but it was felt that a larger column to packing ratio would be the best way to reduce channeling. Since tracer tests were not performed, the extent of the effect of channeling could not be estimated. The mass transfer rate constant, K_La , values for a given packing and flow conditions did not show any tendency for the K_La values to decrease as packing depth increased (Tables 5.24 to 5.26), which is an indication that the proportion of flow channeled, did not increase with depth, probably because of the redistribution rings.

Figure 6.2: Channeling in 12.7 mm
Intalox ϕ saddles, medi-
um liquid flow rate

Figure 6.1: Channeling in 12.7 mm
Raschig rings, medium
liquid flow rate

The empty column runs (Runs 28 to 30) did not accurately reproduce the flow conditions of liquid above and below the packing, as shown in Figs. 6.3 to 6.5. As described in Section 4.3.2, a 10 mm deep layer of 6.35 mm Raschig rings was spread on the screen in the coupling, to break the jets of the distributor cap and change them to small streams. Thus flow conditions in the effluent section of the empty column were probably close to conditions below the packing in a packed column (Figs. 6.3 and 6.5). In the empty column influent section, however, the packing layer was only 10 to 15 mm away from the distributor cap, while the top of the packing in a packed column was approximately 30 mm under the cap (Figs. 6.3 and 6.4). The effect of this difference on NTU and K_La is not known, but it was believed to be negligible. The effect of the packing layer on the empty column gas pressure drop values was certainly more important.

With respect to flow conditions in the effluent section of the packed column, it is worth noting that as the level of the water seal was determined by the setting of the effluent flow rate control valve (Section 4.3.1; Figs. 4.5 and 4.8), this level varied. This variation, however, was kept within 30 mm of the bottom of the section (that was 152.4 mm long), and as the removal in this section was expected to be low in any case (little contact area between gas and liquid, and low driving force since the water was already partly

Figure 6.3: Flow pattern in an empty column

Figure 6.4: Flow pattern above packing, in a packed column

Figure 6.5: Flow pattern below packing, in a packed column

"treated"), the effect of this variation was expected to be negligible.

6.3.1.5 Flow Rates and Temperatures

As mentioned in Section 4.3.4, the flow rate of the concentrated organic solution pumped in the influent pipe had to be readjusted every 10 minutes, since it kept decreasing. Tiny air bubbles that accumulated at the discharge side of the pump, before the rotameter, are thought to have caused the decrease. These bubbles may have resulted from a gas leak in the system, but the Teflon® tubing had to be heated to fit over the glass elbows and the pump and rotameter fittings, and no leak was expected. The bubbles more likely come from an air bubble trapped between the Teflon® resin stopcock and organics solution bag, and from which the small bubbles would have been dragged throughout the run; this explanation is supported by the observation of tiny air bubbles all along the Teflon® tubing between the bag and the pump. Regardless of what may have caused the problem, the flow readjustments kept the influent organics concentrations fairly constant. Appendix D shows that coefficients of variation were usually below 3% for influent concentrations, and below 5% for effluent concentrations. Roberts et al. (1982) considered a coefficient of variation of 10% or less to be an acceptable indication of steady state. Therefore it appears reasonable to assume steady state was reached.

The flow rate of air to the packed column was read and adjusted at the beginning of each run. The gas flow rate was difficult to read, as the centre of the float had to be read. But a hand level eliminated most parallax errors, and since the rotameter's scale was linear, the readings at the top and bottom of the float were averaged. Readings were always around the middle third of the scale (between 30 and 60 on a scale of 0 to 100), which is desirable since rotameters are usually more accurate for mid-scale readings.

Adjustment of the gas flow rates from a gate valve on the compressor's tank was difficult to achieve, and flow rates did vary slightly from one experiment to the next. The variation for a given packing and flow condition was so small (coefficients of variation $\leq 1.2\%$; Table 5.14) that its effect was assumed negligible.

The flow rate of the influent liquid to the packed column also varied. Small air bubbles (5 mm or less in diameter) were sometimes seen in the influent Plexiglas® pipe (19 mm in diameter); they probably came from cavitation at the influent flow rate control gate valve. Because of their small size and number, it was assumed the bubbles would be rapidly saturated with organics, and that they would not affect the liquid flow rate.

The liquid flow rate did decrease, however, probably due to wearing of the machine screw used to stop the influent flow rate control gate valve at a certain opening (Section 4.3.1). As explained in Section 5.3.2.2, the flow

rate variation could not be assessed for the experimental runs with 6.35 mm Raschig rings. These runs were performed with a steel machine screw in the valve and the wearing of the screw, and thus the flow variation, were probably minimal. For the 12.7 mm Raschig rings and Intalox® saddles, the flow rate was assumed to decrease linearly for each run (Section 5.3.2.2). The validity of this assumption is not known, but in view of the small flow rates decrease, this assumption seems reasonable. Since the coefficients of variation were always less than or equal to 1.2% (Table 5.15), liquid flow rate variations were considered negligible.

As described in Section 5.3.3, the effluent water temperature was measured in an aerated basin, and the possible difference in temperature caused by aeration was estimated after all experimental runs were made. Besides liquid flow rate, the temperature change caused by aeration depended on: the water and air temperatures and the relative humidity of air, all of which were not controllable beyond a certain extent; and, the rate of aeration, fixed by eye. Thus the temperature change for given experimental conditions could not be determined with certainty. Since the estimated effluent water temperature change caused an NTU decrease of less than 0.5%, it was considered reasonable to use the uncorrected effluent water temperature.

The liquid temperature varied within a run, as well as from one run to another. Within a run, the influent and ef-

fluent water temperatures increased by 0.1 to 0.5°C in the hour that separated the measurements (temperatures were measured before and after sampling). The effluent water temperature was lower than the influent temperature, but generally by less than 1°C. Since the air was not humidified, evaporation was probably the cause of this temperature drop. These variations being small, it was considered adequate to use the average water temperature (average of influent and effluent water temperatures) in other computations.

For the same packing and flow conditions (e.g., Runs 18, 20, 24, and 27) the maximum difference of average water temperatures (e.g., between Runs 18 and 20) was below 2.6°C for 6.35 mm Raschig rings and 12.7 mm Intalox® saddles, and below 1°C for 12.7 mm Raschig rings (Table 5.16). These differences being small, their effect was assumed to be negligible.

The plots of NTUT against Z (Appendix F) showed no apparent relation between NTUT and average water temperatures, gas flow rates, liquid flow rates, or a combination of these. Since the temperature and flow rate variations were small, the fact that no trend or link could be seen does not mean that there was no relation, but merely that other factors had a more significant influence on NTUT.

6.3.1.6 Concentrations

As stated in Section 4.3.2, the concentrations of some organics in the stock solution had to be increased signifi-

cantly between runs performed at 1.219 m and runs performed at 1.524 m of packed depth, both during the 12.7 mm Raschig rings and Intalox® saddles experiments (Table 4.7). On the plots of NTUT against Z (Appendix F), no variation of NTUT consistent with concentration variation could be observed. For Intalox® saddles at medium flow rates, the data for chloroform, 1,2-dichloroethane, and ether, whose concentrations were not changed throughout the runs, were more linear (i.e., narrower confidence interval, higher r^2 value) than the other compound's data; but the plots for the other compounds at this flow rate did not show NTUT variations that could be associated with concentration variations, and no similar situation was observed at the other flow conditions.

It thus appears that influent organic concentrations did not have a significant influence on NTU. Consequently, results of this work should be applicable to Gloucester's landfill leachate and surrounding groundwater even though the organics concentrations used were different; the difference in water composition, however, may cause discrepancies.

6.3.2 Number of Transfer Units

6.3.2.1 Empty Column NTUC

As explained in Section 5.3.6.1, the empty column NTUC values were obtained at slightly lower liquid flow rates than those at which packed column experiments were performed. Eq. (5.17), similar to an equation of Roberts et al. (1982), was then used to determine NTUC at the desired flow

rates (Table 5.18). Roberts et al.'s (1982) quadratic equation was derived for the case of constant gas flow rate and water temperature (such terms were not included in the equation), and was used here for varying Q_g and T . Since the liquid flow rate deviations were small, the changes in NTUC suggested by Eq. 5.17 were also small, and it was assumed that the effect of Q_g and T would be negligible.

Table 5.18 also shows that at all three flow conditions, empty column NTUC values of trichloroethylene and 1,1-dichloroethane were close to each other; a similar situation was observed for toluene and chloroform at high and medium liquid flow rates, but never for NTUC values extrapolated from NTUT vs Z plots (Table 5.20). The empty column NTUC value for chloroform at low liquid flow rate (Run 30) appeared to be higher than it should be. And the coefficient of variation of the effluent concentration of chloroform for Run 30 was 15.6%, twice the value observed in any other run (Appendix D); this pointed to an isolated error, and toluene and chloroform NTUC values would probably have been close to each other if this error had not occurred.

6.3.2.2 Comparison of NTUC Values

The empty column NTUC values were always below the NTUC values extrapolated from 12.7 mm Raschig rings data and above the NTUC values extrapolated from 12.7 mm Intalox® saddles data, except for chloroform at medium and low liquid flow rates where the empty column NTUC was larger than both

extrapolated NTUC (Appendix F). Empty column NTUC were also usually within the 95% confidence interval limits of both extrapolated NTUC. For chloroform, 1,2-dichloroethane, and ether at medium flow conditions, however, Intalox® saddles experimental data was very linear and the corresponding confidence interval, very narrow, did not include the empty column NTUC value.

The extrapolated NTUC values of 1,1-dichloroethane, chloroform, 1,2-dichloroethane, and ether for Intalox® saddles, at high and medium liquid flows, were negative; NTUC values of chloroform and ether at low liquid flow, still for Intalox® saddles, were also negative. Negative NTUC values mean that organics from the air were dissolved in the water above or below the packing. However, since the air compressor was located in a separate room where the organics were only stored in sealed containers, it is believed that the air was free of organics. The large ratio of air to water flow also suggests that air above the packing was probably not saturated with organics. The negative NTUC values being small (below 10% of the lowest NTUC observed) they may have been caused by small errors in a few NTUC values.

The lack of agreement between NTUC values extrapolated from 12.7 mm Raschig rings and from Intalox® saddles data under similar test conditions, and the negative NTUC values extrapolated from some Intalox® saddles data suggested, as stated earlier by Roberts et al. (1982; 1985), that the flow conditions above and below the packing were too different.

from the plug flow observed in the packing, and that extrapolation from NTUT vs Z plots was not a suitable method of assessing NTUC (Section 2.8). The empty column NTUC values were thus used in further computations.

6.3.2.3 Selected NTUC

Since no empty column tests were performed at flow conditions similar to those for the 6.35 mm Raschig rings experiments, the NTUC values extrapolated from NTUT vs Z plots were used. The coefficient of determination, r^2 , values for 6.35 mm Raschig rings data were similar to r^2 values for the other two packings (Table 5.19), but as only three packing depths were investigated instead of four, the confidence intervals were much broader and the NTUC values correspondingly less reliable.

The empty column NTUC values were obtained from one experimental run only at each flow condition, and were accordingly uncertain. In all cases, however, the empty column NTUC values were below 15% of the corresponding NTUT values; they were thus low enough that an error in the NTUC value would have a relatively small effect on the NTUN values obtained by Eq. (2.50).

As mentioned in Section 5.3.9, the mass transfer rate constants, $K_L a$, were computed for each experimental run using NTUN (Eq. 2.50) instead of NTU. The NTUC values used to compute NTUN were generally found at flow rates and temperatures different from those at which NTUT was measured.

Roberts et al. (1982) developed from their data empirical correlations relating NTUC to Q_G and T at constant Q_L , or to Q_L at constant Q_G and T . These correlations were specific to their experimental conditions. The amount of NTUC data available for this work was too small to derive such correlations. The effect of these variables was, however, believed to be small (Section 6.3.1.5).

6.3.3 Gas Pressure Drops

6.3.3.1 Correction for End Effects

Table 5.21 shows that empty column Δp_{oc} values and Δp_{oc} values obtained by extrapolation from Δp_G vs Z data for 12.7 mm Raschig rings and Intalox® saddles differed by 30 to 50%, at similar flow conditions. Even extrapolated values were different for the two packings at each set of flow conditions. This suggested that pressure drops out of the packing were caused by mechanisms different from those causing pressure drops in the packing, and that the two pressure drops were not additive. The empty column Δp_{oc} would thus be theoretically better; however, because of the possible pressure drop across the shallow packing layer present in the empty column, and because only one empty column run was performed at each flow condition, the extrapolated Δp_{oc} values could be just as close to the true Δp_{oc} . Extrapolated Δp_{oc} values were used in computations.

The coefficients of determination for Δp_{or} vs Z data (Table 5.22), and the coefficients of variation for pressure

drop per unit depth, $\Delta p_o/Z$, data (Table 5.23), were good for 12.7 mm Raschig rings, but not as good for 12.7 mm Intalox® saddles, and even worse for 6.35 mm Raschig rings. However, Δp_o and $\Delta p_o/Z$ values for 12.7 mm Intalox® saddles were much lower than for 12.7 mm Raschig rings; thus a small absolute error, on a relative scale, was much larger for Intalox® saddles. It can be noted that standard deviation values for 12.7 mm Raschig rings and Intalox® saddles were close. For 6.35 mm Raschig rings, flow conditions were very close to the flooding limit (Fig. 2.4), and many factors, such as liquid accumulation, may have affected the pressure drop values. The Δp_{oc} and $\Delta p_o/Z$ values were thus expected to be more reliable for 12.7 mm Raschig rings and Intalox® saddles than for 6.35 mm Raschig rings.

6.3.3.2 Gas Pressure Drop per Unit Depth

The average experimental $\Delta p_o/Z$ values were all between 65 and 95% of the values predicted by Fig. 2.4. Roberts et al. (1982), on the other hand, reported measured pressure drops of 6.5 to 47 mm of water, while drops below 2 mm of water were expected; they attributed their high pressure drops to the effort put into achieving uniform packing. The low $\Delta p_o/Z$ values of this study may be partly due to the liquid channeling, and partly to the fact that no effort was made to achieve uniform packing. Each column section was packed "wet" (Section 4.3.2), and if a large void was detected, the section was emptied and repacked completely;

this yielded porosities close to literature dry bed porosities (Table 5.27).

It is not known what caused the $\Delta p_0/Z$ values to be so low. A direct measurement of pressure drop across the packing would have been preferable to estimation of Δp_{ac} , if it had been possible (it was impossible since water would have plugged the manometer taps). The good porosity values and the low but reasonable $\Delta p_0/Z$ values were taken as an indication that flow conditions and packing characteristics of the column were representative of full scale applications.

6.3.4 Other Parameters and Assumptions

6.3.4.1 Liquid Composition and Volatility Range of Organics

The pH and conductivity of the influent and effluent water were recorded as indicators of the composition of the background water throughout all the runs. The low coefficient of variation values, 1.0 and 2.2% for pH and conductivity (Table 5.17) respectively, were interpreted as indications that the background water composition was basically constant.

The six compounds studied covered a wide range of volatilities (Tables 4.1 and 5.3). Even if the data for chloroform and ether are excluded from computations, the Henry's law constants of the other compounds cover 75% of a logarithmic cycle.

6.3.4.2 Isothermal Operation

The procedure applied to compute mass transfer rate constants assumes no heat transfer to or from the column's surroundings. Since the water used was pumped from a tank where it had stayed for over a day, the water and room temperature were close to one another (Appendix D). The assumption of isothermal operation was then justified.

6.3.4.3 Mass Transfer Rate Constants

The coefficients of variation of K_La values at different depths, for the same flow conditions and packings, shown in Tables 5.24 to 5.26, were never above 7.6%. A little variation could be expected as Q_G , Q_L and T varied from run to run (Tables 5.14 to 5.16). These low values of coefficients of variation indicate the consistency of the data.

6.4 Mass Transfer Rate Constant Models

6.4.1 Application of Models

6.4.1.1 Applicability of Models

Based on a review of existing K_La correlation models (Roberts et al., 1982), Roberts et al. (1985) stated that the models of Onda et al. (1968), Sherwood and Holloway (1940), and Shulman et al. (1955c), were potentially useful for predicting mass transfer in the case of air stripping of volatile organics from water. These three models were the

logical choice for further study of volatile organics air stripping.

The models of Sherwood and Holloway (1940) and Shulman et al. (1955c) could be applied, in this work, to 12.7 mm Raschig rings only, since the values of some constants were not available for the other packings (Table 5.27); for Shulman et al.'s (1955c) model, graphs of effective interfacial area against gas and liquid mass flux also were available for 12.7 mm Raschig rings but not for 6.35 mm Raschig rings or for Intalox® saddles. Onda et al.'s (1968) model could be and was applied to both sizes of Raschig rings. The wetted specific surface area, a_w , formula was derived for Raschig rings, Berl saddles, spheres, and rods made of various materials (Section 2.6.4), but was also applied to Intalox® saddles in this study; this could be done because Onda et al.'s (1968) model's only packing related parameters are a_t , d_p , and σ_c , which are readily available for most commercially available packings.

Liquid and gas loading rates used in this study were in the range $2.5 < L < 4 \text{ kg/m}^2\text{-s}$ and $0.25 < G < 0.5 \text{ kg/m}^2\text{-s}$. These are well within the ranges of loading rates in which the three models were developed and for which they are applicable (Table 2.2). The location of experimental conditions on Fig. 2.4 is an indication that these loading rates are in the range of full scale applications loading rates.

6.4.1.2 Constants

Since the principal objective of this work was to find out which of the three models would yield the best predictions, and not how one could modify the models to make them more suitable for volatile organics air stripping studies, the values of α and n given by Sherwood and Holloway (1940) were used without modification.

For the model of Shulman et al. (1955c), the graphs available in the original papers for the determination of effective interfacial area, a , and of total holdup, ϕ_t , were very small, and plotted on logarithmic coordinates, which made them difficult to read. The correlation formulae for a and ϕ_t , given by Treybal (1980), being easy to apply with a calculator or computer, were used. The values of a and ϕ_t obtained from the correlations, for 12.7 mm Raschig rings, did match those found on the graphs; thus, predicted mass transfer rate constants will not have been affected by the use of the correlations. Since the average water temperatures were close to 20°C, the corrections suggested by Shulman et al. (1955a) for departure of liquid viscosity, density, and surface tension, from those of water at 20°C were found to be negligible.

When applying the model of Onda et al. (1968), it was found that total specific surface area, a_t , values were different from one publication to the next; the values of a_t of Ludwig (1979) were used, since they had been updated in 1978. The model was not modified, but as recommended by

Onda et al. (1968) for packing smaller than 15 mm, 2.0 was used instead of 5.23 as a constant in the k_G formula. The model was also applied to 12.7 mm Intalox® saddles even though the a_w formula was derived from data that did not include that packing type.

6.4.1.3 Densities, Viscosities, and Surface Tension

The correlation formulae of Heggen (1983), used to compute water density, viscosity, and surface tension at experimental temperatures, were derived from large data bases, and the coefficients of determination were good (above 0.9998) in all cases. These formulae are believed to be accurate enough for the purposes for which they are applied here.

Weast (1977) does not give any statistical information about the dry air density correlation formula, which is expected to be very accurate. Since the wet bulb temperature of the air was not measured, its relative humidity was not known, and it was assumed to be dry. The difference between dry and moist air density is small, and the compressed air is not expected to be saturated with water; therefore, dry air density should be a good approximation.

The air viscosity correlation formula perfectly fit the four data points used to derive it (Section 5.4.1.4). The coefficient of determination was 1.0. The effect of small deviations from standard atmospheric pressure on air viscosity was assumed to be negligible.

6.4.1.4 Diffusion Coefficients

The equation of Hayduk and Laudie (1974) was used to compute diffusion coefficients in water, D_L . Tucker and Nelken (1982) recommended this method, stating that it was easier to apply; it was comparable or superior to other methods in terms of input parameters, accuracy, and general applicability to a wide range of compounds; and, because it was validated by a more recently compiled data base. Reid et al. (1977) also recommended Hayduk and Laudie's formula, while Munz and Roberts (1982) used Wilke and Chang's (1955) equation because it involved less empiricism.

To estimate diffusion coefficients in air, D_a , Tucker and Nelken (1982) stated that the Wilke and Lee (1955) method was slightly more accurate for most compounds, and should be used for polar acids and glycols, but that the Fuller, Schettler, and Giddings (1966) method gave better estimates for halogen hydrocarbons. Reid et al. (1977) recommended the method of Fuller, Schettler, and Giddings (1966) for simple, nonpolar systems at moderate temperatures, and the method of Brokaw (1969) for systems containing polar components. They noted that their comparisons (Table 11-2, Reid et al., 1977) showed the Fuller, Schettler, and Giddings (1966) equation yielded slightly better estimations than the Brokaw (1969) or Wilke and Lee (1955) methods. Since the method of Fuller, Schettler, and Gid-

dings (1966) was also easier to apply than the others, it was selected to compute D_0 in this work.

6.4.1.5 Statistical Parameters

Besides the coefficient of determination, the standard error of estimate, SEE, was used to quantify the amount of error involved in the predictions (Section 5.4.2). The term $N-2$ was used as denominator when computing SEE [Eq. (5.32)] to insure an unbiased estimate (Roscoe, 1969); similarly, $N-1$ was used when computing the standard deviation [Eq. (5.7)]. It should be noted that the SEE implies the assumptions that prediction errors are normally distributed, and that they are equally distributed along the range of values (Roscoe, 1969).

6.4.2 Performance of Models

If the correlation was perfect, then:

$$K_{La\text{pred}} = K_{La\text{obsd}} \quad (6.2)$$

or

$$\log_{10} K_{La\text{pred}} = 0.0 + 1.0 \log_{10} K_{La\text{obsd}} \quad (6.3)$$

If channeling in the column is important, the experimental (observed) K_{La} value may be lower than it would be if there was no channeling. However, the predicted K_{La} will not decrease unless some of the experimental conditions are modified to represent the effects of channeling (e.g., lower contact area). It can thus be expected, because of channeling, that observed K_{La} will be lower than predicted K_{La} .

6.4.2.1 Models Performance for All Compounds

To assess the performance of the three models for all compounds, the regression equations, r^2 , and SEE values given in Table 5.35 for 12.7 mm Raschig rings data from all six organics can be compared. It can be seen that the r^2 value for Onda et al.'s (1968) model was slightly lower than r^2 for Shulman et al.'s (1955c) model; however, the regression equation for Onda et al.'s (1968) model was the best of all three, its intercept being closer to zero and slope closer to one.

If r^2 is related to the regression equation, SEE, on the other hand, is related to the 45° line defined by Eq. (6.2); if all points were on the regression line, $r^2 = 1.0$, but if all points were on the 45° line, then $SEE = 0.0$. SEE estimates the amount of error involved in the prediction, as stated earlier (Section 6.4.1.5). The lowest SEE value was computed for Onda et al.'s (1968) model, followed by Sherwood and Holloway's (1940) model. Shulman et al.'s (1955c) model yielded an SEE value slightly higher than the Sherwood and Holloway (1940) SEE, but Shulman's regression equation and r^2 value were better.

The plots of predicted against observed mass transfer rate constants (Figs. 5.29 to 5.31) can help to interpret these values. Thus, Sherwood and Holloway's (1940) model gave a lower SEE value than Shulman et al.'s (1955c) model, and it can be seen that some data points on Sherwood and

Holloway's plot were closer to the 45° line than any point on Shulman's plot. Shulman's data, however, were not as scattered, resulting in a higher r^2 value. Onda et al.'s (1968) data were not as tightly grouped as Shulman et al.'s (1955c) data, but the grouping was better than for Sherwood and Holloway's (1940) data; the r^2 values varied accordingly.

It can be observed (Fig. 5.30) that the Sherwood and Holloway (1940) model predicted very similar K_{La} values for given flow conditions in cases where observed K_{La} values were very different; it even predicted the same values for 1,1-dichloroethane and 1,2-dichloroethane at given experimental conditions (Table 5.32). This is so because for all three models used, the only compound dependent variables in the k_L or k_g expressions were D_L and D_g , raised to the power 1/2 or 2/3, respectively; D_L and D_g do not distinguish between isomers, whose molar volumes are assumed to be the same (Table 5.29). In the Onda et al. (1968) and Shulman et al. (1955c) models, the addition of k_L and k_g to obtain K_{La} involved Henry's law constants, whose values were different for 1,1-dichloroethane and 1,2-dichloroethane, yielding different K_{La} values. The Sherwood and Holloway (1940) model, however, yields K_{La} directly. Roberts et al. (1985) also noted that the Sherwood and Holloway (1940) model gave the same K_{La} values for different observed values.

Fig. 5.31 shows that Shulman et al.'s (1955c) model predicted similar K_{La} values for a compound at all flow con-

ditions; the range of predicted K_La values for each compound is much smaller than the corresponding range for the other two models. Roberts et al. (1982) noted that Shulman et al.'s (1955c) model underpredicted low K_La values and overpredicted high values; Fig. 5.31 is in the range of Roberts et al.'s (1982) high values, and the model does overpredict K_La .

Onda et al.'s (1968) model gave results that were not as tightly grouped as those of Shulman et al.'s (1955c) model, but that were spread more evenly around the 45° line (Fig. 5.29). The values it predicted for one compound or for one flow condition were not as close to one another as for the other models.

The above analysis tends to suggest that Onda et al.'s (1968) model is better to predict K_La for volatile organics air stripping.

6.4.2.2. Exclusion of Chloroform and Ether Data

Since the integration of the ether peak interfered with that of the chloroform peak (Section 6.1.2), and the empty column NTUC value of chloroform at low liquid flow rate was suspicious (Section 6.3.2.1), the data for chloroform and ether could not be considered as reliable as data for the other four compounds.

Table 5.35 shows the regression equations, r^2 , and SEE values obtained for 12.7 mm Raschig rings when the chloroform and ether data are excluded. Shulman et al.'s (1955c)

regression equation did not change much, but its r^2 value dropped; however, its SEE value also decreased, showing that the deleted data was farther away from the 45° line than the remaining data. Sherwood and Holloway's (1940) model had its regression equation improved, its r^2 increased, and its SEE decreased; but the r^2 value is still very low. Onda et al.'s (1968) regression equation became almost perfect ($t = -0.0012 \approx 0.0$; $s = 0.9929 \approx 1.0$); its r^2 value slightly increased, becoming greater than Shulman's r^2 , while the SEE value was also improved.

It is clear in that case that Onda et al.'s (1968) model performed much better than the other two models.

6.4.2.3 Summary

Of the three models considered, that of Onda et al. (1968) performed best in all cases studied. For the most volatile compounds (trichloroethylene, 1,1-dichloroethane, toluene, and chloroform), predictions of the Sherwood and Holloway (1940) model may be suitable for design purposes under conditions similar to those studied here (Fig. 5.30). The model of Shulman et al. (1955c), however, overpredicted K_{La} values for all compounds.

6.4.3 Application of Onda's Model to Other Packings

Since Onda et al.'s (1968) model was the best for 12.7 mm Raschig rings, its performance for other packings should be examined.

The data for 6.35 mm Raschig rings were not as reliable as the data for the other two packings, because flow conditions for these experiments were near the column's flooding limits, and because NTUC values had to be extrapolated from NTUT vs Z plots with three data points only (Section 6.3.2.3). The resulting regression was not as good as that for 12.7 mm Raschig rings (Table 5.35); excluding chloroform and ether data slightly improved the SEE value and the regression equation, but the r^2 value also decreased slightly.

The performance of the model of Onda et al. (1968) for 6.35 mm Raschig rings was comparable to that of the model of Shulman et al. (1955c) for 12.7 mm Raschig rings; however, Fig. 5.28 shows the data to be spread more evenly than in the case of Shulman et al.'s (1955c) model.

For 12.7 mm Intalox® saddles, neglecting the chloroform and ether data improved the SEE value; the r^2 value, that was already very high, decreased slightly. The regression equation obtained was halfway between the equation for Onda et al.'s (1968) model and that for Shulman et al.'s (1955c) model for 12.7 mm Raschig rings data, while the SEE was halfway between that of Sherwood and Holloway's (1940) and that of Onda et al.'s (1968) models, which is still very low. Fig. 5.32 shows that the data were more tightly grouped than the 12.7 mm Raschig rings data, as could be expected from the high r^2 value, but that all values but one were moderately overpredicted. Still the low SEE and high r^2 values indicated the model's prediction may be suitable

for design, even though the formula for a_w was not derived for Intalox® saddles (Section 6.4.1.1).

6.4.4 Comparison to Literature Results

If the results obtained for 12.7 mm Raschig rings when chloroform and ether data were excluded (Table 5.35) are compared to the results Roberts et al. (1985) obtained for 12.7 mm Berl saddles (Table 5.36), it can be seen that in both cases, r^2 was the smallest for the Sherwood and Holloway (1940) model while SEE was the largest for the model of Shulman et al. (1955c). The model of Onda et al. (1968) had the largest r^2 and the smallest SEE value.

In terms of numbers, the r^2 values of Table 5.35 were smaller than those of Roberts et al. (1982); however, the regression equation for Onda et al.'s (1968) model was better than that of Roberts et al. (1982). The SEE values of this work also were better than those of Table 5.36, for all models. Thus, for the model of Onda et al. (1968), Roberts et al. (1985) determined that 68% of the predicted $K_L a$ values lied within a factor of $10^{0.0042} = 1.21$ of the observed values; in this work, 68% of the predicted $K_L a$ values lied within a factor of $10^{0.0224} = 1.05$ of the observed values for Raschig rings. For Intalox® saddles, 68% of the predicted values lied within a factor of 1.11 of the observed values.

The discrepancy between the results of Roberts et al. (1985) and those of this work may be due partly to the gas

and liquid flow rates selected, which kept the stripping factor above 3 while the loading rates were within the range of loading rates for which the correlations were derived. In addition to that, the K_{La} values of this work only covered approximately three tenths (0.3) of a log cycle, while the data of Roberts et al. (1985) covered 1.45 log cycles.

6.4.5 Mass Transfer Rate Constants and Flow Rates

As described in Section 5.4.2, average Q_L and Q_G values were plotted on logarithmic axes against average K_{La} values on the figures in Appendix H. The data points were connected by straight lines, and no attempt was made to represent any relationship by these lines.

As the liquid flow rate, Q_L , decreased, the gas flow rate, Q_G , increased; one was not kept constant as the other changed. Thus, variations of K_{La} as Q_G changed for highly volatile compounds were in fact caused mainly by the Q_L variation occurring simultaneously with Q_G variation. The K_{La} values decrease with increasing Q_G values, observed on plots of 12.7 mm Raschig rings or Intalox® saddles data also can be explained by Q_L variations; constant or increasing K_{La} values would be expected with increasing Q_G values, but the decrease in Q_L simultaneous to Q_G increase caused the K_{La} values to decrease.

The 12.7 mm Raschig rings data plots show that the model of Onda et al. (1968) predictions were closest to observed K_{La} values; predicted values were especially close to

observed values for 1,1-dichloroethane, toluene and trichloroethylene (high H values). For these three compounds, and for chloroform, the predictions of Sherwood and Holloway's (1940) model were closer to observed values than the predictions of Shulman et al.'s (1955c) model. For the two least volatile compounds, Shulman's predictions were closer to observed values than predictions of the model of Sherwood and Holloway (1940) at medium and at high liquid flows (medium and low gas flows, respectively), certainly because of the increasing importance of the gas phase resistance to mass transfer.

Plots of the 12.7 mm Intalox® saddles data show that predictions of the Onda et al. (1968) model were not as close to observed K_La values as for 12.7 mm Raschig rings, but that they were still acceptable. For 6.35 mm Raschig rings data, Onda et al.'s (1968) model did not predict the observed lower K_La value at medium liquid and gas flow rates; errors in the NTUC values at these flow rates (NTUC were extrapolated for 6.35 mm Raschig rings; see Table 5.20) may explain this drop in K_La values.

6.4.6 Required Packing Depth Ratios

The values of required packing depth ratios given in Table 5.37 apply only to the specific case described in Appendix I. Some general conclusions can still be reached from these values. Thus, Onda et al.'s (1968) model predictions were good for all compounds, while, as could be ex-

pected, predictions of the Sherwood and Holloway (1940) model were good for highly volatile compounds (i.e., trichloroethylene), but not so good for low volatility compounds (i.e., 1,2-dichloroethane); the model of Shulman et al. (1955c) predicted $K_L a$ values with an error such that required Z were always 20% less than Z computed from observed $K_L a$ values, for high as well as for low volatility compounds.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

From this study, the following conclusions were reached:

1. The correction for end effects to be applied to the number of transfer units (and to the gas pressure drop) must be obtained from tests performed in the column without packing material; extrapolation to a packing depth of zero of data collected at various packing depths will not give accurate correction values, even at high stripping factor (S) values.
2. The mass transfer rate constant correlation model of Onda et al. (1968) gives better estimates of K_La than the models of Sherwood and Holloway (1940) or Shulman et al. (1955c), at gas and liquid loading rates typical of full scale applications (Table 5.35, and Figs. 5.29 to 5.31).
3. The model of Onda et al. (1968) gave good estimates of K_La for Intalox® saddles (12.7 mm), a packing type for which it has not been derived; these results suggest that it is possible that this model can be applied to other packing types for which it was not initially derived.

4. The model of Sherwood and Holloway (1940) may give K_La estimates suitable for design purposes, for highly volatile compounds, in specific conditions (stripping factor $S > 10$ to 15).
5. The model of Shulman et al. (1955c) should not be used to estimate K_La in volatile organics air stripping; it overpredicts high K_La values, and is reported to underpredict low values (Roberts et al., 1982).

7.2 Improvements

Improvements that could be made to this study are listed below:

1. Organics analysis:

All compounds of interest should be neatly separated on the chromatograms, so that no integration interference occurs.

2. Henry's law constants:

- i. Use larger gas tight syringes (100 ml), and different syringe valves, to increase accuracy of determination and minimize losses.
- ii. Another closed system method of determination should be used to increase accuracy of detection [the "Multiple Equilibrations technique" may be appropriate, depending on the results of Munz (1985; Section 3.1.2.3)].

3. Channeling:

- i. To reduce the amount of channeling, the column to packing diameter ratio should be increased, and the distributor cap should be changed so that the water jets coming from it go straight down into the packing.
- ii. A tracer test should be performed to give an indication of the amount of channeling.

4. End effects:

A packing support plate (gas-injection weir-type) should be used at the bottom of the column, to facilitate reproduction of the packed column flow conditions in the "empty column" tests.

5. Flow rates:

- i. The tube extending from the volatile organics stock solution bag to the Teflon resin stopcock should be filled with liquid before every experimental run, to help obtain a constant stock solution flow rate.
- ii. A flow meter should be used to monitor the column's influent liquid flow rate, which could be readjusted with the gate valve.

6. Temperatures:

The effluent water temperature should be measured before the aerated effluent basins, to avoid the temperature change caused by aeration.

7. Air:

The compressed air should be saturated with water before reaching the packed column, resulting in less evaporation of the liquid in the packed column.

8. Correction for end effects:

Empty column NTUC values should be obtained at many flow and temperature conditions, and empirical correlations between NTUC and Q_G , Q_L , and T should be developed, so that NTUC can be known at any experimental conditions.

9. Mass transfer rate constants range:

Different gas and liquid loading rates, still in the range of typical full scale applications values, should be used so that the mass transfer rate constant values cover a wider range.

10. System check:

Effluent packed column air samples should be collected, to allow a mass balance of the system to be made.

7.3 Recommendations

Future research could look into these topics:

1. Henry's law constants:

Experimental investigation of the effects of solute concentration and of concentration of methanol on the Henry's law constants.

2. Packed column air stripping:

- i. Application of the model of Onda et al. (1968) to data gathered from full scale packed towers used for volatile organics air stripping.
- ii. Application of the model of Onda et al. (1968) to packings larger than 15 mm, such that the original form of Eq. (2.39) (with 5.23 as a constant) may be used.
- iii. Application of the model of Onda et al. (1968) to other packings for which it was not initially derived.

APPENDIX A

EXPERIMENTAL DETERMINATION OF HENRY'S LAW CONSTANTS

The experimental data and results of first calculations for Henry's law constants determination are presented in the tables following this sample calculation.

Table 4.1 lists the abbreviations used in the table headings.

A.1 Sample Calculation

Note: since concentration ratios are always used, the concentrations in $\mu\text{g/l}$ were not converted to kg/m^3 .

For syringe no. 1 and 1,1-dichloroethane, at 19.9°C :

Losses:

initial concentration ($\mu\text{g/l}$) $C_{L0} = 1366.3$

concentration after
one day ($\mu\text{g/l}$) $C_{L1} = 1315.3$

ratio $\frac{C_{L1}}{C_{L0}} = \frac{1315.3}{1366.3} = 0.96267$

Henry's law constants:

initial concentration ($\mu\text{g/l}$) $C_{L0} = 1313.7$

equivalent initial concentration accounting for
losses of a day ($\mu\text{g/l}$) $C_{L1} = 1313.7 \times 0.96267$
 $= 1264.7$

Equilibrium concentration
($\mu\text{g/l}$) $C_L = 1112.2$

Henry's law constant (-) $H = \frac{1264.7}{1112.2} - 1 = 0.137$

Table A.1:

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LOSSES IN SYRINGES, 19.9°C

Syringe	Parameter	1,1-DCA	Ether	CHCl ₃	1,2-DCA	TCE	Toluene
1	C _{LO}	1366.3	904.81	7557.4	1466.3	1829.3	1589.1
	C _{L1}	1315.3	858.58	7286.5	1383.1	1640.8	1467.3
	C _{L1} /C _{LO}	0.96267	0.94891	0.96415	0.94326	0.89700	0.92335
2	C _{LO}	1374.3	902.75	7597.9	1468.6	1840.3	1485.9
	C _{L1}	1294.8	845.34	7174.6	1360.0	1615.6	1344.6
	C _{L1} /C _{LO}	0.94215	0.93641	0.94429	0.91484	0.87790	0.90491
R1	C _{LO}	1356.2	897.39	7491.2	1458.4	1840.6	1440.5
	C _{L1}	1285.8	842.45	7143.9	1357.2	1629.7	1312.4
	C _{L1} /C _{LO}	0.94809	0.93878	0.95364	0.93061	0.88542	0.91107
R2	C _{LO}	1343.6	880.30	7424.1	1437.2	1819.9	1409.8
	C _{L1}	1324.1	867.50	7305.9	1409.1	1673.4	1335.2
	C _{L1} /C _{LO}	0.98549	0.98546	0.98408	0.98045	0.91950	0.94708
3	C _{LO}	1384.0	914.97	7638.1	1483.5	1856.3	1494.0
	C _{L1}	1277.8	836.55	7070.8	1344.2	1578.7	1317.7
	C _{L1} /C _{LO}	0.92327	0.91429	0.92573	0.90610	0.85046	0.88199
4	C _{LO}	1401.6	919.48	7740.6	1496.4	1875.1	1498.1
	C _{L1}	1300.6	847.43	7203.0	1365.2	1626.0	1335.5
	C _{L1} /C _{LO}	0.92794	0.92164	0.93055	0.91232	0.86715	0.89146
R3	C _{LO}	1348.8	888.74	7453.7	1448.3	1830.5	1399.2
	C _{L1}	1309.9	856.65	7242.8	1395.2	1636.4	1297.7
	C _{L1} /C _{LO}	0.97116	0.96389	0.97171	0.96334	0.89396	0.92746
R4	C _{LO}	1358.0	894.42	7494.7	1456.5	1840.9	1434.6
	C _{L1}	1288.7	841.79	7160.7	1357.8	1628.9	1307.4
	C _{L1} /C _{LO}	0.94897	0.94116	0.95544	0.93223	0.88484	0.91133

HENRY'S LAW CONSTANTS, 19.9°C

Syringe	Parameter	1,1-DCA	Ether	CHCl ₃	1,2-DCA	TCE	Toluene
1	C _{LO}	1313.7	879.10	7275.6	1422.3	1776.6	1376.7
	C _{L1}	1264.7	834.19	7014.8	1341.6	1593.6	1271.2
	C _L ^E	1112.2	852.23	6526.3	1348.6	1244.9	1095.1
	H	0.137	-0.021*	0.075	-0.005*	0.280	0.161
2	C _{LO}	1353.7	899.17	7483.2	1458.3	1835.9	1403.3
	C _{L1}	1275.4	841.99	7066.3	1334.1	1611.7	1269.9
	C _L ^E	1088.9	830.86	6399.5	1319.2	1225.9	1065.5
	H	0.171	0.013	0.104	0.011	0.315	0.192
R1	C _{LO}	1401.5	918.73	7733.0	1493.8	1882.1	1494.1
	C _{L1}	1328.7	862.49	7374.5	1390.1	1666.4	1361.2
	C _L ^E	1066.4	805.45	6244.8	1280.7	1210.4	1306.7
	H	0.246	0.071	0.181	0.085	0.377	0.042
R2	C _{LO}	1389.5*	908.63	7669.7	1480.2	1862.2	1513.7
	C _{L1}	1369.3	895.42	7547.6	1451.3	1712.3	1433.6
	C _L ^E	1057.8	814.05	6200.7	1286.2	1175.3	-----**
	H	0.294	0.100	0.217	0.128	0.457	-----
3	C _{LO}	1374.4	900.72	7580.8	1468.9	1861.0	1469.7
	C _{L1}	1268.9	823.52	7017.8	1331.0	1582.7	1296.3
	C _L ^E	1077.6	828.32	6331.7	1310.8	1200.7	1081.8
	H	0.178	-0.006*	0.108	0.015	0.318	0.198
4	C _{LO}	1417.1	930.69	7815.4	1516.3	1941.9	1472.7
	C _{L1}	1315.0	857.76	7272.6	1383.4	1683.9	1312.9
	C _L ^E	1048.1	802.99	6164.8	1273.0	1148.9	983.91
	H	0.255	0.068	0.180	0.087	0.466	0.324
R3	C _{LO}	1391.7	913.28	7686.8	1487.2	1864.3	1477.6
	C _{L1}	1351.6	880.30	7469.3	1432.7	1666.6	1370.4
	C _L ^E	1084.8	820.36	6341.1	1304.5	1218.0	1625.0
	H	0.246	0.073	0.178	0.098	0.368	-0.157*
R4	C _{LO}	1378.6	903.46	7612.2	1471.3	1844.9	1458.0
	C _{L1}	1308.3	850.30	7273.0	1371.6	1632.4	1328.7
	C _L ^E	1083.0	820.10	6334.3	1302.4	1216.8	1118.9
	H	0.208	0.037	0.148	0.053	0.342	0.188

* Result physically impossible. All results for the syringe concerned were not used in subsequent computations

** False result due to a malfunction of the integrator. All results for the syringe concerned were not used in subsequent computations

APPENDIX F

NTUT AGAINST Z PLOTS

The following figures are plots of NTUT against Z, along with the best fit line and confidence interval limits for each compound and flow condition. Equations of the best fit line and coefficient of determination values are given on each plot. Empty column NTUC values are also plotted where available.

TRICHLOROETHYLENE

LOW LIQUID FLOW
6.35 MM RASCHIG RINGS

Figure F.1.

1,1-DICHLOROETHANE

Figure F.2

TOLUENE

Figure F.3

CHLOROFORM

Figure F.4

1,2-DICHLOROETHANE

Figure F.5

ETHER

Figure F.6

TRICHLOROETHYLENE

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Figure F.7

Figure F.8

TOLUENE

Figure F.9

CHLOROFORM

366

Figure F.10

1,2-DICHLOROETHANE

MEDIUM LIQUID FLOW
6.35 MM RASCHIG RINGS

Figure F.11

ETHER

Figure F.12

Figure F.13

1,1-DICHLOROETHANE

Figure F.14

TOLUENE

Figure F.15.

CHLOROFORM

Figure F.16

1,2-DICHLOROETHANE

Figure F.17

ETHER

Figure F.18

Figure F.19

Figure F.20

Figure F.21

Figure F-22

Figure F.23

Figure F.24

Figure F.25

Figure F.26

Figure F.27.

Figure F.28

Figure F.29

Figure F.30

Figure F.31

Figure F.32

Figure F.33

Figure F.34

Figure F.35

Figure F.36

APPENDIX G

EXPERIMENTAL AND PREDICTED MASS TRANSFER RATE CONSTANTS

A sample calculation of the experimental mass transfer rate constant, K_{La} , and of the K_{La} values predicted by the models of Onda et al. (1968), Sherwood and Holloway (1940), and Shulman et al. (1955c), is given below. Listings of the Fortran WATFIV programs used to perform the computations for all experimental runs follow the sample calculation.

G.1 Sample Calculation

The calculations for 1,1-dichloroethane and experimental Run 18 are presented in the following sections. Symbols used in the computer programs are also used below.

G.2 Input Data

$$NTUC = NTUC = 0.321$$

$$Z = Z = 0.914 \text{ m}$$

$$Q_L = Q_L = 2.3500 \times 10^{-3} \text{ m}^3/\text{s}$$

$$Q_G = Q_G = 314.50 \times 10^{-3} \text{ m}^3/\text{s}$$

$$TWA = 23.825^\circ\text{C} \text{ (packed column room temperature)}$$

$$TA = 23.475^\circ\text{C} \text{ (liquid's average temperature)}$$

$$P_a = P_B = 762.10 \text{ mm Hg}$$

$$NTUT = NTUT = 2.736$$

6.3 Flow Rates

The liquid and gas flow rates were multiplied by 60000, to convert them to l/min, and for each flow condition (approximately same Q_L and Q_G value, only packing depth differing; e.g., Runs 18, 20, 24, and 27), the average, standard deviation, and standard deviation/average ratio were computed [Eqs. (5.6) and (5.7)]. Similar computations were presented in Appendices C and E.

6.4 Experimental Mass Transfer Rate Constants

The liquid density and mass flux were computed as in Section C.4, yielding:

$$\rho_L = \rho_L = 997.13 \text{ kg/m}^3$$

$$L = L = 2.890 \text{ kg/m}^2 \cdot \text{s}$$

$$\text{From Eq. (2.50): } NTUN = NTUN = 2.736 - 0.321 = 2.415$$

$$\text{From Eqs. (2.16) and (2.22)}$$

$$KLa = KLa = 2.415 \times 2.890 / (997.13 \times 0.914)$$

$$KLa = 7.658 \times 10^{-3} \text{ s}^{-1}$$

6.5 Predicted Mass Transfer Rate Constants

6.5.1 Density, Viscosity, Surface Tension

The parameter σ_L was needed only for Onda et al.'s (1968) model, while Sherwood and Holloway's (1940) model required only ρ_L and μ_L .

From Eq. (5.25)

$$\mu_L = ML = \left[0.20319 + 1.5883 \exp \frac{-23.475^\circ}{22} \right] \times 10^{-3}$$

$$ML = 0.933 \times 10^{-3} \text{ kg/m}\cdot\text{s}$$

From Eq. (5.26)

$$\sigma_L = SL = (20987 - 92.613 \times 23.475) \times 10^{-3}$$

$$SL = 72.199 \times 10^{-3} \text{ kg/s}^2$$

From Eq. (5.27)

$$\rho_G = RG = \frac{1.293}{1 + 0.00367 \times 23.825} \times \frac{762.10}{760}$$

$$RG = 1.192 \text{ kg/m}^3$$

From Eq. (5.28)

$$\mu_G = MG = (1.71 + 0.005 \times 23.825) \times 10^{-3}$$

$$MG = 1.829 \times 10^{-3} \text{ kg/m}\cdot\text{s}$$

G.5.2 Gas Mass Flux, and Henry's Law Constant

From Eq. (5.24): $G = G = 314.50 \times 10^{-3} \times 1.192 / 0.008107$

$$G = 0.462 \text{ kg/m}^2\cdot\text{s}$$

Absolute liquid temperature:

$$T_a = TK = 23.475 + 273.15 = 296.625^\circ\text{K}$$

From Eq. (5.9): $H = H = \exp \left[4.790 - \frac{1851}{296.625} \right] = 0.235$

G.5.3 Diffusion Coefficients

From Eq. (5.29)

$$D_L = DL = \left[\frac{13.26 \times 10^{-3}}{(1000 \times 0.933 \times 10^{-3})^{1.14} (93.6)^{0.009}} \right] \times 10^{-4}$$

$$DL = 0.990 \times 10^{-9} \text{ m}^2/\text{s}$$

Absolute room temperature:

$$T_a = T_{WK} = 23.825 + 273.15 = 296.975^\circ\text{K}$$

From Eq. (5.31)

$$M_R = (28.97 + 98.96) / (28.97 \times 98.96) = 0.045 \text{ mole/g}$$

From Eq. (5.30)

$$D_G = D_G = \left[\frac{10^{-3} \times 296.975^{1.75} \times 0.045^{1/2}}{(762.10 / 760) (20.1^{1/3} + 79.92^{1/3})} \right] \times 10^{-4}$$

$$D_G = 90.653 \times 10^{-7} \text{ m}^2/\text{s}$$

6.5.4 Sherwood and Holloway's Prediction

From Eq. (2.28)

$$Sc_L = \frac{0.933 \times 10^{-3}}{997.13 \times 0.990 \times 10^{-9}} = 945.137$$

From Eq. (2.27)

$$kLa = KLAP = 10.764 \times 280 \times \left[\frac{0.3048 \times 2.890}{0.933 \times 10^{-3}} \right]^{1-0.35} \times 945.14^{0.5} \times 0.990 \times 10^{-9}$$

$$KLAP = 7.880 \times 10^{-3} \text{ s}^{-1}$$

6.5.5 Shulman et al.'s Prediction

From Eq. (2.37) $\beta = 1.508 \times 0.01774^{0.376} = 0.331$

From Eq. (2.33)

$$\theta_z = PT = \frac{2.09 \times 10^{-6} \times (737.5 \times 2.890)^{0.331}}{0.01774^2} = 0.084$$

From Eq. (2.32) $\epsilon = 0.63 - 0.084 = 0.546$

From Eq. (2.34)

$$Re_{LD} = 0.01774 \times 2.890 / (0.933 \times 10^{-3}) = 54.950$$

From Eq. (2.35)

$$Re_{GD} = 0.01774 \times 0.462 / (1.829 \times 10^{-5}) = 448.107$$

From Eq. (2.36)

$$Sc_a = 1.829 \times 10^{-5} / (1.192 \times 90.653 \times 10^{-7}) = 1.693$$

From Eq. (2.31)

$$a = AE = 14.69 \times \left[\frac{808 \times 0.462}{1.192 \times 10^{-5}} \right]^{0.01114 \times 2.890 + 0.148} \times 2.890^{-0.111}$$

$$AE = 37.372 \text{ m}^2/\text{m}^3$$

From Eq. (2.29)

$$k_L = KL = 25.1 \times \frac{0.990 \times 10^{-9}}{0.01774} \times 54.950^{-0.45} \times 945.137^{-0.5}$$

$$KL = 2.614 \times 10^{-4} \text{ m/s}$$

From Eq. (2.30)

$$k_a = KG = 1.195 \times \frac{90.653 \times 10^{-7}}{0.01774} \times (1 - 0.546)^{-0.36}$$

$$\times 448.107^{-0.44} \times 1.693^{-0.33}$$

$$KG = 2.722 \times 10^{-2} \text{ m/s}$$

From Eq. (2.7)

$$KLa = KLAP = \left[\frac{1}{2.614 \times 10^{-4} \times 37.372} + \frac{1}{0.235 \times 2.722 \times 10^{-2} \times 37.372} \right]^{-1}$$

$$KLAP = 9.385 \times 10^{-3} \text{ s}^{-1}$$

6.5.6 Onda et al.'s Prediction

From Eq. (2.41)

$$Fr_L = \frac{2.890^2 \times 407}{997.13^2 \times 9.81} = 3.485 \times 10^{-4}$$

From Eq. (2.42)

$$Re_{aa} = \frac{0.462}{407 \times 1.829 \times 10^{-5}} = 62.063$$

From Eq. (2.43)

$$Re_{La} = \frac{2.890}{407 \times 0.933 \times 10^{-3}} = 7.611$$

From Eq. (2.44)

$$We_L = \frac{2.890}{997.13 \times 72.199 \times 10^{-3} \times 407} = 2.850 \times 10^{-4}$$

From Eq. (2.40)

$$a_w = AE = 407 - 407 \exp \left\{ -1.45 \times \left[\frac{61 \times 10^{-3}}{72.199 \times 10^{-3}} \right]^{0.75} \times 7.611^{0.1} \right. \\ \left. \times (3.485 \times 10^{-4})^{0.05} \times (2.850 \times 10^{-4})^{0.2} \right\}$$

$$AE = 148.919 \text{ m}^2/\text{m}^3$$

From Eq. (2.45)

$$Re_{LW} = \frac{2.890}{148.919 \times 0.933 \times 10^{-3}} = 20.800$$

From Eq. (2.38)

$$k_L = KL = 0.0051 \times \left[\frac{997.13}{0.933 \times 10^{-3} \times 9.81} \right]^{-1/3} \times 20.800^{2/3} \\ \times 945.137^{0.5} \times (407 \times 0.0127)^{0.4}$$

$$KL = 5.073 \times 10^{-3} \text{ m/s}$$

From Eq. (2.39)

$$k_G = KG = 2.00 \times (407 \times 90.653 \times 10^{-7})^{-1} \times 62.063^{0.7} \\ \times 1.693^{1/3} \times (407 \times 0.0127)^{-2}$$

$$KG = 5.925 \times 10^{-3} \text{ m/s}$$

From Eq. (2.7)

$$KLa = KLAP = \left[\frac{1}{5.073 \times 10^{-3} \times 148.919} + \frac{1}{0.235 \times 5.925 \times 10^{-3} \times 148.919} \right]^{-1} \\ KLAP = 7.288 \times 10^{-3} \text{ s}^{-1}$$

6.6 Standard Error of Estimate

For Onda et al.'s (1968) model:

$$(\log_{10} KLa_{pred} - \log_{10} KLa_{obsd})^2 =$$

$$(\log_{10} 7.288 \times 10^{-3} - \log_{10} 7.658 \times 10^{-3})^2 = 4.626 \times 10^{-4}$$

For a given packing and model, the value of this difference for all compounds must be added, and then be divided by $N-2$. The square root of this sum will yield SEE.

G.7 Computer Programs

The following three WATFIV programs were used to compute experimental K_{La} , and K_{La} predicted by the models of Onda et al. (1968), Sherwood and Holloway (1940), and Shulman et al. (1955c), respectively.

These programs were slightly modified when the regression equation coefficients, r^2 , and SEE were computed for all data excluding the data for chloroform and ether.

```

$JOB
C PROGRAM COMPUTING KLA OBSERVED AND PREDICTED BY ONOJA ET AL.
C USE DATA FILES "PP(PK) (NO) (NZ) (NC) DATA" (E. G. PP2346 DATA).
C
C ASSIGN VARIABLES TYPE, READ INPUT DATA, AND PRINT SCHE.
C
1  INTEGER PK,RUNO(3,4)
2  REAL NTUC(3,6),Z(3,4),QL(3,4),QG(3,4),TWA(3,4),TA(3,4),PR(3,4),NTU
3  ST(3,4,6),SUMQL(3),SUMQG(3),SUMQL2(3),SUMQG2(3)
4  REAL PL(3,4),L(3,4),NTUN(3,4,6),KLAD(3,4,6)
5  REAL AVOL(3),AVOG(3),SDQL(3),SDQG(3),SAQL(3),SAQG(3)
6  REAL VLM(6),VC(6),MC(6),RQ(6),RT(6)
7  REAL ML(3,4),OL(3,4,6),KLAP(3,4,6)
8  REAL Q(3,4),RG(3,4),MG(3,4),TK(3,4),TWK(3,4),G(3,4),RT(3,4),AF(3,4)
9  S1,DG(3,4,6),H(3,4,6),KL(3,4,6),KG(3,4,6)
10 REAL SL(3,4)
11
12 READ,PK,NQ,NZ,NC
13 DO 10 I=1,NQ
14   READ,(NTUC(I,J),J=1,NC)
15   DO 30 K=1,NZ
16     READ,RUNO(I,K),7(I,K),QL(I,K),QG(I,K),TWA(I,K),TA(I,K),P
17     SB(I,K)
18     READ,(INTUT(I,K,LA),LA=1,NC)
19
20   CONTINUE
21   PRINT 20,'THE FLOW RATES STUDIED ARE:'
22   FORMAT('1',T5,A27)
23   PRINT 40,'RUN #','DEPTH','FLOW RATES (L/MIN)'
24   FORMAT('1',T23,A5,T30,A5,T38,A5,T46,A5)
25   PRINT 50,'Z (M)','LIQUID,QL','GAS,QG'
26   FORMAT(T30,A5,T38,A5,T46,A5,T54,A5,/, '0')
27   DO 60 NM=1,NQ
28     SUMQL(NM)=SUMQG(NM)=SUMQL2(NM)=SUMQG2(NM)=0.0
29     DO 70 NN=1,NZ
30       SUMQL(NM)=SUMQL(NM)+60000.*QL(NM,NN)
31       SUMQL2(NM)=SUMQL2(NM)+(60000.*QL(NM,NN))**2
32       SUMQG(NM)=SUMQG(NM)+60000.*QG(NM,NN)
33       SUMQG2(NM)=SUMQG2(NM)+(60000.*QG(NM,NN))**2
34       PRINT 80,RUNO(NM,NN),7(NM,NN),60000.*QL(NM,NN),60000.*QG
35       S(NM,NN)
36       FORMAT(T25,I2,T30,F5.3,T40,F6.4,T50,F6.2)
37
38     CONTINUE
39     AVOL(NM)=SUMQL(NM)/NZ
40     AVOG(NM)=SUMQG(NM)/NZ
41     SDQL(NM)=SQRT((NZ*SUMQL2(NM)-SUMQL(NM)**2)/(NZ*(NZ-1)))
42     SDQG(NM)=SQRT((NZ*SUMQG2(NM)-SUMQG(NM)**2)/(NZ*(NZ-1)))
43     SAQL(NM)=SDQL(NM)/AVOL(NM)
44     SAQG(NM)=SDQG(NM)/AVOG(NM)
45     PRINT 90,'AVERAGE',AVOL(NM),AVOG(NM)
46     FORMAT('0',T11,A7,T40,F6.4,T50,F6.2)
47     PRINT 100,'STANDARD DEVIATION',SDQL(NM),SDQG(NM)
48     FORMAT(T5,A18,T40,F6.4,T50,F6.2)
49     PRINT 110,'STANDARD DEVIATION/AVERAGE',SAQL(NM),SAQG(NM)
50     FORMAT(T2,A26,T40,F6.3,T50,F6.3,/, '0')
51
52   60 CONTINUE
53
54 C COMPUTE AND PRINT OBSERVED KLA'S.
55 C
56 DO-130 M=1,NQ

```

```

47      DO 140 N=1,NZ
48          RL(M,N)=1000.*(1.-1.9549/10**5*(TA(M,N)-4.1)**1.58)-
49          L(M,N)=QL(M,N)*QL(M,N)/0.00A107
50          DO 150 II=1,NC
51              NTUN(M,N,II)=NTUT(M,N,II)-NTUC(M,II)
52              KLAO(M,N,II)=NTUN(M,N,II)*L(M,N)/(RL(M,N)*Z(M,N))
53      CONTINUE
54      140 CONTINUE
55      130 CONTINUE
56      PRINT 160, 'THE EXPERIMENTAL (OR OBSERVED) KLA VALUES (1/S) ARE:'
57      160 FORMAT(' ',/, ' ', T2, A52)
58      CALL AVERAG(NZ,NC,KLAO,RUND)
C
C      COMPUTE AND PRINT PREDICTED KLA'S USING ONDA ET AL. MODEL.
C
59      GC=9.81      SC=81.      E=1./3.      F=2./3.
60      MAIR=28.97      VAIR=20.1
61      MC(1)=131.39      MC(2)=98.95      MC(3)=92.15
62      MC(4)=119.38      MC(5)=98.95      MC(6)=74.12
63      VC(1)=93.48      VC(2)=79.92      VC(3)=111.14
64      VC(4)=76.98      VC(5)=79.92      VC(6)=91.24
65      VLB(1)=107.1      VLB(2)=93.6      VLB(3)=115.2
66      VLB(4)=92.3      VLB(5)=93.6      VLB(6)=105.1
67      BO(1)=5.041      BO(2)=4.790      BO(3)=25.742
68      BO(4)=4.457      BO(5)=11.872      BO(6)=13.708
69      BI(1)=-1768.      BI(2)=-1851.      BI(3)=-8100.
70      BI(4)=-1863.      BI(5)=-4384.      BI(6)=-4968.
71      IF(PK.EQ.1) THEN DO
72          DP=0.00635      AT=764.
73      END IF
74      IF(PK.EQ.2) THEN DO
75          DP=0.0127      AT=407.
76      END IF
77      IF(PK.EQ.3) THEN DO
78          DP=0.0127      AT=823.
79      END IF
80      DO 170 IL=1,NQ
81          DO 180 IM=1,NZ
82              ML(IL,IM)=0.20319+1.5883*EXP(TA(IL,IM)**0.9/(-22.1))
83              RG(IL,IM)=1.293/(1.+0.00357*TWA(IL,IM))*DB(IL,IM)/760.
84              MG(IL,IM)=1.71+0.005*TWA(IL,IM)
85              TK(IL,IM)=TA(IL,IM)+273.15
86              TWK(IL,IM)=TWA(IL,IM)+273.15
87              G(IL,IM)=QG(IL,IM)*QG(IL,IM)/0.00A107
88              SL(IL,IM)=20987.-92.613*TA(IL,IM)**0.4344
89              AE(IL,IM)=AT*(1.-EXP(-1.45*(SC/SL(IL,IM))**0.75*(1000.*L
90              AE(IL,IM)=AT*(1.-EXP(-1.45*(SC/SL(IL,IM))**0.75*(1000.*L
91              AE(IL,IM)=AT*(1.-EXP(-1.45*(SC/SL(IL,IM))**0.75*(1000.*L
92              S(IL,IM)/(AT*ML(IL,IM))**0.1/(L(IL,IM)/RL(IL,IM))**2*AT/GC)**0.05
93              S=(1000.*L(IL,IM)**2/(RL(IL,IM)*SL(IL,IM)*AT)**0.2))
94              DO 190 IN=1,NC
95                  DL(IL,IM,IN)=13.26/(ML(IL,IM)**1.14*VLB(IN)**0.589)
96                  DG(IL,IM,IN)=(TWK(IL,IM)**1.75*SQRT(MAIR*MC(IN)))/(
97                  (PB(IL,IM)/760.*(VAIR**E*VC(IN)**E)**2)
98                  H(IL,IM,IN)=EXP(RG(IN)+RT(IN)/TK(IL,IM))
99                  KL(IL,IM,IN)=0.0051/(1000.*RL(IL,IM)/(ML(IL,IM)*GC)
100                  S)**E*(1000.*L(IL,IM)/(AE(IL,IM)*ML(IL,IM)))**F/SQRT(1000000.*ML(IL
101                  S,IM)/(RL(IL,IM)*DL(IL,IM,IN))*(AT*DP)**0.4
102                  KG(IL,IM,IN)=2.0*AT*DG(IL,IM,IN)/10.**7*(10.**5*G(I
103                  S,IM)/(AT*MG(IL,IM))**0.7*(100.*MG(IL,IM)/(RG(IL,IM)*DG(IL,IM,IN)
104                  S))**E/(AT*DP)**2
105                  KLAO(IL,IM,IN)=1./(1./(KL(IL,IM,IN)*AE(IL,IM))+1./

```

```

124      SH(IL,IM,IN)*KG(IL,IM,INI*AE(IL,IM)))
125      190      CONTINUE
126      140      CONTINUE
127      170      CONTINUE
128      PRINT 200, 'THE KLA VALUES PREDICTED BY ONQA ET AL. EQUATIONS ARE:'
129      200      FORMAT(' ', /, ' ', T2, A55)
130      CALL AVERAG(NQ,NZ,NC,KLAP,RUNO)
131
132      C COMPUTE AND PRINT COEFF. OF DETERMINATION, R**2, AND SEE.
133      C
134      SIGKO=SIGKP=SIGKO2=SIGKP2=SIGKOP=SIGMOP=0.0
135      DO 210 MK=1,NQ
136      DO 220 MM=1,NZ
137      DO 230 MN=1,NC
138      SIGKO=SIGKO+ALOG10(KLAP(MK,MM,MN))
139      SIGKP=SIGKP+ALOG10(KLAP(MK,MM,MN))
140      SIGKO2=SIGKO2+ALOG10(KLAP(MK,MM,MN))**2
141      SIGKP2=SIGKP2+ALOG10(KLAP(MK,MM,MN))**2
142      SIGKOP=SIGKOP+ALOG10(KLAP(MK,MM,MN))*ALOG10(KLAP(MK,MM,MN))
143      SIGMOP=SIGMOP+(ALOG10(KLAP(MK,MM,MN))-ALOG10(KLAP(MK,MM,MN)))**2
144      SIGKO2=SIGKO2-SIGKO**2
145      SIGKP2=SIGKP2-SIGKP**2
146      SIGKOP=SIGKOP-SIGKO*SIGKP
147      A=ANUM/DENO
148      B=BNUM/DENO
149      R2=(BNUM/SQRT(DENO*DENP))**2
150      SEE=SQRT(SIGMOP/(NQ*NZ*NC-2))
151      PRINT 240, 'LOG10 KLAP = ', A, ' ', B, ' LOG10 KLAP'
152      240      FORMAT(' ', /, ' ', T5, A12, T15, F7.4, T25, A1, T35, F7.4, T45, A10)
153      PRINT 250, 'COEFFICIENT OF DETERMINATION, R**2: ', R2
154      250      FORMAT(' ', T5, A35, T41, F6.4)
155      PRINT 260, 'STANDARD ERROR OF ESTIMATE, SEE: ', SEE
156      260      FORMAT(' ', T5, A32, T40, F7.4, /, ' ', /, ' ', /, ' ', /, ' ')
157      STOP
158      END
159
160      C SUBROUTINE COMPUTING AND PRINTING KLA, THEIR AVERAGE AND STD DEVIAT.
161      C
162      SUBROUTINE AVERAG(NQ,NZ,NC,KLA,RUNO)
163      INTEGER RUNO(3,4)
164      REAL KLA(3,4,6),SUMK(3,6),SUMK2(3,6)
165      REAL AVK(3,6),SDK(3,6),SAK(3,6)
166      PRINT 510, 'RUN #', 'TCE', '1,1-DCA', 'TOLUENE', 'CHCL3', '1,2-DCA'
167      510      FORMAT(' ', T23, A5, T33, A3, T46, A7, T61, A7, T77, A5, T91, A7, T107, A5,
168      510      /, ' ')
169      DO 520 LN=1,NQ
170      DO 530 MI=1,NC
171      SUMK(LN,MI)=SUMK2(LN,MI)=0.0
172      CONTINUE
173      DO 540 LK=1,NQ
174      DO 550 LM=1,NC

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```

172      DO 560 LL=1,NZ
173          SUMK(LK,LM)=SUMK(LK,LM)+KLA(LK,LL,LM)
174          SUMK2(LK,LM)=SUMK2(LK,LM)+KLA(LK,LL,LM)**2
175      560  CONTINUE
176          AVK(LK,LM)=SUMK(LK,LM)/N7
177          SDK(LK,LM)=SQRT((N7*SUMK2(LK,LM)-SUMK(LK,LM)**2)/(N
      SZ=(NZ-1.))
178          SAK(LK,LM)=SDK(LK,LM)/AVK(LK,LM)
179      550  CONTINUE
180      DO 570 LJ=1,N7
181          PRINT 540,RUND(LK,LJ),(KLA(LK,LJ,LI),LI=1,NC)
182          FORMAT(T25,I2,T30,6(1PE9.3,5X))
183      570  CONTINUE
184          PRINT 590,'AVERAGE',(AVK(LK,KN),KN=1,NC)
185          FORMAT('0',T11,A7,T30,6(1PE9.3,5X))
186      590  PRINT 600,'STANDARD DEVIATION',(SDK(LK,KN),KN=1,NC)
187          FORMAT(T6,A19,T30,6(1PE9.3,5X))
188      600  PRINT 610,'STANDARD DEVIATION/AVERAGE',(SAK(LK,KN),KN=1,
      SNC)
189          FORMAT(T2,A25,T31,6(1PE9.3,5X))
190          PRINT 620,' '
191          620  FORMAT(T1,A1)
192      540  CONTINUE
193      RETURN
194      END

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SENTRY


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$JOB
C PROGRAM COMPUTING KLA OBSERVED AND PREDICTED BY SHERWOOD AND HOLLOWAY
C USE DATA FILES "PR(PK)(NQ)(NZ)(NC) DATA" (E. G. P02 346 DATA).
C
C ASSIGN VARIABLES TYPE, READ INPUT DATA, AND PRINT SCHE.
C

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```

1  INTEGER PK, RUNO(3,4)
2  REAL NTUC(3,6), Z(3,4), OL(3,4), OG(3,4), TWA(3,4), TA(3,4), PP(3,4), NTU
3  ST(3,4,6), SUMOL(3), SUMOG(3), SUMOL2(3), SUMOG2(3)
4  REAL RL(3,4), L(3,4), NTUN(3,4,6), KLAN(3,4,6)
5  REAL AVOL(3), AVOG(3), SDOL(3), SDOG(3), SAOL(3), SAOG(3)
6  REAL VLR(6), VC(6), MC(6), RO(6), RI(6)
7  REAL ML(3,4), DL(3,4,6), KLAN(3,4,6)
8  REAL Q(3,4), RG(3,4), MG(3,4), TK(3,4), TWK(3,4), G(3,4), PT(3,4), AE(3,4)
9  SI, OG(3,4,6), HI(3,4,6), KL(3,4,6), KG(3,4,6)
10 REAL SL(3,4)
11
12 C
13 READ, PK, NQ, NZ, NC
14 DO 10 I=1, NQ
15   READ, (NTUC(I, J), J=1, NC)
16   DO 30 K=1, NZ
17     READ, RUNO(I, KI, Z(I, K), OL(I, K), OG(I, K), TWA(I, K), TA(I, K), P
18     SB(I, K)
19     READ, (NTUT(I, K, LA), LA=1, NC)
20   CONTINUE
21   PRINT 20, 'THE FLOW RATES STUDIED ARE:'
22   FORMAT('1', T5, A27)
23   PRINT 40, 'RUN #1, DEPTH, FLOW RATES (L/MIN)'
24   FORMAT('1', T23, A5, T30, A5, T38, A18)
25   PRINT 50, 'Z (M), LIQUID, OL, GAS, OG'
26   FORMAT(T30, A5, T38, A9, T50, A5, /, '0')
27   DO 60 NM=1, NQ
28     SUMOL(NM)=SUMOG(NM)=SUMOL2(NM)=SUMOG2(NM)=0.0
29     DO 70 NN=1, NZ
30       SUMOL(NM)=SUMOL(NM)+60000.*OL(NM, NN)
31       SUMOL2(NM)=SUMOL2(NM)+(60000.*OL(NM, NN))**2
32       SUMOG(NM)=SUMOG(NM)+60000.*OG(NM, NN)
33       SUMOG2(NM)=SUMOG2(NM)+(60000.*OG(NM, NN))**2
34       PRINT 80, RUND(NM, NN), 7(NM, NN), 60000.*OL(NM, NN), 60000.*OG
35     S(NM, NN)
36     FORMAT(T25, T2, T30, F5.3, T40, F5.4, T40, F5.2)
37   CONTINUE
38   AVOL(NM)=SUMOL(NM)/NZ
39   AVOG(NM)=SUMOG(NM)/NZ
40   SDOL(NM)=SQRT((NZ*SUMOL2(NM)-SUMOL(NM)**2)/(NZ*(NZ-1)))
41   SDOG(NM)=SQRT((NZ*SUMOG2(NM)-SUMOG(NM)**2)/(NZ*(NZ-1)))
42   SAOL(NM)=SDOL(NM)/AVOL(NM)
43   SAOG(NM)=SDOG(NM)/AVOG(NM)
44   PRINT 90, 'AVERAGE', AVOL(NM), AVOG(NM)
45   FORMAT('0', T11, A7, T40, F5.4, T50, F5.2)
46   PRINT 100, 'STANDARD DEVIATION', SDOL(NM), SDOG(NM)
47   FORMAT(T5, A18, T40, F5.4, T50, F5.2)
48   PRINT 110, 'STANDARD DEVIATION/AVERAGE', SAOL(NM), SAOG(NM)
49   FORMAT(T2, A26, T40, F5.3, T50, F5.3, /, '0')
50   60 CONTINUE
51 C
52 C COMPUTE AND PRINT OBSERVED KLA'S.
53 C
54 DO 130 M=1, NQ

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DO 140 N=1,NZ
  RL(M,N)=1000.*(1.-1.9549/10**5*(TA(M,N)-4.1**1.66)
  L(M,N)=CL(M,N)*RL(M,N)/0.008107
  DO 150 II=1,NC
    NTUN(M,N,II)=NTUT(M,N,II)-NTUC(M,II)
    KLAO(M,N,II)=NTUN(M,N,II)*L(M,N)/(PL(M,N)*Z(M,N))
  150 CONTINUE
  140 CONTINUE
  130 CONTINUE
  PRINT 150, 'THE EXPERIMENTAL (OR OBSERVED) KLA VALUES (1/S) ARE:'
  150 FORMAT('1-',/, '1-', T2, A52)
  CALL AVERAG(INQ,NZ,NC,KLAO,RUND)
C
C COMPUTE AND PRINT PREDICTED KLA'S USING SHERWOOD AND HOLLOWAY'S MODEL
C
  AL=260. ; SHN=0.35
  VLR(1)=107.1 ; VLB(2)=93.6 ; VLR(3)=114.2
  VLR(4)=92.3 ; VLB(5)=93.6 ; VLR(6)=105.1
  DO 170 IL=1,NQ
    DO 180 IM=1,NZ
      ML(IL,IM)=0.20319+1.5883*EXP(TA(IL,IM)**2.9/(-22.))
      DO 190 IN=1,NC
        DL(IL,IM,IN)=13.26/(ML(IL,IM)**1.14*VLR(IN)**0.589)
        KLAP(IL,IM,IN)=10.764*AL*(174.4*ML(IL,IM)/DL(IL,IM,IN))
        S=((1.-SHN)*SQRT(1000000.*ML(IL,IM)/(PL(IL,IM)*DL(IL,IM,IN)))*DL(IL,
        S,IM,IN)/10.**9
      190 CONTINUE
    180 CONTINUE
  170 CONTINUE
  PRINT 200, 'THE KLA VALUES PREDICTED BY SHERWOOD AND HOLLOWAY ARE:'
  200 FORMAT('1-',/, '1-', T2, A54)
  CALL AVERAG(INQ,NZ,NC,KLAP,RUND)
C
C COMPUTE AND PRINT COEFF. OF DETERMINATION, R**2, AND SEE.
C
  SIGK0=SIGKP=SIGK02=SIGKP2=SIGKOP=SIGMOP=0.0
  DO 210 MK=1,NQ
    DO 220 MM=1,NZ
      DO 230 MN=1,NC
        SIGK0=SIGK0+ALOG10(KLAO(MK,MM,MN))
        SIGKP=SIGKP+ALOG10(KLAP(MK,MM,MN))
        SIGK02=SIGK02+ALOG10(KLAO(MK,MM,MN))**2
        SIGKP2=SIGKP2+ALOG10(KLAP(MK,MM,MN))**2
        SIGKOP=SIGKOP+ALOG10(KLAO(MK,MM,MN))*ALOG10(KLAP(MK
        S,MM,MN))
        SIGMOP=SIGMOP+(ALOG10(KLAP(MK,MM,MN))-ALOG10(KLAO(M
        S,MM,MN)))*2
      230 CONTINUE
    220 CONTINUE
  210 CONTINUE
  DENO=NQ*NZ*NC*SIGK02-SIGK0**2
  DENP=NQ*NZ*NC*SIGKP2-SIGKP**2
  ANUM=SIGK02*SIGKP-SIGK0*SIGKOP
  BNUM=NQ*NZ*NC*SIGKOP-SIGK0*SIGKP
  A=ANUM/DENO
  B=BNUM/DENO
  R2=(BNUM/SQRT(DENO*DENP))**2
  SEE=SQRT(SIGMOP/(NQ*NZ*NC-2.))
  PRINT 240, 'LOG10 KLAO =', A, '1-',/, '1-', LOG10 KLAP
  240 FORMAT('1-',/, '1-', T5, A12, T18, F7.4, T26, A1, T28, F7.4, T36, A10)

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107 PRINT 250, 'COEFFICIENT OF DETERMINATION, R**2:', R2
108 FORMAT('0', T5, A35, T41, F8.4)
109 PRINT 260, 'STANDARD ERROR OF ESTIMATE, SEE:', SEE
106 260 FORMAT('0', T5, A32, T40, F7.4, /, ' ', /, ' ', /, ' ', /, ' ')
105 STOP
107 END

C
C SUBROUTINE COMPUTING AND PRINTING KLA, THEIR AVERAGE AND STD DEVIAT.
C

108 SUBROUTINE AVERAG(NQ,NZ,NC,KLA,RUND)
109 INTEGER RUND(3,4)
110 REAL KLA(3,4,6), SUMK(3,6), SUMK2(3,6)
111 REAL AVK(3,6), SDK(3,6), SAK(3,6)
112 PRINT 510, 'RUN #', 'TCE', '1,1-DCA', 'TOLUENE', 'CHCL3', '1,2-DCA',
113 $, 'ETHER'
114 510 FORMAT(' ', T23, A5, T33, A3, T45, A7, T51, A7, T77, A5, T91, A7, T107, A5,
115 $, ' ')
116 DO 520 LN=1, NQ
117 DO 530 MI=1, NC
118 SUMK(LN, MI)=SUMK2(LN, MI)=0.0
119 530 CONTINUE
120 520 CONTINUE
121 DO 540 LK=1, NQ
122 DO 550 LM=1, NC
123 DO 560 LL=1, NZ
124 SUMK(LK, LM)=SUMK(LK, LM)+KLA(LK, LL, LM)
125 SUMK2(LK, LM)=SUMK2(LK, LM)+KLA(LK, LL, LM)**2
126 560 CONTINUE
127 AVK(LK, LM)=SUMK(LK, LM)/NZ
128 SDK(LK, LM)=SORTI(NZ*SUMK2(LK, LM)-SUMK(LK, LM)**2)/(N
129 $Z*(NZ-1.))
130 SAK(LK, LM)=SDK(LK, LM)/AVK(LK, LM)
131 550 CONTINUE
132 DO 570 LJ=1, NZ
133 PRINT 580, RUND(LK, LJ), (KLA(LK, LJ, LI), LI=1, NC)
134 580 FORMAT(T25, I2, T30, 6(1PE9.3, 6X))
135 570 CONTINUE
136 PRINT 590, 'AVERAGE', (AVK(LK, KN), KN=1, NC)
137 590 FORMAT('0', T11, A7, T30, 6(1PE9.3, 6X))
138 PRINT 600, 'STANDARD OF VARIATION', (SDK(LK, KM), KM=1, NC)
139 600 FORMAT(T6, A11, T30, 6(0PE9.3, 6X))
140 PRINT 610, 'STANDARD DEVIATION/AVERAGE', (SAK(LK, KK), KK=1,
141 $NC)
142 610 FORMAT(T2, A26, T31, 6(F6.3, 9X))
143 PRINT 620, ' '
144 620 FORMAT(T1, A1)
145 540 CONTINUE
146 RETURN
147 END

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SENTRY

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SJOB
C PROGRAM COMPUTING KLA OBSERVED AND PREDICTED BY SHULMAN ET AL.
C USE DATA FILES "PR(PK)(NQ)(NZ)(NC) DATA" (E. G. 002345 DATA).
C
C ASSIGN VARIABLES TYPE, READ INPUT DATA, AND PRINT SOME.
C
1  INTEGER PK,RUND(3,4)
2  REAL NTUC(3,6),Z(3,4),OL(3,4),OG(3,4),TWA(3,4),TA(3,4),PR(3,4),NTU
3  ST(3,4,6),SUMQL(3),SUMQG(3),SUMQL2(3),SUMQG2(3)
4  REAL RL(3,4),L(3,4),NTUN(3,4,6),KLA(3,4,6)
5  REAL AVOL(3),AVOG(3),SDQL(3),SDQG(3),SAQL(3),SAQG(3)
6  REAL VLR(6),VC(6),MC(6),RD(6),RT(6)
7  REAL KL(3,4),DL(3,4,6),KLA(3,4,6)
8  REAL Q(3,4),RG(3,4),MG(3,4),TK(3,4),TWX(3,4),G(3,4),PT(3,4),AE(3,4)
9  SI,DG(3,4,6),H(3,4,6),KL(3,4,6),KG(3,4,6)
10 REAL SL(3,4)
11
12 C
13 READ,PK,NQ,NZ,NC
14 DO 10 I=1,NQ
15   READ,(NTUC(I,J),J=1,NC)
16   DO 30 K=1,NZ
17     READ,RUND(I,K),Z(I,K),OL(I,K),OG(I,K),TWA(I,K),TA(I,K),P
18     SB(I,K)
19     READ,(NTUT(I,K,LA),LA=1,NC)
20   CONTINUE
21 10 CONTINUE
22 PRINT 20,'THE FLOW RATES STUDIED ARE:'
23 FORMAT('1',T5,A27)
24 PRINT 40,'RUN #','DEPTH','FLOW RATES (L/MIN)'
25 40 FORMAT('1',T23,A5,T30,A5,T38,A18)
26 PRINT 50,'Z (M)','LIQUID,OL','GAS,OG'
27 50 FORMAT(T30,A5,T38,A9,T50,A6,/, '0')
28 DO 60 NM=1,NQ
29   SUMQL(NM)=SUMQG(NM)=SUMQL2(NM)=SUMQG2(NM)=0.0
30   DO 70 NN=1,NZ
31     SUMQL(NM)=SUMQL(NM)+60000.*OL(NM,NN)
32     SUMQL2(NM)=SUMQL2(NM)+(60000.*OL(NM,NN))**2
33     SUMQG(NM)=SUMQG(NM)+60000.*OG(NM,NN)
34     SUMQG2(NM)=SUMQG2(NM)+(60000.*OG(NM,NN))**2
35     PRINT 80,RUND(NM,NN),Z(NM,NN),60000.*OL(NM,NN),60000.*OG
36     S(NM,NN)
37     FORMAT(T25,I2,T30,F5.3,T40,F6.4,T50,F6.2)
38   70 CONTINUE
39   AVOL(NM)=SUMQL(NM)/N7
40   AVOG(NM)=SUMQG(NM)/N7
41   SDQL(NM)=SQRT((NZ*SUMQL2(NM)-SUMQL(NM)**2)/(NZ*(NZ-1)))
42   SDQG(NM)=SQRT((NZ*SUMQG2(NM)-SUMQG(NM)**2)/(NZ*(NZ-1)))
43   SAQL(NM)=SDQL(NM)/AVOL(NM)
44   SAQG(NM)=SDQG(NM)/AVOG(NM)
45   PRINT 90,'AVERAGE',AVOL(NM),AVOG(NM)
46   80 FORMAT('0',T11,A7,T40,F6.4,T50,F6.2)
47   PRINT 100,'STANDARD DEVIATION',SDQL(NM),SDQG(NM)
48   100 FORMAT(T6,A18,T40,F6.4,T50,F6.2)
49   PRINT 110,'STANDARD DEVIATION/AVERAGE',SAQL(NM),SAQG(NM)
50   110 FORMAT(T2,A26,T40,F6.3,T50,F6.3,/, '0')
51 60 CONTINUE
52 C
53 C COMPUTE AND PRINT OBSERVED KLA'S.
54 C
55 DO 130 M=1,NQ

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47      DO 140 N=1,NZ
48          RL(M,N)=1000.*(1.-1.9549/10***(TA(M,N)-4.1)*1.68)
49          L(M,N)=OL(M,N)*RL(M,N)/0.003107
50          DO 150 II=1,NC
51              NTUN(M,N,II)=NTUT(M,N,II)-NTUC(M,II)
52              KLAO(M,N,II)=NTUN(M,N,II)-L(M,N)/(RL(M,N)*Z(M,N))
53      CONTINUE
54      150 CONTINUE
55      140 CONTINUE
56      PRINT 160, 'THE EXPERIMENTAL (OR OBSERVED) KLA VALUES (1/S) ARE:'
57      160 FORMAT(' ',/, ' ', T2, A52)
58      CALL AVERAG(NQ,NZ,NC,KLAO,RUNO)

C
C      COMPUTE AND PRINT PREDICTED KLA'S USING SHULMAN ET AL. MODEL.
C

59      BT=0.33114      :      EPD=0.53      :      DS=0.01774
60      SD=14.69      :      SH=-0.111      :      E=1./3.
61      MAIR=28.97      :      VAIR=23.1
62      MC(1)=131.39      :      MC(2)=99.96      :      MC(3)=92.15
63      MC(4)=119.39      :      MC(5)=98.96      :      MC(6)=74.17
64      VC(1)=93.48      :      VC(2)=79.92      :      VC(3)=111.14
65      VC(4)=76.98      :      VC(5)=79.92      :      VC(6)=91.29
66      VLB(1)=107.1      :      VLB(2)=93.5      :      VLB(3)=114.7
67      VLB(4)=92.3      :      VLB(5)=93.6      :      VLB(6)=106.1
68      BO(1)=5.041      :      BO(2)=4.790      :      BO(3)=25.747
69      BO(4)=4.457      :      BO(5)=11.872      :      BO(6)=13.708
70      BI(1)=-1768.      :      BI(2)=-1851.      :      BI(3)=-3100.
71      BI(4)=-1863.      :      BI(5)=-4384.      :      BI(6)=-4964.
72
73      DO 170 IL=1,NQ
74          DO 180 IM=1,NZ
75              ML(IL,IM)=0.20312+1.5883*EXP(TA(IL,IM)*0.9/(-22.))
76              RG(IL,IM)=1.293/(1.+0.00357*TWA(IL,IM)*0.9/(IL,IM)/760.
77              MG(IL,IM)=1.71+0.005*TWA(IL,IM)
78              TK(IL,IM)=TA(IL,IM)+273.15
79              TWK(IL,IM)=TWA(IL,IM)+273.15
80              GI(IL,IM)=OG(IL,IM)*RG(IL,IM)/0.003107
81              Q(IL,IM)=0.01114*L(IL,IM)+0.148
82              PT(IL,IM)=(737.5*L(IL,IM)*RT/DS**2*2.34/10.**5
83              AE(IL,IM)=SD*(804.*GI(IL,IM)/SQRT(RG(IL,IM)))*0.0*(IL,IM)*L
84              S(IL,IM)**SH
85
86              DO 190 IN=1,NC
87                  DL(IL,IM,IN)=13.26/(ML(IL,IM)*1.14*VLB(IN)*0.519)
88                  DG(IL,IM,IN)=TWK(IL,IM)*1.75*SQRT((MAIR*MC(IN))/
89                      (PB(IL,IM)/760.*(VAIR**F+V*(IN)*F)**2)
90                  H(IL,IM,IN)=EXP((RG(IN)+RT(IN)/TK(IL,IM))
91                  KL(IL,IM,IN)=25.1*DL(IL,IM,IN)/(DS*12.**9)*(1000.*D
92                      S*L(IL,IM)/ML(IL,IM))*0.45*SQRT(ML(IL,IM)*10.**6/(RL(IL,IM)*OL(IL
93                      S,IM,IN)))
94                  KG(IL,IM,IN)=1.19*DG(IL,IM,IN)/(DS*10.**7)*(1.-EPD
95                      S+PT(IL,IM))*0.36*(DS*GI(IL,IM)*10.**6/MG(IL,IM))*0.64*(100.*MS(IL
96                      S,IM)/(RG(IL,IM)*DG(IL,IM,IN))*0.33
97                  KLAP(IL,IM,IN)=1./(1./(KL(IL,IM,IN)*AE(IL,IM))+1./I
98                      SH(IL,IM,IN)*KG(IL,IM,IN)*AE(IL,IM)))
99
100          CONTINUE
101      180 CONTINUE
102      170 CONTINUE
103      PRINT 200, 'THE KLA VALUES PREDICTED BY SHULMAN ET AL. EQUATIONS AR
104      SE:'
105      200 FORMAT(' ',/, ' ', T2, A57)
106      CALL AVERAG(NQ,NZ,NC,KLAP,RUNO)

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C COMPUTE AND PRINT COEFF. OF DETERMINATION, R**2, AND SEE.

```

121 SIGKO=SIGKP=SIGKO2=SIGKP2=SIGKOP=SIGMOP=0.0
122 DO 210 MM=1,NQ
123     DO 220 MN=1,NZ
124         DO 230 MK=1,NC
125             SIGKO=SIGKO+ALOG10(KLAD(MK,MM,MN))
126             SIGKP=SIGKP+ALOG10(KLAP(MK,MM,MN))
127             SIGKO2=SIGKO2+ALOG10(KLAD(MK,MM,MN)**2)
128             SIGKP2=SIGKP2+ALOG10(KLAP(MK,MM,MN)**2)
129             SIGKOP=SIGKOP+ALOG10(KLAD(MK,MM,MN))*ALOG10(KLAP(MK
130             SK,MM,MN))
131             SIGMOP=SIGMOP+(ALOG10(KLAP(MK,MM,MN))-ALOG10(KLAD(M
132             SK,MM,MN)))**2
133     CONTINUE
134     DENO=NQ*NZ*NC*SIGKO2-SIGKO**2
135     DENP=NQ*NZ*NC*SIGKP2-SIGKP**2
136     ANUM=SIGKO2*SIGKP-SIGKO*SIGKOP
137     BNUM=NQ*NZ*NC*SIGKOP-SIGKO*SIGKP
138     A=ANUM/DENO
139     B=BNUM/DENO
140     R2=(BNUM/SQRT(DENO*DENP))**2
141     SEE=SQRT(SIGMOP/(NQ*NZ*NC-2.))
142     PRINT 240, LOG10 KLAD, A, B, LOG10 KLAP
143     FORMAT(' ',/, ' ', T5, A12, T11, F7.4, T26, A1, T21, F7.4, T36, A10)
144     PRINT 250, COEFFICIENT OF DETERMINATION, R**2: R2
145     PRINT 260, STANDARD ERROR OF ESTIMATE, SEE: SEE
146     PRINT 260, STANDARD ERROR OF ESTIMATE, SEE: SEE
147     STOP
148     END
149

```

C SUBROUTINE COMPUTING AND PRINTING KLA, THEIR AVERAGE AND STD DEVIAT.

```

150 SUBROUTINE AVERAG(NQ,NZ,NC,KLA,PUNO)
151     INTEGER RUNO(3,4)
152     REAL KLA(3,4,6),SUMK(3,6),SUMK2(3,6)
153     REAL AVK(3,6),SDK(3,6),SAX(3,6)
154     PRINT 510, RUN, 'TCE', '1,1-DCA', 'TOLUENE', 'CHCL3', '1,2-DCA'
155     S, 'ETHER'
156     FORMAT(' ', T23, A5, T33, A3, T46, A7, T61, A7, T77, A5, T91, A7, T107, A5,
157     S, ' ')
158     DO 520 LN=1,NQ
159         DO 530 MI=1,NC
160             SUMK(LN,MI)=SUMK2(LN,MI)=0.0
161         CONTINUE
162     CONTINUE
163     DO 540 LK=1,NQ
164         DO 550 LM=1,NC
165             DO 560 LL=1,NZ
166                 SUMK(LK,LM)=SUMK(LK,LM)+KLA(LK,LL,LM)
167                 SUMK2(LK,LM)=SUMK2(LK,LM)+KLA(LK,LL,LM)**2
168             CONTINUE
169             AVK(LK,LM)=SUMK(LK,LM)/NZ
170             SDK(LK,LM)=SQRT((NZ*SUMK2(LK,LM)-SUMK(LK,LM)**2)/(N
171             SZ*(NZ-1.)))

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```

169      SAK(LK,LM)=SDK(ILK,LM)/AVK(ILK,LM)
170      CONTINUE
171      DO 570 LJ=1,N7
172      PRINT 580,RUND(ILK,LJ),IKSAILK,LJ,LI,LI=1,NC)
173      FORMAT(T25,I2,T30,6(1PE9.3,6X))
174      CONTINUE
175      PRINT 590,'AVERAGE',(AVK(ILK,KM),KM=1,NC)
176      FORMAT(T11,M7,T10,6(1PE9.3,6X))
177      PRINT 600,'STANDARD DEVIATION',(SDK(ILK,KM),KM=1,NC)
178      FORMAT(T6,A14,T30,6(0ME9.3,6X))
179      PRINT 610,'STANDARD DEVIATION/AVERAGE',(SAK(ILK,KM),KM=1,
180      SNC)
181      FORMAT(T2,A24,T31,6(1PE9.3,6X))
182      PRINT 620,
183      FORMAT(T1,A1)
184      CONTINUE
185      RETURN
186      END

```

SENTRY

APPENDIX H

PLOTS OF FLOW RATES AGAINST MASS TRANSFER RATE CONSTANTS

On the following figures, the logarithms (base 10) of the average gas and liquid flow rates are plotted against the logarithms of the corresponding average observed and predicted mass transfer rate constants, for each packing and each compound.

Figure H.1

Figure H.2

Figure H.3

Figure H.4

Figure H.5

Figure H.6

Figure H.7

Figure H.8.

Figure H.9

Figure H.10

Figure H.11

Figure H.12

Figure H.13

Figure H.14

Figure H.15

Figure H.16

Figure H.17

Figure H.18

APPENDIX I

VARIATION OF TOWER HEIGHT WITH PREDICTION MODEL USED

The purpose of the following computations was simply to see the difference in required packing heights resulting from the use, in the packed tower design model, of a mass transfer coefficient predicted by one of the three models studied or obtained from experimental measurements. Therefore, parameters were selected on the basis of convenience. The conditions of experimental Run 18 (temperature, Q_G/Q_L ratio) were assumed to prevail, and the K_{La} and S values of Run 18 were used.

Computations were made for trichloroethylene, chloroform, and 1,2-dichloroethane, using 12.7 mm Raschig rings as a packing.

I.1 Data from Run 18

Liquid mass flux: $L = 2.890 \text{ kg/m}^2\text{-s}$

Liquid density : $\rho_L = 997.13 \text{ kg/m}^3$

Table I.1 presents the other data.

I.2 Concentrations

Influent concentrations were selected based on the Gloucester landfill site concentrations (Table 4.1), except

Table I.1: Data of Run 18

Parameter	TCE	CHCl ₃	1,2-DCA
Stripping factor, S	53.366	21.604	7.308
Experimental K _{La} (s ⁻¹)	7.501×10 ⁻³	7.218×10 ⁻³	6.682×10 ⁻³
Predicted K _{La} (s ⁻¹) (Onda et al.)	7.106×10 ⁻³	7.204×10 ⁻³	6.538×10 ⁻³
Predicted K _{La} (s ⁻¹) (Sherwood and Holloway)	7.574×10 ⁻³	7.913×10 ⁻³	7.881×10 ⁻³
Predicted K _{La} (s ⁻¹) (Shulman et al.)	9.165×10 ⁻³	9.260×10 ⁻³	8.319×10 ⁻³

Table I.2: Influent and effluent concentrations

Concentration	TCE	CHCl ₃	1,2-DCA
Influent, C _i (μg/l)	250	1000	350
Effluent, C _e (μg/l)	5	5	5

for chloroform, which was present in extremely high concentration in the Gloucester groundwater. The concentrations used are presented in Table I.2.

I.3 Required Packing Heights

For TCE:

From Eq. (2.19)

$$NTU = \left[\frac{53.366}{53.366 - 1} \right] \ln \left\{ \frac{(250/5) (53.366 - 1) + 1}{53.366} \right\}$$

$$NTU = 1.019$$

For experimental K_La :

From Eq. (2.16)

$$HTU = 2.890 / (997.13 \times 7.501 \times 10^{-3}) = 0.386 \text{ m}$$

$$\text{From Eq. (2.22)} \quad Z = 1.019 \times 0.386 = 0.394 \text{ m}$$

Table I.3 presents the packing depths computed for the other K_La values.

Table I.3: Required packing depths

K _{La} value	TCE	CHCl ₃	1,2-DCA
NTU values			
	1.019	5.506	4.754
HTU values (m)			
Experimental	0.386	0.402	0.434
Predicted (Onda et al.)	0.407	0.402	0.443
Predicted (Sherwood and Holloway)	0.383	0.366	0.368
Predicted (Shulman et al.)	0.316	0.313	0.348
Z values (m)			
Experimental	0.394	2.211	2.062
Predicted (Onda et al.)	0.416	2.215	2.108
Predicted (Sherwood and Holloway)	0.390	2.017	1.748
Predicted (Shulman et al.)	0.322	1.723	1.656

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