# Evaluation Of Mass Transfer Correlations For Packed Column Air Stripping Of Volatile Organic Contaminants From Water Supplies

by

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(ABSTRACT)

The application of packed column air stripping systems to the removal of volatile organic contaminants (VOCs) from drinking water sources was investigated. The crucial element for the design of such systems exists in obtaining accurate predictions of mass transfer rates. The first phase of this study evaluated three semi-empirical correlations available for predicting packed column mass transfer rates. From this initial screening, the Onda model was selected for further investigation. A test data base was established from water treatment pilot study results reported in the literature. Ten separate studies were selected for evaluation, encompassing approximately 450 data points. Eleven different VOCs were encountered in these investigations, and the basic packing types tested included rings, saddles, Tri-Packs, and Tellerettes. Comparison of measured mass transfer rates with the corresponding rates predicted by the Onda correlation yielded a relative standard deviation of 17%. A ± 30% accuracy value was therefore assigned to the model based on 90% confidence limits. This assessment agrees with the observed accuracy of the correlation for the chemical engineering-based system results utilized in the model's original derivation. From the overall evaluation,

no severe deficiencies and/or limitations with the Onda correlation were noted. In particular, gas-phase resistance predictions appeared reasonably accurate. However, further investigative studies involving observed column performance with larger packing materials ($\geq 2$ inches in nominal size) is encouraged to verify the accuracy of the correlation for such situations.

Within the context of the evaluation procedure, several related areas were investigated. First, Henry's constant temperature relations reported in the literature were established within approximately 20% for common VOCs at low concentration levels. Secondly, the transfer unit performance model for calculating observed mass transfer rates was found sensitive to experimental measurement errors below a stripping factor of 1.5. Therefore, measured results obtained under such operating conditions must be viewed with appropriate caution. Finally, economic design boundaries for column operational parameters were established based upon optimization study results reported in the literature.

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# CHAPTER 1

# INTRODUCTION

## 1.1 CURRENT WATER QUALITY CONCERNS

The increasing frequency with which organic contaminants are being detected in both surface and ground water sources is causing much concern because of the potential health risks associated with ingestion of these substances. One class of organic contaminants which receiving considerable attention in recent years is that of volatile organic chemicals (VOCs), so named because of their characteristic high volatility relative to other organic compounds such as pesticides.

VOCs can be divided into two separate groups based on their general occurrence in water sources. The first category is comprised of trihalomethanes (THMs) which are structural variations of methane with halogen atoms (chloride, bromide, iodide, and floride) substituted for hydrogen atoms. The THMs most commonly found present in drinking water supplies are chloroform, bromodichloromethane, dibromochloromethane, and bromoform. These four compounds are the most widely and frequently detected VOCs in finished drinking water [31]. They are formed mainly from reactions involving naturally occurring organic matter (fulvic and humic acids) and bromide in combination with the chlorine used for disinfection treatment purposes. The Environmental Protection Agency has established a drinking water maximum contaminant level (MCL) of 100 ug/l for total trihalomethanes [31].

The second category of VOCs encompass a host of various man-made chemicals employed mainly as industrial solvents and degreasers. The principal contaminants are halogenated hydrocarbons of low molecular weight. A partial list of these volatile synthetic organic contaminants (SOCs) include:

1) Trichloroethylene
2) Tetrachloroethylene (Perchloroethylene)
3) Carbon tetrachloride
4) 1,2 - Dichloroethane
5) 1,1 - Dichloroethylene
6) Vinyl chloride
7) Benzene
8) 1,1,1 - Trichloroethane
9) Chlorobenzene
10) Dichlorobenzene
11) Trichlorobenzene
12) Methylene chloride
13) Cis-1,2 - Dichloroethylene
14) Trans-1,2 - Dichloroethylene

The first eight compounds listed are of particular significance, having been singled out for potential regulation by the Environmental Protection Agency [31]. The first seven compounds are considered carcinogenic, and a proposed recommended MCL (RMCL) of zero has been put forth. The eighth compound, 1,1,1-trichloroethane, is not considered carcinogenic and the proposed RMCL for it is 0.2 mg/l. In general, chronic exposure to various VOCs may cause cancer and skin disease, as well as dizziness, tremors, and blindness [8].

With common industrial usage, such synthetic compounds can enter into water sources via accidental spills, illegal dumping, and landfill operations. In surface waters, these substances are typically detected only at extremely low levels ( < 10 ug/l total VOCs) since natural aeration processes release these volatile compounds into the atmosphere [17]. In contrast, groundwaters can contain appreciable quantities of VOCs ( > 1 mg/l) as such natural aeration does not occur to a significant extent and the synthetic compounds remain relatively unbiodegraded in natural subsurface environments. It has been estimated that 15-20% of all groundwater supplies in the United States contain SOCs [51]. In one survey, five different chlorinated hydrocarbon solvents were detected in 15 to 25% of the groundwater sites tested [16]. A summary of one consulting firm's experiences with volatile SOC groundwater contamination showed trichloroethylene (TCE) to be present in a large majority of cases (>75%), while tetrachloroethylene (PCE) was observed about one-half of the time [18]. The municipal well contamination sites generally contained total VOC levels less than 500 ug/l, while industrial sites had levels typically exceeding 1000 ug/l. This widespread discovery of groundwater contamination, only recently made possible by analytical techniques capable of measurement at the ug/l level, has changed the long-accepted notion that groundwater represents a pure and pristine source for drinking water, requiring only minimal treatment for human consumption.

## 1.2 TREATMENT OPTIONS

In response to the growing water supply contamination problem, research into appropriate treatment technology has flourished. From this effort, air stripping has been shown to be a viable option for VOC removal from finished drinking water, contaminated groundwater, landfill leachate, and municipal sewage [2,21,33,36,39,40,44,56,60]. Potential stripping operations include diffused aeration, spray aeration, surface aeration, and packed tower aeration. Diffused aeration offers an optimum system for the dissolution, rather than stripping, of a gas, while the spray and surface aeration options are often not economically competitive with packed columns. In general then, the best suited stripping system for VOC removal has been found through the use of packed tower aeration, achieving the high removal efficiencies (90-99+% removal) typically required at a relatively low cost. Compared to the other aeration systems, packed columns provide a greater effective area for mass transfer to occur via the use of packing materials with large surface areas. Also, very high air to water ratios can be achieved with a packed column system. This design results in continuous and thorough contact of the contaminated water with the air and minimizes the thickness of the water layer on the packing, thereby promoting efficient mass transfer.

For strict VOC removal, packed tower air stripping has also been found clearly preferable to activated carbon treatment based on cost considerations. One typical situation involving trichloroethylene (TCE) contamination showed an activated carbon system to cost four times as much as a packed column system ($0.28 vs. $0.07 per 1000 gallons) [6]. For trihalomethane control, an EPA study showed activated carbon to be five times as expensive as packed towers ($0.15 vs. $0.03 per 1000 gallons) [64]. The total costs for packed column operation cited in the literature range from $0.03 to $0.20 per 1000 gallons, with the higher costs corresponding to lower system flow rates [3,6,11,43,56,64].

## 1.3 FOCUS OF STUDY

The packed tower aeration process is well established within the chemical engineering industry. A standard method exists for evaluating tower performance in terms of mass transfer rates. In addition, numerous correlations are available to predict these transfer values for design purposes. However, application of this technology to the drinking water industry is new and proposed systems are based upon pilot-plant testing results. Such designs require sufficient precision in providing for the high removal efficiencies typically needed to protect human health and comply with applicable standards while avoiding costly overdesigns due to uncertainties in predicted performance calculations. This study looks at the application of these chemical engineering-based concepts to drinking water contamination situations and seeks to evaluate the most promising mass transfer correlation(s) available from the literature for potential design use.

The specific objectives of this study are:

1) Evaluation of the available packed column mass transfer rate correlations based on general theoretical considerations and previous experimental studies involving VOC stripping.
2) Establishment of a raw data base from pilot-scale VOC stripping studies reported upon in the literature for use in further testing the most promising correlation(s) found from the first phase of the study.
3) Determination of the accuracy for the chosen transfer rate model(s) based upon the selected data base.
4) Establishment of particular areas of weakness for the models evaluated with potential modifications offered and/or suggested areas for further research.

In meeting these general objectives, the following subject areas are also addressed:

1) Review and analysis of general mass transfer theory.
2) Review and analysis of proposed Henry's constant temperature relations for common VOCs reported upon in the literature.
3) Establishment of economical design ranges for packed tower operational parameters.
4) Evaluation of the experimental procedures used in pilot-scale packed column studies with regards to producing reliable results.
5) Evaluation of the impact of parameter measurement errors on predicted and observed mass transfer rates.

# CHAPTER 2

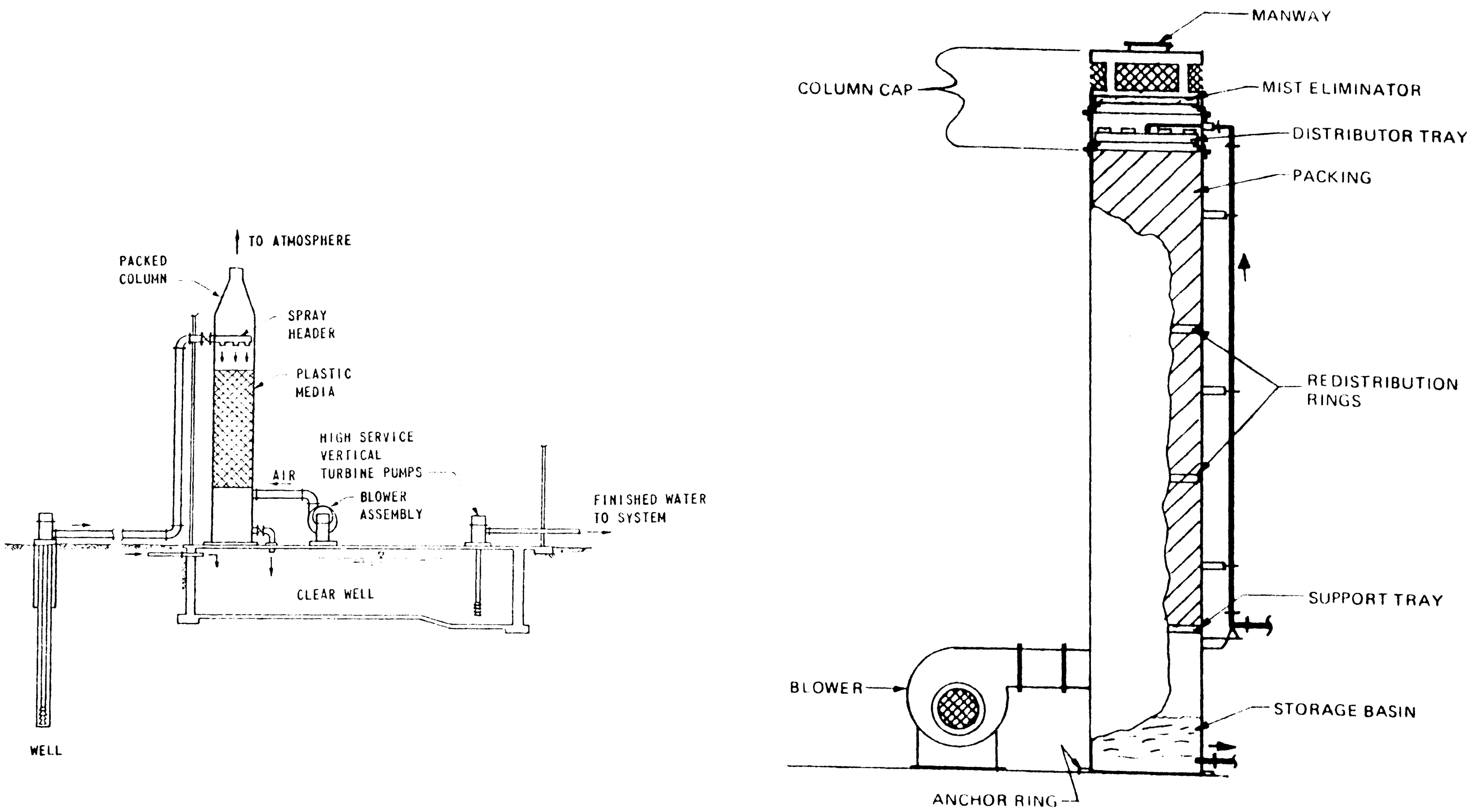
# LITERATURE REVIEW AND ANALYSIS

## 2.1 PACKED COLUMN OPERATION

### 2.1.1 System Components

A typical packed tower system consists of a cylindrical column filled with randomly dumped packing material which is either ceramic or plastic. Countercurrent flow is used to insure maximum transfer efficiency. A centrifugal fan provides a forced-draft air flow up through the column, while water cascades down over the packing. The water can be initially introduced at the top of the column using spray nozzles, overflow weirs, or simple distribution trays. Internal redistributors are installed at regular intervals to maintain even flow conditions. The bottom packing support is also designed to provide good initial air distribution. An entrainment eliminator prevents the exiting air flow from carrying off VOC-laden liquid droplets as a mist. A diagram depicting a typical set-up is shown in Figure 1. Specific operational parameter values are considered in section 3.1.1.4.

The key to the system lies in the packing. By providing a large specific surface area, the thickness of the water layer on the packing is minimized. This allows for continuous and thorough contact of the contaminated water with the clean air, thereby promoting mass transfer.



(a) Overall groundwater treatment system. After Dyksen & Hess [16].

(b) Packed Column Components. After Nyer [43].

Figure 1. Packed Tower System Components

For water treatment applications, plastic packings of various configurations with a nominal size of one to two inches are commonly chosen. Such packings yield specific surface area values ranging from 30-40 square feet per cubic foot of packing for the two-inch size to 55-65 square feet per cubic foot for the one-inch size. Specific packing shapes include saddles, rings, and spiral balls. These configurations are depicted below in Figure 2.

Plastic packing material is the choice for water treatment purposes, being chemically inert in such situations while costing eight to ten times less than comparable ceramic packings [43]. Plastic packings also have significantly higher void space (85-95%) compared to ceramic equivalents (60-80%). The increased void space allows for freer passage of the air, reducing the pressure drop through the column which, in turn, decreases the associated air blower costs for column operation.

### 2.1.2 Basic Operational Concepts

The basic concepts behind the use of a countercurrent packed column for VOC removal are fairly straight-forward. Water is introduced at the top of the column, flowing downwards by gravity, while clean air is forced upwards through the column. The water contains an excess of VOCs relative to the air, which is assumed devoid of these compounds. Therefore, as the water proceeds down through the column, more of a given VOC will be transferred from the liquid to the gaseous state as an equilibrium condition is sought. For dilute solutions, as typically encountered in

(a) Raschig ring

(b) **partition ring**

(*c*) Berl saddle

(d) Intalox saddle

(e) Tellerette

(f) Pall ring

Figure 2. Typical Packing Elements After Perry & Chilton [47]

environmental practice, this equilibrium state can be described by Henry's Law:

$$C^*_{G(A)} = C^*_{L(A)}\left(\frac{H}{P_T}\right) \qquad \{1\}$$

where: $C^*_{G(A)}$ - equilibrium concentration of compound A in the gas-phase

$C^*_{L(A)}$ - equilibrium concentration of compound A in the liquid-phase

H - Henry's law constant (partition coefficient)

$P_T$ - total pressure (assumed 1 atm for environmental work)

It is important to note that different forms of Henry's Law are often used in terms of the concentration units cited (molar, mass, and volume) and the relative values for Henry's constant are affected by the choice of units. This point is further discussed in section 3.2.2 which examines reported values for Henry's constant.

Based on equation {1}, a larger Henry's constant will yield a higher equilibrium concentration of compound A in the air. Thus, contaminants with higher Henry's constants are generally more easily removed by air-stripping. Furthermore, a calculated equilibrium concentration for the gas phase based upon a given concentration in the liquid phase can be interpreted as a capacity term for the stripping of a particular compound into the air. At any given point in the column, the difference between this calculated equilibrium capacity value for the air and the corresponding actual concentration of the compound in the air represents the driving force for mass transfer of a magnitude proportional to that difference. This can be expressed as:

$$J_A \propto (C_G^* - C_G) \qquad \{2\}$$

where: $J_A$ - molar flux rate

(moles transferred per unit interfacial area per time)

$C_G^*$ - air concentration of the compound which would be in equilibrium with the actual liquid concentration as predicted by Henry's Law (mass per volume)

$C_G$ - actual compound concentration in the air (mass per volume)

This can be alternatively viewed from the liquid side, where the calculated equilibrium concentration for the liquid phase based upon the actual concentration in the air phase represents the lowest liquid concentration achievable via aeration. The corresponding driving force is:

$$J_A \propto (C_L - C_L^*) \qquad \{3\}$$

where: $C_L^*$ - liquid concentration of the compound which would be in equilibrium with the actual air concentration as predicted by Henry's Law (mass per volume)

$C_L$ - actual compound concentration in the liquid mass per volume)

The countercurrent mode of operation takes advantage of these concepts: by introducing clean air at the bottom of the column, the maximum obtainable driving force is realized in the lower portion of the column. The capacity for the air to accept VOC transfer then increases as it proceeds up the column in accordance with Henry's Law since the VOC concentration in the water also increases. Compared to an identical co-current system, the overall mass transfer efficiency is greater for the counter-current system, thereby yielding the maximum potential for mass transfer [63].

A point to be emphasized is that mass transfer is dependent on the driving force (difference between the actual and equilibrium concentrations) and not on the absolute magnitude of these concentrations. Therefore, the behavior of a given compound remains the same regardless of its absolute concentration level.

### 2.1.3 Modeling Packed Column Performance

Flow through a packed column is complex and non-uniform. As the packing is placed in a random fashion, the space between packing units is irregular and the slopes of the surfaces range from vertical to horizontal. This leads to local variations in both gas and liquid flow rates. Some of the contaminated water can be under turbulent flow conditions, while other portions may form stagnant pools within the various cracks and crevices between packing units. Not all of the packing surface area is covered with liquid, and the actual wetted area changes with time. Finally, not all of the gas-liquid interfacial surface area is equally effective for mass transfer.

Despite such complications, the basic theory for performance of countercurrent packed tower gas-liquid absorption/desorption processes has been well developed in the chemical engineering literature

[7,29,37,63]. Performance is evaluated based upon the "transfer unit" approach first developed in the mid-1930's. The basic equation in this approach is:

$$Z = (HTU) \times (NTU) \qquad \{4\}$$

where: Z - height of the packing in the column

HTU - height of a transfer unit

NTU - number of transfer units

This fundamental equation for air-stripping operations is derived from consideration of the rate of mass transfer per unit volume of packing:

$$(L)\,\frac{dC_{L(A)}}{dZ} = K_L a \left( C_{L(A)} - C^{*}_{L(A)} \right) \qquad \{5\}$$

where: L - liquid volume flux (volume per time per unit area)

Z - column height

$K_L$ - overall mass transfer coefficient (based on liquid concentrations)

a - effective interfacial area for mass transfer

$C_{L(A)}$ - actual bulk liquid concentration of compound A

$C^{*}_{L(A)}$ - liquid concentration of compound A which would be in equilibrium with the actual gas phase concentration as determined by Henry's Law

Upon separation of terms and partial integration of equation {5}, one obtains:

$$Z = \frac{L}{K_L a} \int_{C_{L(IN)}}^{C_{L(OUT)}} \frac{dC_{L(A)}}{C_{L(A)} - C^{*}_{L(A)}} \qquad \{6\}$$

where: IN - influent concentration of A

OUT - effluent concentration of A

Looking at the right hand side of equation {6}, the integral term represents the number of transfer units (NTU), while the leading term is the height of a transfer unit (HTU). The HTU term, inversely proportional to the overall mass transfer term, characterizes the efficiency of mass transfer. A larger value for the mass transfer rate results in a smaller value for HTU, indicating more efficient mass transfer. The HTU term thus accounts for the kinetics side of the stripping process.

The NTU term, which incorporates the driving force concentration difference, characterizes the relative difficulty in removing a particular compound from solution. As the liquid concentration is reduced and approaches the equilibrium value, further separation becomes increasingly difficult. This is reflected within the integral value, which approaches infinity under such conditions. Therefore, the NTU term incorporates equilibrium considerations in the stripping process.

For dilute solutions, as encountered in environmental work, the NTU integral can be evaluated analytically as outlined by Kavanaugh and Trussell [32]. From any point in the column, a material balance can be set up around either the upper or lower portion of the column. Taking this balance around the lower portion yields:

$$(C_G - C_{G(IN)})\, G = (C_L - C_{L(OUT)})\, L \qquad \{7\}$$

where: G,L - volume flux (volume per time per unit area) for the gas (air) and liquid (water) respectively

From Henry's Law:

$$C_L^* = \frac{C_G}{H} \tag{8}$$

Combining {7} & {8} and noting that the influent air concentration of compound A is zero yields:

$$C_L^* = (C_L - C_{L(OUT)}) \frac{L}{HG} \tag{9}$$

or

$$C_L^* = \frac{C_L - C_{L(OUT)}}{R} \tag{10}$$

where: R - stripping factor $( = \frac{HG}{L} )$

Upon substitution of equation {10} into equation {6} and integrating:

$$NTU = \frac{R}{R-1} \ln\left[\frac{(C_{L(IN)}/C_{L(OUT)})(R-1)+1}{R}\right] \quad \text{if } R \neq 1 \tag{11a}$$

At the local point of discontinuity:

$$NTU = [C_{L(IN)}/C_{L(OUT)}] - 1 \quad \text{if } R = 1 \tag{11b}$$

The stripping factor represents an equilibrium term. If R>1, then there is sufficient gas-phase capacity for complete removal of the particular compound given a sufficiently tall column. If, however, R<1, then the system's performance is limited by equilibrium and complete removal is not possible for any tower height. For this case, the maximum fractional removal possible will approach the value of R as the column height approaches infinity [54]. Therefore, the stripping factor represents a crucial design factor. Graphical solutions relating R to NTU and removal efficiency have been developed for general design use [32,63]. These solutions are provided below in Figure 3.

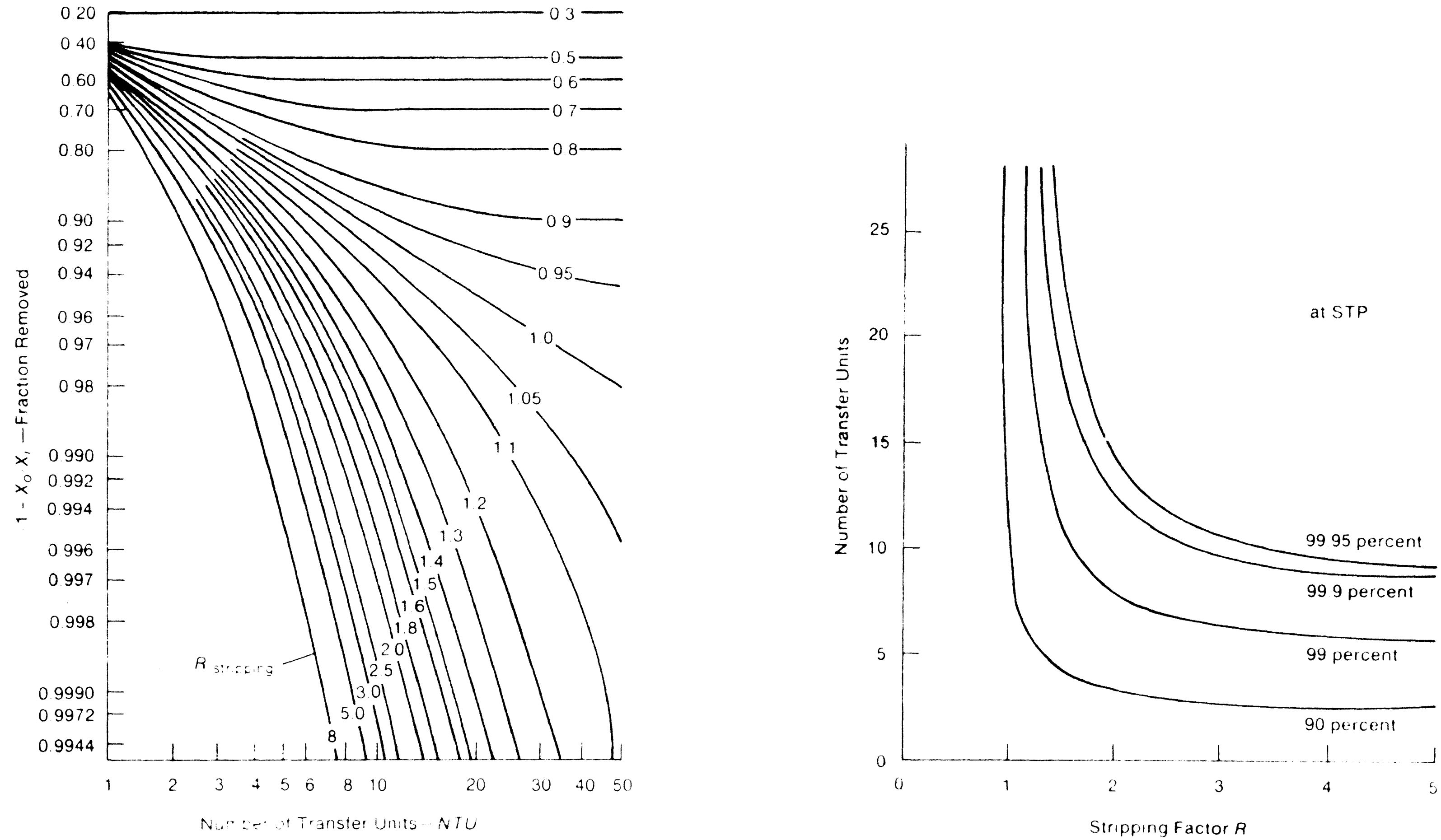
The assumptions incorporated within this overall derivation are:

1) Plug flow conditions exist for both air and water flow.
2) The influent air contains no VOCs.
3) Henry's Law is valid for describing the equilibrium state.

From these equations, the basic factors affecting performance are:

1) Particular VOC
2) Packing type
3) Packing depth
4) Air & water loading rates
5) Air to water ratio
6) Water temperature

In regards to design procedures, the two basic parameters required are: the Henry's Law constant, H, which affects the stripping factor (and therefore NTU), and the overall mass transfer coefficient, which affects HTU. Predictions for Henry's constant using compound solubility values appear in error based on direct experimental results [23,55]. While keeping the potential variability of experimental Henry's constants in mind, however, the present investigation focuses upon the predictive models for calculating mass transfer rate coefficients.



(a) Design diagram

(b) Stripping factor vs. NTU

Figure 3. Relationships between column removal, required NTU, and the stripping factor. After Kavanaugh & Trussell [32].

## 2.2 MASS TRANSFER THEORY

### 2.2.1 General Theory

In looking at interphase mass transfer, the two-resistance theory is generally accepted [7,29,37,59]. Under this theory, the overall resistance to mass transfer is the sum of two separate resistances, a liquid-phase and a gas-phase resistance. Using Henry's Law to describe phase equilibrium, the following equation is obtained:

$$K_L a = \frac{1}{\dfrac{1}{k_L a} + \dfrac{1}{H\,(k_G a)}} \qquad \{12\}$$

where: $K_L$ - overall liquid-phase mass transfer coefficient (length per time)

$k_L$ - individual liquid phase coefficient (1/time)

$k_G$ - individual gas phase coefficient (1/time)

a - effective interfacial area per unit volume of liquid

The assumptions involved with the two-resistance theory are that:

1) No resistance is encountered at the actual phase interface. Resistance to diffusion resides solely in the fluids themselves.
2) There is instant equilibrium at the interface.
3) Henry's Law applies in describing equilibrium conditions.
4) The overall mass transfer rate is proportional to the difference between the bulk concentration in one phase

and the concentration which would be in equilibrium with the bulk concentration in the other phase.

The model was originally derived in conjunction with the film theory (presented below), but it has been reconciled with subsequent general mass transfer theories [29]. This is noted because the two-resistance theory is unfortunately often referred to as the two-film theory, incorrectly implying a direct dependence on film theory.

The two resistance-theory can be restated as:

$$\text{Total Resistance} = \text{Liquid Resistance} + \text{Gas Resistance} \tag{13a}$$

or

$$(K_L a)^{-1} = (k_L a)^{-1} + (H k_G a)^{-1} \tag{13b}$$

Relationships can be drawn between the resistances, namely:

$$\frac{r_L}{r_T} = \left(1 + \frac{k_L}{H\, k_G}\right)^{-1} \tag{14}$$

and

$$\frac{r_L}{r_G} = \frac{H\, k_G}{k_L} \tag{15}$$

where: r - resistance value (liquid, gas, and total)

From these equations, the significance of gas-phase resistance can be evaluated. If $H(k_G / k_L) >> 1$, then the gas-phase resistance may be neglected, a situation termed liquid-phase control. Otherwise, both phases must be taken into account for predicting and interpreting mass transfer rates. It is important to note that Henry's constant can significantly affect the value of the overall mass transfer term. Therefore, Henry's constant will affect both the NTU term directly (via Henry's Law) and the HTU term indirectly (via $K_La$). Thus, accurate values for Henry's constant are critical in obtaining accurate performance and design numbers.

## 2.2.2 General Transfer Models

### 2.2.2.1 Introduction

Several theoretical models have been put forth to describe interphase mass transfer. The three most widely recognized models are the Lewis-Whitman film model [35], the Higbie penetration model [28], and the Danckwerts surface renewal model [13]. Differences between these models lie in their physical interpretation of the transfer process.

### 2.2.2.2 Film Theory

The Lewis-Whitman film theory [35] hypothesizes that turbulence in the two phases is negligible near the interface. Therefore, the total resistance to mass transfer can be modeled by a fictitious thin stagnant film with an effective thickness $\delta$ that exists on each side of the interface. Concentration gradients in the film are established within a relatively short time frame compared to the total contact time such that steady-state diffusion can be assumed to predominate. Under this steady-state condition, Fick's First Law of Diffusion applies:

$$J = -D\frac{dC}{dx} \tag{16}$$

Upon integration of equation {16}, the mass transfer coefficient is predicted to have a first-order dependence on the molecular diffusivity.The specific relation obtained is:

$$k = \frac{D}{\delta} \tag{17}$$

where: $\delta$ - effective film thickness

Subsequent studies have generally discredited the film theory [29,59,63]. For turbulent conditions, such as those encountered in packed columns or mechanical aeration processes, the exposure time for a fluid element to undergo mass transfer is believed to be so brief that a steady-state concentration gradient cannot be established. The unstableness of the fluid-fluid interface, with both the gas and liquid surfaces having a non-zero velocity, also points to inherently unsteady-state conditions. In support of these contentions, the predicted first-order dependency on diffusivity values has not been found experimentally [30,59,68].

#### 2.2.2.3 Penetration Theory

In response to the deficiencies noted for the film theory, Higbie [28] presented his penetration theory in 1935. This theory postulates that small packets of the bulk fluid are continuously transported to and from a laminar layer existing at the interface by turbulent eddy flows. All of the packets are assumed to remain at the interface for the same period of time, but the actual time frame is not long enough to obtain a steady-state condition. In this case, transient molecular diffusion governs mass transfer and Fick's Second Law of Diffusion applies:

$$\frac{dC}{dt} = D\frac{d^2C}{dx^2} \qquad \{18\}$$

From this law:

$$k = 2\sqrt{\frac{D}{\pi t_o}} \qquad \{19\}$$

where: $t_o$ - time a packet remains at the interface

#### 2.2.2.4 Surface Renewal Theory

Danckwerts viewed Higbie's assumption of a constant interfacial exposure time as unrealistic and put forth his surface renewal theory in 1951 [13]. This model amends Higbie's interpretation of mass transfer by allowing for random replacement of the fluid packets at the interface via the introduction of a probability function. Replacement of the surface elements was assumed independent of the time a particular element had resided at the surface, allowing that packet's exposure time to potentially range from zero to infinity. Thus, the constant exposure time assumption was replaced by an average exposure time determined from an assumed fluid element age distribution. This model yields the following general transfer relation:

$$k = \sqrt{D\,s} \tag{20}$$

where: s - fractional rate of surface renewal

### 2.2.2.5 Combined Behavior Theories

In reviewing the general relation $k \propto D^n$, both the penetration and surface renewal theories predict "n" to equal 1/2, rather than 1 as predicted by the film theory. Experimental absorption/stripping studies with packed towers have yielded intermediate "n" values between 1/2 and 1 [29,59,63], with a suggested value of 2/3 [29,30,59].

To account for the experimental results, two "combined behavior" theories have been proposed. The first, put forth by Toor & Marchello [62], involves a combined film-penetration theory. The total resistance to mass transfer is assumed to occur in a laminar surface film at the fluid interface, in accordance with film theory, but the transfer process is assumed to be unsteady, occurring via short-term eddy penetration as postulated by surface renewal theory. The general equation, derived from Fick's Second Law, has two separate cases. The first, for "young" surface elements, has a form similar to that predicted by penetration theory:

$$k = \sqrt{\frac{D}{\pi\,t}}\left[1 + 2\exp\left(-\frac{\delta^2}{D}\,t\right)\right] \qquad \pi \leq \frac{\delta}{D\,t} < \infty \tag{21}$$

The second case, for "older" elements, has a form related to film theory:

$$k = \frac{D}{\delta}\left[1 + 2\exp\left(-\frac{\pi^2 D t}{\delta^2}\right)\right] \qquad 0 < \frac{\delta^2}{D} t \leq \pi \tag{22}$$

Under appropriate conditions, the general equations reduce to both the penetration and film theories. These equations yield a power dependency on diffusivity varying from 1/2 to 1 based on the average surface element's age. Transfer through old surface elements follows the film theory, while transfer through young elements obeys the penetration theory. It can be reasonably anticipated that many typical situations would involve mainly intermediate age elements, where both mechanisms would be significant in defining the exact diffusivity dependency relation.

The second combined theory was proposed by Dobbins [15] as reported by Treybal [63]. Dobbins noted that the penetration and surface renewal theories assume the interfacial layer of surface elements to be essentially infinitely deep, thereby not accounting for the possibility of the solute reaching the region of constant bulk concentration below. His modification incorporates a finite depth of surface elements into the basic surface renewal relation. The resulting equation is:

$$k = \sqrt{D s}\;\coth\sqrt{\frac{s z_b^2}{D}} \tag{23}$$

where: $z_b$ - depth of surface elements

Again, $k \propto D^n$ where n= 0.5 - 1.0. For rapid penetration (large D), small surface renewal rates (low s), or thin depth of surface elements (small $z_b$ ), film theory behavior is approached. For slow penetration, rapid renewal, or thicker depths of surface elements, penetration/surface renewal behavior is predicted.

These two combined behavior theories postulate that the film and penetration/surface renewal theories are not separate, unrelated concepts, but rather are limiting cases of a more general model. For packed columns, the prevailing turbulent flow patterns would tend to favor the penetration/surface renewal theory. Therefore, an average dependency for mass transfer on diffusivity to the 2/3 power (as has been indicated experimentally) appears to be a reasonable expectation.

## 2.2.3 Mass Transfer Correlations

### 2.2.3.1 Introduction

In developing models for the prediction of mass transfer coefficients in packed columns, the semi-empirical relationship generally utilized is of the form [37]:

$$Sh = Re^{m}\, Sc^{n} \qquad \{24\}$$

where: Sh - Sherwood number $= (k\, l) / (D)$

Re - Reynolds number $= (M\, l) / (\mu)$

Sc - Schmidt number $= (\mu) / (\rho\, D)$

k - mass transfer coefficient (length per time)

$l$ - characteristic length term

$D$ - diffusion coefficient (area per time)

$M$ - mass flux (mass per time per unit volume)

$\mu$ - viscosity (mass per length per time)

$\rho$ - density (mass per volume)

The three specific correlations available for countercurrent packed column operations are the: 1) Sherwood-Holloway, 2) Shulman, and 3) Onda models. Each of the models is described below.

#### 2.2.3.2 Sherwood-Holloway Correlation

The Sherwood-Holloway model was developed from a study of the desorption of hydrogen, carbon dioxide, and oxygen from water in a countercurrent air column alternatively filled with several sizes of Raschig ring and Berl saddle packing material [57]. Packing depths ranged from 8 to 49 inches, while the tower itself was 20 inches in diameter. Liquid loading rates ranged from 0.4 to 64 gpm per square foot.

As the gaseous solutes tested by Sherwood and Holloway have sufficiently large Henry's constants ($H \gg 1$ on a volume basis) such that liquid-phase resistance controls, the overall transfer rate equation was based upon liquid flow properties only - i.e., gas-phase resistance could be neglected. In addition, no separate determination of the effective interfacial area was made. The interfacial area term was directly grouped together with the mass transfer coefficient. The resulting equation obtained is as follows:

$$\frac{K_L a}{D_L} = x\,\alpha \left(\frac{y\,L_M}{\mu_L}\right)^{1-n} \left(\frac{\mu_L}{\rho_L D_L}\right)^{0.5} \qquad \{25\}$$

where: $\alpha$ , $n$ - empirically determined packing parameters

$L_M$ - liquid mass flux (mass per time per unit area)

x - equals: 1 - English units (lb, hrs, ft)

10.746 - SI units (N, sec, m)

y - equals: 1 - English units (lb, hrs, ft)

0.3048 - SI units (N, sec, m)

The empirical constants $\alpha$ and n can be determined from a log-log plot of the data. Ball et al. [1], in conducting VOC stripping studies, noted that for typical operating conditions such plots yield data points lying relatively far away from the y-axis. Therefore, the results are quite sensitive to changes in one parameter ($\alpha$ or n) without significant corresponding changes in the other. Because of this fact, $\alpha$ and $n$ must be taken as paired parameters, not considered individually.

The Sherwood-Holloway model has been the most widely used in studies involving VOC stripping for water treatment [1,3,32,48,64]. Most of the previous work conducted has involved fitting data from individual pilot studies to the equation. A summary of empirical constants reported for these studies is given in Table 1. While the correlation utilizes $\alpha$ and n as strictly empirical packing parameters, independent of other factors, their values have been found to vary from study to study, and seem not only affected by the particular packing used, but also the specific VOC

Table 1. REPORTED EMPIRICAL CONSTANTS FOR THE SHERWOOD-HOLLOWAY CORRELATION

| Packing Type | Nominal Size (inches) | Empirical Constants alpha | n | Compounds Tested | Reference |
|---|---|---|---|---|---|
| Raschig Rings (ceramic) | 2.0 | 80 | 0.22 | Oxygen &<br>Carbon Dioxide | [57] |
| Raschig Rings (ceramic) | 1.5 | 90 | 0.22 | " | " |
| Raschig Rings (ceramic) | 1.0 | 100 | 0.22 | " | " |
| Raschig Rings (ceramic) | 0.5 | 280 | 0.35 | " | " |
| Berl Saddles (ceramic) | 1.5 | 160 | 0.28 | " | " |
| Berl Saddles (ceramic) | 1.0 | 170 | 0.28 | " | " |
| Berl Saddles (ceramic) | 0.5 | 150 | 0.28 | " | " |
| Berl Saddles (ceramic) | 1.0 | 12 | 0.25 | Chloroform | [3] |
| Saddles (plastic) | 1.0 | 63 | 0.28 | Trihalomethanes | [64] |
| Saddles (plastic) | 1.0 | 27 | 0.22 | Chloroform | [3] |
| Saddles (plastic) | 1.0 | 696 | 0.55 | Carbon Tetra.<br>PCE, TCE<br>Chloroform | [1] |
| Saddles (plastic) | 1.0 | 972 | 0.68 | Bromoform | " |
| Tri-Packs (plastic) | 2.0 | 41 | 0.14 | 1,1,1-Trichloroethane | [3] |
| Tri-Packs (plastic) | 2.0 | 43 | 0.16 | 1,1-Dichloroethane | " |
| Tri-Packs (plastic) | 2.0 | 66 | 0.28 | Trichloroethylene | " |

being removed. Such results indicate that factors not fully definable by the Sherwood-Holloway model affect packed-column mass transfer.

A major cause for this discrepancy can be attributed to the underlying limits of the correlation. For the VOCs of concern, Henry's constant values are much lower than for the compounds studied by Sherwood and Holloway, and therefore the assumption that the gas-phase resistance can be neglected may not be valid. This would be indicated by a dependence of the removal efficiencies on the air flow rate. Such results are indeed clearly seen in the data from various pilot-scale studies [9,23,48].

Therefore, given the variability of the empirical values obtained from different studies and the clear indication that gas-phase resistance affects VOC mass transfer, the use of this approach seems questionable even for extrapolating data. Certainly, it has little value for a priori prediction of mass transfer rates in VOC stripping operations.

#### 2.2.3.3 Shulman Correlation

The two-resistance model proposed by Shulman et al. [58] calculates both gas- and liquid-phase resistance values. A separate estimation of interfacial contact area is also given.

The approach taken in the development of this correlation is as follows. First, original studies were conducted involving mass transfer from dry naphthalene packings to obtain a general relation for the gas-phase transfer value ($k_G$). As the packing itself vaporized, the effects of varying interfacial area with changing loading rates were eliminated since the interfacial area equaled the actual packing surface area which remained constant. Then, using previously published data for which the effects of the interfacial area were not eliminated (i.e., $k_Ga$ rates), effective area values were obtained by dividing this data by calculated $k_G$ values using the correlation initially determined. The $k_Ga$ data set chosen involved ammonia absorption into water where the packings employed were Raschig rings and Berl saddles ranging in size from 1/2 to 2 inches.

Finally, the interfacial area results were applied to $k_La$ data to obtain a separate correlation for $k_L$ alone. The liquid-phase data set used included the work Sherwood and Holloway [57] performed in the development of their own model. Overall, the liquid-phase studies chosen involved oxygen and carbon dioxide desorption and utilized Berl saddles and Raschig rings from 1/2 to 2 inches in nominal size.

The equations obtained for the individual transfer coefficients are:

$$\frac{k_L d_s}{D_L} = 25.1 \left(\frac{d_s L_M}{\mu_L}\right)^{0.45} \left(\frac{\mu_L}{\rho_L D_L}\right)^{0.5} \tag{26}$$

and

$$\frac{k_G d_s}{D_G} = 1.195 \; (1 - \varepsilon)^{0.36} \left(\frac{d_s G_M}{\mu_G}\right)^{0.64} \left(\frac{\mu_G}{\rho_G D_G}\right)^{0.33} \tag{27}$$

where: $d_s$ - diameter of a sphere having an equivalent surface area as a single piece of packing

$\varepsilon$ - void fraction of the packing

The main item of concern for the Shulman model lies in the prediction of interfacial area. First, no general correlation was obtained. The results are presented in graphical form and apply only to the specific situations investigated. This is a critical deficiency since the original work involved only a limited number of packing types. Furthermore, the packings examined have since been replaced by more efficient and economical types [7,29]. Therefore, without further information on the appropriate values of interfacial area for use with modern packings, this method is extremely limited in terms of potential applications.

### 2.2.3.4 Onda Correlation

The equations developed by Onda et al. [46] allow for the direct and separate calculation of the individual phase resistance values and the interfacial area. The basic assumption made by this theory is that the specific interfacial area can be taken as the specific wetted packing area. The equation for calculation of the wetted area is as follows:

$$\frac{a_w}{a_t} = 1 - \exp\left[ -1.45\,(\sigma_C/\sigma_L)^{0.75}\,(Re_L)^{0.1}\,(Fr_L)^{-0.05}\,(We_L)^{0.2} \right] \qquad \{28\}$$

where: $a_t$ - total specific surface area of the packing

$a_w$ - wetted specific surface area of the packing

$\sigma$ - surface tension

L subscript - for the liquid

c subscript - for the particular packing material

$g$ - gravitational constant

$Re_L$ - liquid-phase Reynolds number $= (L_M)/(a_t \mu_L)$

$Fr_L$ - liquid-phase Froude number $= (L_M^2 a_t)/(\rho_L^2 g)$

$We_L$ - liquid-phase Weber number $= (L_M^2)/(\rho_L \sigma_L a_t)$

This equation predicts that as the liquid loading rate is increased, the wetted area asymptotically approaches the total (dry) surface area. It also accounts for different materials of construction though the use of material surface tension. The relation is claimed to be accurate within 20% for saddles, spheres, and rods constructed of ceramic, glass, and PVC, along with wax coated materials [46].

The proposed individual liquid-phase mass transfer coefficient is given by the following equation:

$$\left(\frac{k_L}{a_t D_L}\right)\left(\frac{\mu_L^2 a_t^3}{\rho_L^2 g}\right)^{1/3} = 0.0051\left(\frac{L_M}{a_w \mu_L}\right)^{2/3}\left(\frac{\mu_L}{\rho_L D_L}\right)^{1/2}(a_t d_p)^{0.4} \qquad \{29a\}$$

which reduces to:

$$k_L\left(\frac{\rho_L}{\mu_L g}\right)^{1/3} = 0.0051\left(\frac{L_M}{a_w \mu_L}\right)^{2/3}\left(\frac{\mu_L}{\rho_L D_L}\right)^{-1/2}(a_t d_p)^{0.4} \qquad \{29b\}$$

where: $(\mu_L^2 a_t^3)/(\rho^2 g)$ - Galileo number

$d_p$ - nominal size of packing

$(a_t d_p)$ - shape factor

The corresponding gas-phase relation is:

$$\frac{k_G}{a_t D_G} = c\left(\frac{G_M}{a_t \mu_G}\right)^{0.7}\left(\frac{\mu_G}{\rho_G D_G}\right)^{1/3}(a_t d_p)^{-2} \qquad \{30\}$$

where: c = 2.0 if $d_p < 15\ mm$

= 5.23 otherwise

The liquid-phase correlation is based on a large data base which included the work of Sherwood and Holloway [57]. The gas-phase correlation used available mass transfer studies involving both absorption and vaporization. The overall accuracy for the model was placed at 20% in the original work [46]. The defining plots for the individual mass transfer coefficients are provided in Figure 4.

### 2.2.3.5 Modified Onda Correlation

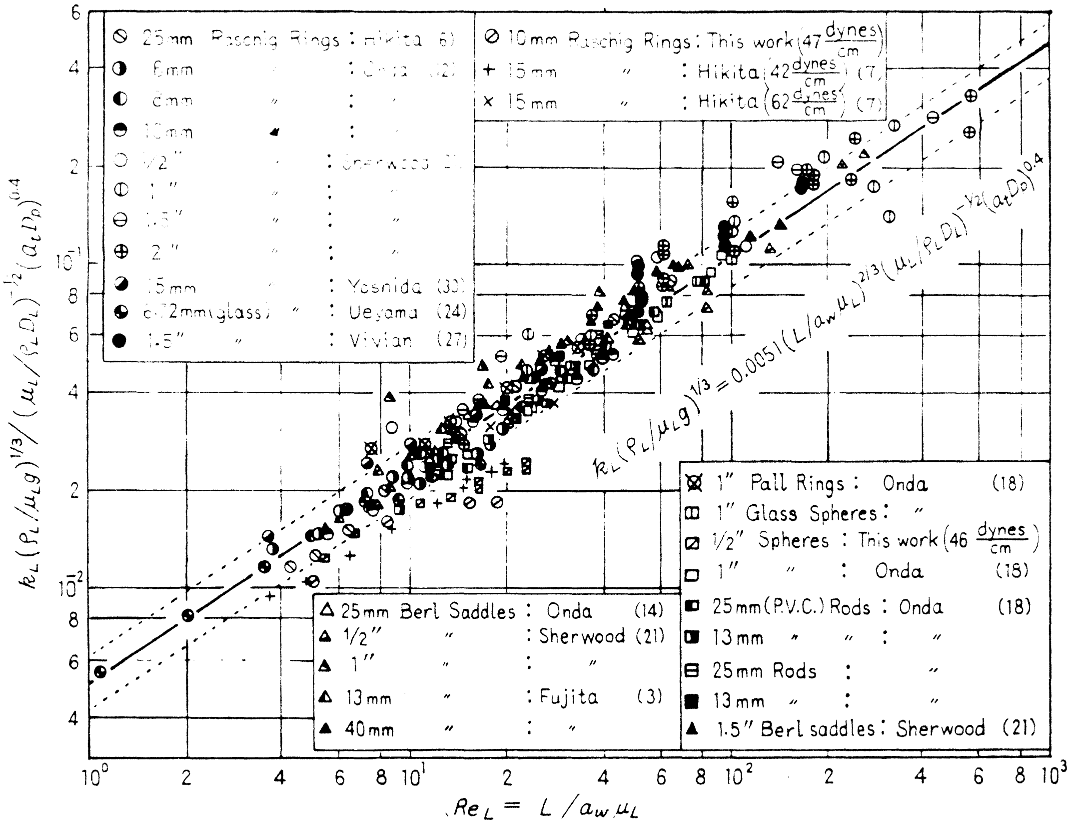
Gossett et al. [23] presented a convenient method for potential adjustment of the Onda relations given supporting data. This alteration consists of modifying the individual liquid- and gas-phase mass transfer correlations by constant factors "a" and "b", respectively, which represents changing the constants appearing in the original Onda equations. The values for "a" and "b" can be arrived at through the following relationship:

$$\%D = 100\left(\frac{1}{a} - 1\right) + (\%R_G)_o\left(\frac{1}{b} - \frac{1}{a}\right) \qquad \{31\}$$

where: a - modification factor for the individual Onda liquid-phase correlation (equation {29})

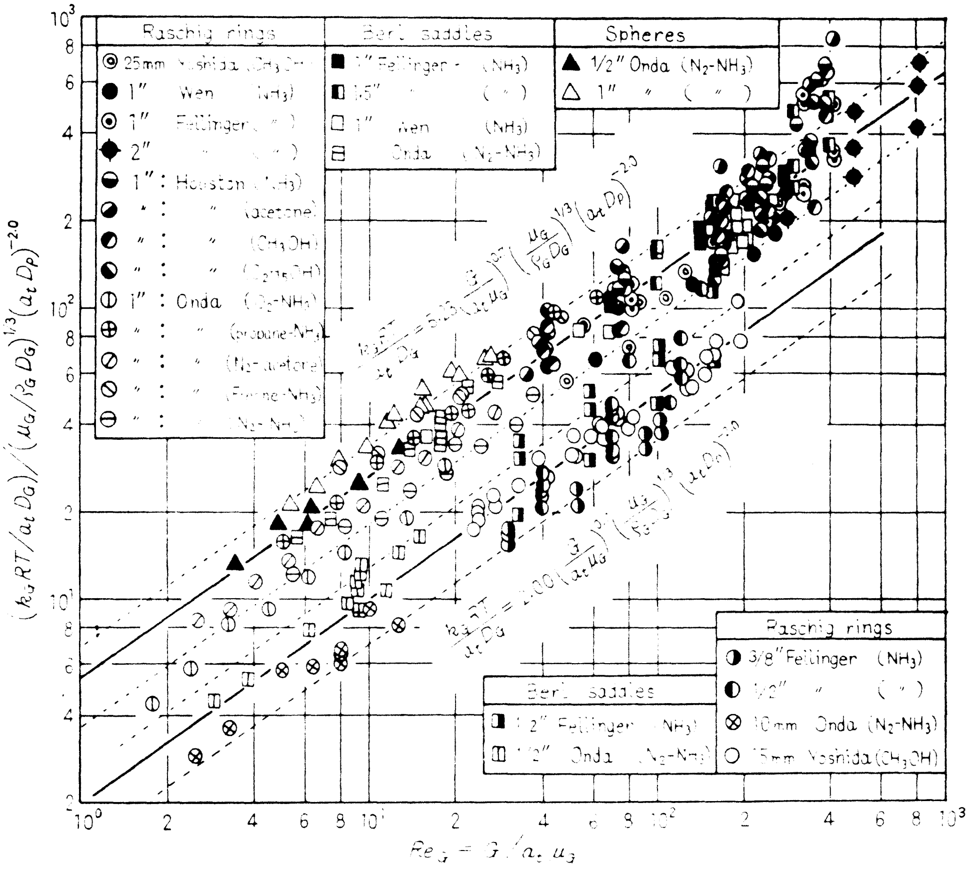
b - modification factor for the individual Onda gas-phase correlation (equation {30})

$\%D$ - percentage difference of Onda-predicted $K_La$ compared to measured $K_La$



(a) Correlation of liquid-phase data for gas absorption and desorption using water.

Figure 4. Definition plots for the Onda correlation. After Onda <u>et al.</u> [46].



(b) Correlation of gas-phase data for absorption into water.

Figure 4 (cont.). Definition plots for the Onda correlation. After Onda *et al.* [46].

$(\%R_G)_O$ - percent gas-phase control as predicted by the Onda relations, $= (k_L a) / (H\, k_G a)$

If such a simplistic modification is appropriate, a plot of percent difference versus percent gas-phase resistance will yield a straight line, with the factors determined from the resulting slope and intercept values.

Theoretically, this adjustment may be justified by arguing that there is a distinct overall difference in the stripping of low-level VOCs as opposed to the chemical engineering systems considered in development of the original Onda model. In lieu of such a fundamental difference, the modification can also be used to further refine the Onda relation in terms of performance differences between various packing types. The Onda equations were originally derived with a majority of the data based on the use of Raschig rings, a virtually obsolete packing type. One can conceive that not only nominal size considerations, but also fundamental shape configurations can play a significant role in performance. These effects may not be adequately taken into account by the shape factor employed in the Onda model. Therefore, if consistently different results were obtained with one general type of packing versus another (say, rings versus saddles), perhaps a simple change of constant values would improve the predictive power of the Onda correlation. The Gossett modification can effectively evaluate if such an approach is appropriate.

### 2.2.3.6 Comparison of Mass Transfer Correlations

**Theoretical Comparison:** Each correlation is based on the general model accepted for mass transfer in packed columns as given by equation {24}. However, the particular approaches taken have yielded different governing relations. A theoretical review of the approaches provides insight into the relative strengths and weaknesses of each correlation. Subsequent identification of potential problem areas is useful when actual results are reviewed to determine each correlation's relative accuracy. Predictive errors may then be corrected via theoretical modifications of the correlations. In this regard, a review of individual terms common to each model is presented below.

Schmidt Number: The first point for consideration is the dependence of predicted transfer rates on diffusivity in accordance with the general theories presented earlier in section 2.2.2. For the liquid-phase transfer value, each of the three correlations utilizes the Schmidt number raised to the 1/2 power, yielding $k_L \propto D^{1/2}$ . This dependency agrees with penetration and surface-renewal theory predictions. However, for the gas-phase (not considered by Sherwood-Holloway), both the Shulman and Onda models predict $k_G \propto D^{2/3}$ based on the use of the Schmidt number raised to the 1/3 power. One might reasonably expect that for interphase mass transfer, similar dimensionless factors for the two phases would affect the transfer process in the same relative way.

Therefore, a review of the literature can be used to potentially rectify this difference. First, the $k_G \propto D^{2/3}$ relation is in accord with expectations for pure gas mass transfer in a turbulent boundary layer at small values of the Schmidt number [55]. In support of this view, Houston and Walker [30] experimentally found a 2/3 power dependency experimentally for the absorption of ammonia, methanol, ethanol, and acetone by water using Raschig rings. Secondly, as previously noted, experimental results have indicated a general relation of $k \propto D^n$, with "n" lying between 1/2 and 1 [29,59,63]. Combined behavior theories by Toor & Marchello [62] and Dobbins [15] can account for the varying results. If one assumes an average value for "n" of 2/3, as supported by Hines & Maddox [29] and Skelland [59], then relative agreement would be reached between the liquid and gas phases. Such a modification would appear to be both more theoretically and experimentally satisfying. This alteration has already been proposed by Van Krevelen & Hoftijzer [67], whose specific correlation for packed columns employs both gas and liquid phase Schmidt numbers raised to the 1/3 power, resulting in the desired $k \propto D^{2/3}$ relation.

Reynolds Number: The next factor to be considered is the Reynolds number. First, the form incorporated into the Sherwood-Holloway correlation is dimensionally unsound, lacking a characteristic length term. The lengths utilized in both the Shulman and Onda models reflect the particular packing employed. The introduction of a similar theoretically sound Reynolds number into the Sherwood and Holloway relation should yield a constant experimentally determined value for the empirical "n" factor that is independent of the packing type chosen. This would improve the model theoretically, as the powers modifying the various dimensionless numbers are not expected to be dependent upon the particular packing material. It also would likely reduce the experimental inconsistencies previously noted in regards to differing $\alpha$ and n values obtained from one study to the next.

The characteristic lengths for the Reynolds number employed in the Shulman and Onda correlations also need to be examined. The Reynolds number is a measure of fluid turbulence and the appropriate characteristic length (in analogy to pipe flow) is one which measures an equivalent fluid flow diameter. For air flow in packed columns, this diameter will remain the same regardless of the actual air loading rate. Although the air flow diameter will be decreased by an increasing water loading rate, this effect may be assumed negligible since normal operation is well below flooding conditions, and the relatively small volume of water present in the column should not restrict the air flow diameter to an unreasonable degree. Therefore, a measure of the dry packing size seems a proper term to incorporate into the gas-phase Reynolds number. Both the Shulman and Onda models use the total specific surface area of the packing to characterize the dry packing size. The Onda relations employ an indirect measure of the diameter term as represented by the inverse of the dry packing specific surface area. In this case, smaller equivalent pipe diameters correspond to larger specific surface areas. Although this may at first seem inconsistent, it becomes clear in that larger specific surface areas generally correspond to smaller nominal-sized packings. The Shulman equations, on the other hand, incorporate the diameter of a sphere which possesses an equivalent surface area as a single piece of packing. The concept of an equivalent diameter term based on a specific packing's size and shape appears more appropriate as compared to the indirect term utilized in the Onda model.

For water flow in a packed column, the liquid flow diameter will significantly change based on the actual liquid loading rate (air, as a compressible fluid, would not affect the water flow diameter). The Reynolds number for film flow of a liquid is given as $\Gamma/\mu$ where $\Gamma$ is the liquid rate per length of wetted periphery [70]. As the effective wetted periphery per unit cross section of a column is numerically equal to the effective area of packing per unit volume, $\Gamma$ equals $L/a_e$ [70]. This is exactly the form of the liquid-phase Reynolds number seen in the Onda correlation. The Shulman model, on the other hand, continues to use the same measure of dry packing flow diameter found in the air phase relation. Since this value remains constant for a given packing, changes in the equivalent flow diameter (effective wetted periphery) due to variations in the water loading rate are not taken into account. Furthermore, as the water flows only over roughly one-half of the total packing surface area, the use of a "dry flow" area does not seem appropriate to begin with. Finally, one may again look to see if similar factors affect the two phases in a similar manner. For the Shulman correlation, using the exact same form of the Reynolds number for both phases, the liquid-phase transfer rate varies with Reynolds number raised to the 0.45 power, while the gas-phase value is proportional to the Reynolds number to the 0.64 power. In contrast, the Onda model shows the liquid-phase power to be 0.67, while the gas-phase power is 0.70. The power values are in close agreement except for the Shulman liquid-phase correlation which is exactly where the theoretical question over the proper flow diameter term arises.

One particular problem with differing power values can be seen by considering the resulting resistance ratio:

$$\frac{k_G}{k_L} \propto \frac{G^a}{L^b} \tag{32}$$

For the Shulman equations, a=0.64 and b=0.45. Therefore, unlike for the Onda model, the Shulman phase resistance ratio is not constant for a given air to water ratio, but rather depends on the actual magnitude of both loading rates. Consider, for example, a changing air to water ratio: if the ratio is decreased, it is possible to accomplish this either by raising both loading rates or lowering both values by appropriate amounts. However, the resulting new resistance ratio may either be larger (for the larger flows) or smaller (for the smaller flows) than the original ratio, as illustrated by the following general example:

| $\frac{G}{L}$ | $\frac{G^{0.64}}{L^{0.45}}$ |
|---|---|
| 3/1 = 3 | 2.02 |
| .2/.1 = 2 | 1.01 |
| 20/10 = 2 | 2.41 |

Such varying behavior is not consistent with the general transfer unit performance model, where the air to water ratio is the controlling factor independent of absolute flow rates.

Sherwood Number: Like the Reynolds number, the Sherwood number also raises concerns in defining an appropriate characteristic length. Such a length needs to be in accord with diffusional considerations. For the liquid-phase, an appropriate measure would be one based on the depth of the liquid stream flowing over the packing. Increased depth leads to lower transfer rates per volume of liquid, and a Sherwood number which incorporates a depth term as the characteristic length would correctly model the phenomenon. Recognizing this, Onda et al. [45] first proposed a direct measure for liquid depth consisting of the liquid hold-up value (the quantity of water contained in the column at a given time) divided by the wetted surface area. However, liquid hold-up, as at the time of the original work, remains a poorly understood subject area [55]. Therefore, the equation for the depth of a laminar layer as it flows across an inclined plane was chosen by Onda et al. as a measure of the relative depth of the interfacial region. After some further simplifications, an equation was arrived at which included incorporation of the Galileo number (see equation {29a}). This particular dimensionless number accounts for gravitational considerations, which especially appears appropriate since the liquid flows down through the column under the force of gravity. Although the underlying basis for this initial analysis was the film theory, the general equation obtained was alternatively arrived at by Onda et al. [45] using penetration theory and strict dimensional analysis. Therefore, the Onda liquid-phase relation appears theoretically sound in this regard. For the gas-phase, a similar diffusional length term would be the nominal radius of the packing, since the air occupies most of the space in a packing unit while the liquid flows over the packing surface. The usage of dry specific surface area as the characteristic length in the Onda gas-phase relation represents an indirect measure of this radius.

The Shulman model, on the other hand, continues to use an equivalent diameter term reflecting the surface area of dry packing as a universal characteristic length. For the gas-phase Sherwood number, this appears to be slightly preferable to the specific dry packing surface area term seen in the corresponding Onda relation. However, its usage in the liquid-phase Sherwood number fails to take into account the physical phenomena that these different dimensionless numbers are attempting to model.

Packing Parameters: The incorporation of specific packing parameters is next examined. As previously noted, the empirical "n" value used in the Sherwood and Holloway correlation to modify the Reynolds number would not be expected to be a function of packing type; this discrepancy could be resolved via the introduction of a dimensionally sound Reynolds number. Therefore, packing effects would be represented by the $\alpha$ value alone, with the need to experimentally determine the appropriate $\alpha$ for each general shape and nominal size of packing.

The Shulman model generally accounts for the effects of different packing sizes within the basic dimensionless numbers through the characteristic length terms. However, for the gas-phase transfer coefficient, a factor reflecting the effects of void space is also included. Whether such a term would apply unaltered to plastic packings which have significantly larger void spaces than the ceramic counterparts considered in the defining data base for the Shulman relations remains to be seen.

The Onda equations incorporate a final dimensionless number, the "shape factor," which seeks to account for packing variations. The liquid-phase value was determined to be directly proportional to this factor, while the gas-phase value was found inversely related to it. No explanation was offered in the original work [46] for the difference in relative dependency between the two phases. The shape factor may not be adequate for the Onda gas-phase correlation, since it is necessary to employ two apparent values for the leading constant term, 2.0 for small (<15 mm) packings and 5.23 for larger packings. Again, no explanation was given in the original work [46] for this change in constant values.

Interfacial Area: The Shulman correlation represents the most fundamentally acceptable modeling approach by separately determining the actual effective interfacial area. However, the assumption made by the Onda model in using the wetted packing surface area as an estimate may not be in serious error. First, a listing of components which make up the effective interfacial area include:

1) Wetted area of packing.
2) Droplets falling through the column.
3) Ripples on the liquid surface.
4) Gas bubbles rising through liquid pools.
5) Water film running down column walls.

From this list, items 2 through 5 would lead to an increase in the effective interfacial area over that of the wetted area. However, offsetting this increase would be the formation, due to liquid hold-up, of isolated pools of stagnant water which are relatively ineffective for mass transfer. In any regard, compared to the wetted area value, these other items may well represent only second-order effects. Secondly, in looking at gas flow effects, Shulman et al. [58] found the effective interfacial area to be relatively independent of gas loading rates, in agreement with accepted views [5]. Following such expectations, the Onda wetted surface area equation is independent of air flow rates.

In any case, the use of wetted packing surface area, although perhaps an oversimplification, offers a parameter which has been correlated numerically. The incorporation of surface tension effects allows the model to be applied to all available packing materials directly. On the other hand, the lack of generality in determining the effective interfacial area for a wide variety of practical situations represents a crucial deficiency in the Shulman model.

**Experimental Comparison.:** The single study available in the literature offering direct comparison of the three correlations for VOC stripping applications was performed by Roberts et al. [54]. The test packing was 1/2-inch ceramic Berl saddles. Empirical packing parameters were obtained from the original work of Sherwood and Holloway [57]. The effective interfacial areas were available from the original presentation by Shulman et al. [58]. The reported accuracy values based on relative standard error were:

1) Sherwood & Holloway Correlation - 33%
2) Shulman Correlation - 58%
3) Onda Correlation - 21%

The Shulman model had a strong tendency to underpredict at low mass transfer values, while overpredicting at high transfer rates. This may be explained by a deficiency previously noted with the underlying theory in respect to the Reynolds number. In the Roberts study, tests were conducted under an air to water ratio of 1, but in one case it was achieved with loading rates of 1 liter/minute each, and in the second case the values were 10 liters/minute. At flow rates of 1 liter/minute, the relative ratio of predicted $k_G / k_L$ will be lower than at 10 liters/minute. This, in turn, will yield a lower predicted $r_L / r_G$ ratio, indicating increased relative gas-phase resistance at the lower loading rates. This inflated relative resistance at low flow rates, if inaccurate, would result in a tendency to underpredict true mass transfer values, while leading to an overprediction at higher flow rates. Such a trend was indeed noted for the data reported in the Roberts study.

The Roberts study indicated that the simplifying assumption of liquid-phase control for mass transfer was valid only for highly volatile solutes such as oxygen and dichlorodifluoromethane. For moderately volatile solutes such as tetrachloroethylene, trichloroethylene, and chloroform, however, the gas-phase resistance was found to affect the overall transfer rate to an increasing degree with decreasing solute volatility. The importance of gas-phase resistance is greatest at lower air to water ratios, as generally predicted by the Onda relations. However, although the Onda correlation modeled this phenomenon significantly better than either the Sherwood-Holloway or Shulman correlations, the Roberts study data indicated that a sharper transition from liquid-phase to gas-phase control exists than predicted by the Onda model.

The Roberts study concluded that for the typical VOCs encountered, operation at a minimum stripping factor of 10 is needed to justify the neglection of gas-phase resistance (as assumed by the Sherwood-Holloway correlation) with less than a 10% error. However, as outlined in the typical column operation section of this report (section 3.1.1.4), the economical design region lies at stripping factors varying from 3 to 5. Therefore, it appears that gas-phase resistance should always be accounted for in predicting the performance of packed towers in stripping VOCs.

### 2.2.4 Summary of Analysis

From both a theoretical and experimental standpoint, the Onda model represents the most promising mass transfer correlation available. The

Sherwood-Holloway correlation suffers from theoretical deficiencies and does not appear to be valid for VOC stripping operations where significant gas-phase resistance affects transfer rates. The Shulman model lacks necessary generality and performed the worst in the Roberts comparative study, probably due to the apparent theoretical deficiencies noted in the preceding analysis. The Onda model generally conformed to theoretical expectations, and Roberts study clearly indicated that its predictive ability surpasses the other models.

Therefore, the Onda correlation was selected for further evaluation in predicting mass transfer rates for packed column VOC stripping operations. From the previous discussion, three areas of concern were kept in mind during the subsequent evaluation. First, the coefficient on the liquid-phase Schmidt number could be potentially modified from the 1/2 to the 1/3 power in line with general experimental results and combined film-penetration behavior theories. Secondly, the gas-phase relation was questioned due to the fact that two different constant values are needed based upon the nominal packing size. Supporting this contention was the fact that the Roberts study concluded that gas-phase resistance was apparently underestimated by the correlation. The specific focus area for potential modification would be the shape factor. Finally, in regards to the effects of particular packing configurations on performance results, the analysis suggested by Gossett _et al._ (equation {31}) for simple modification of the Onda relations was used.

# CHAPTER 3
# METHODS AND MATERIALS

## 3.1 DATA BASE FORMULATION

### 3.1.1 General Evaluation Criteria

### 3.1.1.1 End Effects

The transfer unit approach for evaluating packed column performance (outlined in section 2.1.3) will provide true mass transfer rates only if the removal term used to compute the number of transfer units (see equation {11}) is based strictly on the removal which occurred within the packing itself [64]. For an actual system, however, some removal will also take place during both the introduction of the water at the top of the column via a distribution system and as the water falls off the lower packing support plate into the wet well below. Spray nozzle distribution units in particular can cause this "extra" removal, although the installation of mist eliminators at the top of the column (as typically practiced) will mitigate much of the effect [63]. This overall additional mass transfer phenomenon is termed "end effects." Common sampling techniques utilizing influent line samples prior to column introduction and effluent samples from the wet well represent uncorrected data. Such data yield higher removal rates than that actually caused by the packing itself, This resulting in subsequent calculation of higher NTU, lower HTU, and higher mass transfer rates than the corresponding "true" values for the respective terms.

A simple method can be arrived at to determine and eliminate end effects for a specific system. First, recognizing that

$$NTU_{(\text{Packing})} = NTU_{(\text{Measured})} - NTU_{(\text{End Effects})} \qquad \{33\}$$

and combining this with the basic transfer unit equation {4} yields:

$$NTU_{(\text{Measured})} = \left(\frac{1}{HTU}\right)(Z) + NTU_{(\text{End Effects})} \qquad \{34\}$$

From this relation, end effects can be evaluated by operating a pilot column at different packing heights under the same loading conditions. This is easily accomplished by providing sampling ports at regular intervals in a pilot column, with the samples taken down the length of the column effectively representing increased packing heights. For given loading conditions, a plot of $NTU_{\text{Measured}}$ versus packing depth (sampling port depth) should be linear with a slope of $1/HTU$ and an intercept of $NTU_{\text{End Effects}}$ .

The procedure outlined above greatly increases sampling requirements. Fortunately, the analysis is not always required. Referring back to equation {33}, $NTU_{\text{Measured}}$ can be used as an estimate for $NTU_{\text{Packing}}$ without serious error if $NTU_{\text{Packing}} >> NTU_{\text{End Effects}}$ . As end effects are independent of packing height, $NTU_{\text{End Effects}}$ remains constant. $NTU_{\text{Packing}}$, on the other hand, increases directly with packing height. Therefore, a sufficiently tall column will meet the above requirement to justify neglecting $NTU_{\text{End Effects}}$ .

Viewing this from a different perspective, the removal caused by end effects remains constant, while increased packing depth increases the removal due to the packing itself. Therefore, for pilot columns approaching full-scale heights, the additional end effects removal will be dwarfed by the packing removal, and resulting errors are small [55]. It becomes much more critical to account for the end effects phenomenon with lab-scale columns (say <6 feet in depth). For example, Umphres et al. [64] found in stripping low-volatile trihalomethanes that up to one-half of the total measured NTU could be attributed to end effects at packing heights of 1.75 and 3.75 feet.

While data corrected for end effects was desired in establishing the data base, most of the reported studies did not take into account this phenomenon with samples simply taken from the influent and effluent lines. However, the test columns used generally contained at least ten feet of packing material, and therefore the resulting error is expected to be relatively minor. It will be emphasized again that errors due to end effects yield an apparent mass transfer rate which is higher than the true value for the packing alone.

#### 3.1.1.2 Channeling

When the packing material is placed in a column, there is a natural tendency for the packing to arrange itself such that the packing density (pieces per volume) is less in the immediate vicinity of the tower walls [63]. As a result, the liquid flow tends to migrate towards the walls, while the air flow will concentrate up through the center of the column. Therefore, the entire volume of packing is not effectively utilized. This phenomenon is termed "channeling" and leads to reduced removals via a reduction in the effective interfacial area for mass transfer along with lower average liquid residence times in the column. Similar effects may be noted for both poor liquid distribution systems and due to the improper initial placement of the packing material which can result in the formation of large internal void spaces [29].

Channeling effects can be detected in pilot systems both visibly and from plots of observed NTU versus packing depth under constant loading conditions [64]. In the later case, a non-linear plot may indicate that significant channeling had taken place since the effects of channeling increase as the packing depth increases, yielding a decrease in the relative removal per foot of packing. This will result in calculated NTU values which tend to level off rather than steadily increase as the packing depth increases. Correspondingly, the height of a transfer unit (equal to 1/slope for a plot of observed NTU versus packing depth from equation {34}) would appear to increase as the packing depth increased, when HTU should remain independent of packing depth.

Channeling effects can be minimized via two approaches. The first method, critical for pilot-scale systems, is to maintain a minimum ratio of the column diameter to the nominal packing size. An absolute minimum value of 8/1 is typically cited with a recommended ratio of at least 15/1 [63]. The second remedy involves the installation of redistribution rings positioned at regular intervals within the column. The maximum recommended vertical distance between the rings is from 2 to 10 times the tower diameter [7]. For all the studies considered, at least one of the two measures cited were employed within these general guidelines. Therefore, serious channeling problems were not expected to be visible from the results of the selected studies.

#### 3.1.1.3 Flooding

The design of a packed column includes consideration of air pressure drop characteristics, usually in regards to economical operation in terms of blower costs. However, under certain extreme operating conditions, the resulting pressure drop can also greatly affect performance [21,29,63].

Air flow through a packed column is analogous to gas flow through a restriction. Given a particular packing and a constant liquid loading, the pressure drop increases with increasing air flow as indicated by the generalized log-log plot presented in Figure 5. From this plot, three distinct regions can be identified. First, at relatively low air loading rates, a direct linear relationship is noted between the air flow and the resulting pressure drop. In this region, the liquid hold-up (the quantity of liquid contained in the packed column) is relatively constant despite any change in the air flow rate. Pressure drop increases are due mainly to increased fluid friction at higher air loadings.

As the air flow becomes sufficiently large, a region is reached where significant increases in liquid hold-up occur. The initial boundary for this region is termed the "loading point" and is typically defined

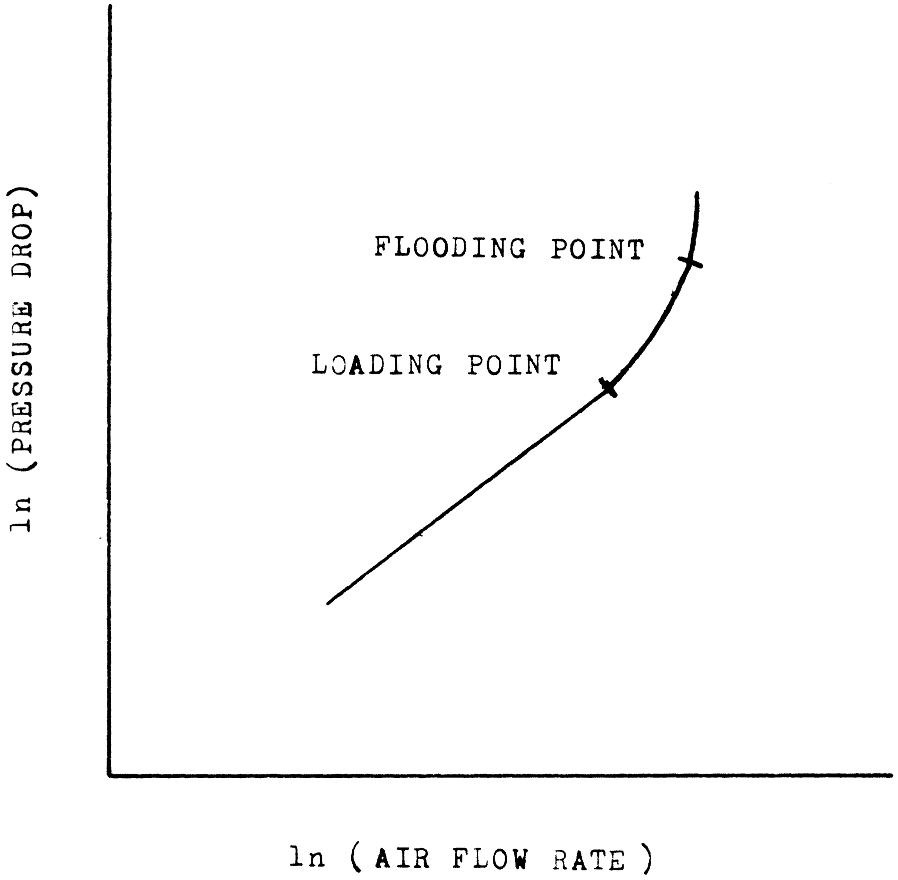


Figure 5. Generalized pressure drop relationship at a given liquid loading rate. Adapted from Treybal [63].

where the slope of the curve exceeds two [29]. Within this operational area, the liquid hold-up rapidly increases with the air flow rate. The additional volume of liquid reduces the effective area for air flow, leading to a rapid increase in pressure drop. The enhanced hold-up also leads to increased liquid flow depths over the packing and the formation of stagnant pools, both of which decrease performance via a reduction in the effective interfacial area. Some offset is realized, however, since the average liquid residence time in the column is increased, providing a longer air-liquid contact period for mass transfer to take place.

Finally, as the air loading is still further increased, flooding conditions are reached. Visible indications of flooding include the formation of a liquid layer at the top of the packing, at the redistribution rings, or at the bottom packing support [63]. Entrainment of the liquid by the air ensues, the column fills with water, and the air pressure drop increases infinitely. A "burping action" then occurs, with a water slug passing through the column followed by air slug. Performance is highly reduced and practical operation is not possible.

A more generalized plot accounting for variations in liquid flow rates is given in Figure 6. The primary effect of increased liquid loading is in physically occupying the available void space, thereby reducing the effective area for air flow. Therefore, at a fixed air loading rate, the air pressure drop will increase with increased liquid flow.

Further review of such general effects leads to the identification of two extreme operating conditions. Both cases are important to consider

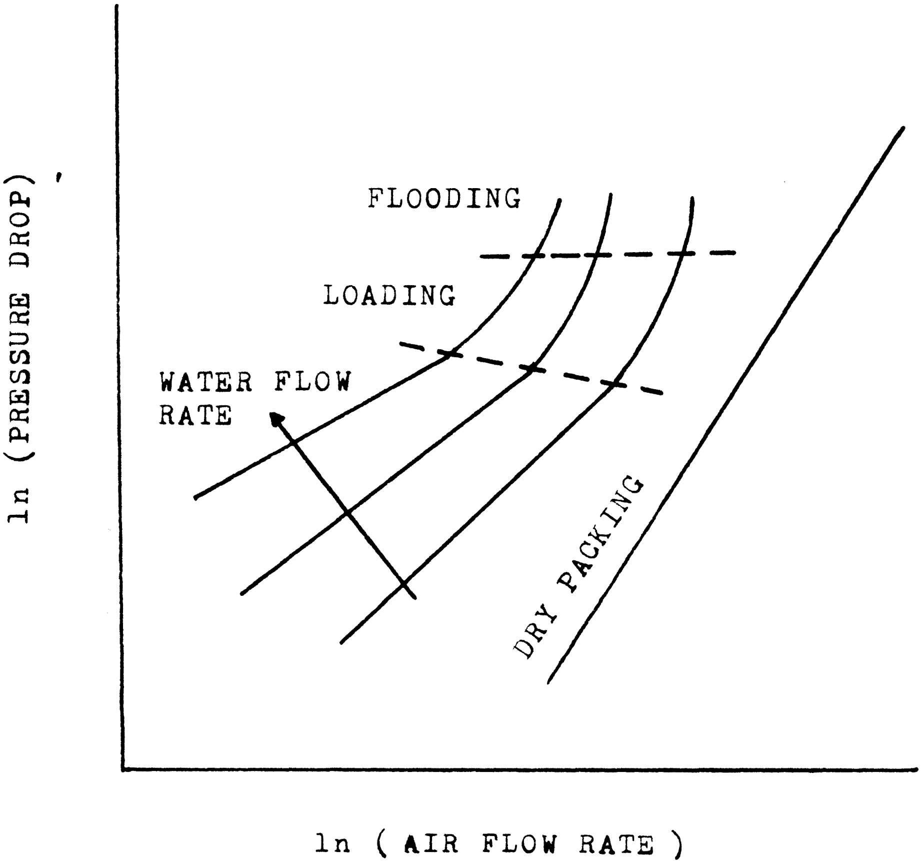


Figure 6. Generalized pressure drop relationship under varying liquid loading rates. Adapted from Treybal [63].

since they represent predictive limits for the evaluation of mass transfer correlations. The first case involves a low absolute liquid load at a high air to water ratio, conditions which yield the highest removal efficiencies obtainable for a given system. Under such operation, the relative liquid hold-up is greater than for a low or moderate air to water ratio, thereby offering the benefits of longer liquid residence times. Also, since the liquid flow itself is so low, the wetted surface area of the packing may increase to a significant extent due to the turbulent action of the large air flow "flattening out" the low mass of water present over more of the packing surface area. Such gas loading rate effects on interfacial area for low liquid flows have previously been noted by Shulman et al. [58]. Thus, these two processes will result in enhanced performance under such loading conditions.

The second extreme case involves a high absolute liquid load at a low air to water ratio, conditions which result in the lowest removal efficiency for a given system. For this situation, the low air flow will cause relatively little turbulence within the large liquid mass stream. Also, the increase in wetted packing surface area is relatively small since the large water mass, already covering a large portion of the packing surface, will tend to build up in depth rather than spread out in breadth. Therefore, relative performance is diminished. In addition, as lower air to water ratios yield increased relative gas-phase resistance, transfer rates are further reduced. As operation at high liquid loading and low air to water ratios can offer economical system designs, such effects are particularly important to consider and accurately model.

Empirical flooding curves for packed columns are available [20,63]. However, inconsistent experimental results question the use of these generalized plots, as flooding conditions have been noted in several cases where it was not predicted theoretically [2,55]. Typical operations are believed to be at or just below the loading point [63,65]. Therefore, the possibility of reduced performance due to operation above the loading point must be kept in mind.

### 3.1.1.4 Typical Ranges For Operational Parameter Values

To properly mimic full-scale operation, pilot scale studies should reproduce anticipated conditions as much as possible. Therefore, such conditions must be established. Typical water loading rates suggested by Bishop & Cornwell [3] range from 10 to 50 gpm per square foot (0.4 to 2.0 $m^3/m^2$). Air loadings are based upon the stripping factor chosen. The appropriate values for this factor (given on a volume basis) are discussed below.

The results of various optimization studies [1,11,25,32,53,64] give design ranges for the stripping factor based upon the particular VOC to be removed. From strictly a performance standpoint, the design graph previously presented in Figure 3 can be considered. Based on the graph, Kavanaugh & Trussell [32] put forth that stripping factors between 2 and 5 are most appropriate. Below 2, the number of transfer units required rapidly increases, resulting in a sharp increase in required tower height. Above 5, there is little reduction in the required NTU; therefore, the required tower height essentially remains the same.

Other factors, such as tower diameter and air pressure drop must also be reviewed to arrive at an economical design. Several studies have looked at such considerations, utilizing both the Sherwood-Holloway and Onda correlations for predicting mass transfer rates. The results are summarized below.

Umphres et al. [64], looking at trihalomethane removal using the Sherwood-Holloway correlation for mass transfer rates, recommended a design combination of low air pressure drop, low water loading rate, and a stripping factor from 3 to 5 for cost effectiveness. The optimum stripping factor was given as 4; cost savings below 4 were marginal and the tower's performance became sensitive to changes in the stripping factor below a value of 3. Operational expenditures in the form of air blower costs were found to have the greatest influence on total system economics.

Ball et al. [1] presented a typical design example for chloroform removal using the Sherwood-Holloway model to generate mass transfer data. The favorable design range for stripping factors varied from 3 to 10. An optimum range of 3 to 4 was cited with respect to minimizing capital costs (represented by required tower volume), while values from 5 to 10 were determined optimal with respect to operating expenditures (reflected in air blower and water pumping requirements). Overall, the most economical conditions existed at a stripping factor of 5. The strong influence of operating costs on optimum design was noted with very low design air pressure drops (10 to 50 $N/m^2/m$) suggested. Again, stripping values below 2 were not recommended since the sharp decline in performance leads to excessive column height requirements.

Hand et al. [25], in a detailed design example involving removal of trichloroethylene with the Onda correlation used for mass transfer predictions, presented design curves which indicated economical stripping factors ranging from 2 to 4.5, with 3 as the optimum value. This range held for both capital and operating costs, and included air pressure drops from 50 to 400 $N/m^2/m$. An air pressure drop of 50 $N/m^2/m$ was recommended for design.

Cummins and Westrick [11], for 90+% removal of trichloroethylene, reported an optimum stripping factor range from 2.5 to 4.5, with an optimum air pressure drop from 150 to 250 $N/m^2/m$. The Sherwood-Holloway relation was utilized in estimating mass transfer rates.

Finally, Roberts and Levy [53], in looking at trihalomethane removal using the Onda correlation, cited an economical stripping factor range of 2 to 5.

The overall results from these studies indicate that the optimum design region lies within a stripping factor range from 3 to 5. Based upon reliable Henry's constant values for a particular VOC at a given temperature, the corresponding optimum air to water ratios can be calculated. A summary of such values for the VOCs considered by this study is presented in Table 2 below. The optimum design air pressure drop seems to lie between 50 and 250 $N/m^2/m$ (0.06 to 0.31 inches of water per

Table 2. Optimum Design Air To Water Ratios For Selected VOCs

| Compound | Air to Water Ratio (vol / vol) | Assumed Henry's Constant Relation |
|---|---|---|
| Tetrachloroethylene | 8 - 14 | Gossett *et al.* - EPICS Method [23] |
| 1,1,1-Trichloroethane | 8 - 13 | Gossett *et al.* - EPICS Method [23] |
| Trichloroethylene | 14 - 23 | Gossett *et al.* - EPICS Method [23] |
| Trans-1,2-Dichloroethane | 11 - 18 | Ervin *et al.* [21] |
| Toluene | 19 - 31 | Leighton & Calo [34] |
| Benzene | 22 - 37 | Leighton & Calo [34] |
| Methylene Chloride | 45 - 74 | Gossett *et al.* - EPICS Method [23] |
| Chloroform | 38 - 63 | Nicholson *et al.* [42] |
| Bromodichloromethane | 71 - 118 | Nicholson *et al.* [42] |
| Dibromochloromethane | 130 - 216 | Nicholson *et al.* [42] |
| Bromoform | 264 - 440 | Nicholson *et al.* [42] |

NOTE: Based on an optimum stripping factors range of 3 to 5. Assumed water temperature of 55° F (typical groundwater temperature).

foot of packing), below the typically cited range of 200 to 400 N $/m^2/m$ [32,63]. This is probably due to the prevailing use of plastic packings, which possess a much larger void space than the older ceramic packings, resulting in lower air pressure drops.

Temperature represents another important parameter. For volatile SOC contamination of groundwaters, water temperature would not be expected to fluctuate to any significant degree year round. However, depending upon location, a U.S. Geological Survey study [66] cited by Tchobanoglous & Schroeder [61] found the temperature of non-thermal wells to range from 40 to 80° F. For trihalomethane contamination of surface waters, however, wide temperature fluctuations on a yearly basis are noted. As an example, river water temperatures can range from a low of 33 to 37°F in the winter to a high from 74 to 80°F in the summer for much of the U.S. [61]. Therefore, mass transfer correlations need to take into account changes due to water temperature fluctuations from 33 to 80°F, be it because of geographic location or time of year.

Given these established operating regions, mass transfer correlations can be effectively evaluated for design purposes. Correlation errors involving testing conditions significantly removed from these ranges would not seriously question a model's practical usefulness. Instead, the critical assessment for a proposed correlation lies in the results seen under typical full-scale operating conditions.

### 3.1.2 Selected Data Base Literature Studies

The studies chosen from the literature encompass a wide variety of operations since the individual investigators generally sought different objectives in conducting their respective pilot tests. Therefore, the data base created for this work provides for an extensive evaluation of the Onda model. Ten reports were selected for evaluation. Overall, eleven VOCs were tested in these studies using various sizes of rings, saddles, Tri-Pack, and Tellerette packing materials. Loading rates utilized ranged from 15 to 214 cfm per square foot (4.6 to 65 $m^3/m^2$) for air and 4 to 66 gpm per square foot for water (0.16 to 2.7 $m^3/m^2$), yielding air to water ratios ranging from 5 to 103 (volume basis). Water temperatures ranged from 43 to 86°F (6 to 30°C). A total of 449 data points were evaluated. A summary of the studies selected including pertinent test conditions for each is given in Table 3. Original raw data gathered from each report is included in Appendix A. A general outline and discussion of the individual studies is presented below.

The study performed by Gossett et al. [23] represents the most comprehensive research work reported to date. Five separate VOCs (tetrachloroethylene, trichloroethylene, 1,1,1-trichloroethane, chloroform, and methylene chloride) were added to a finished water source for testing. Samples were taken at one-foot intervals along the column length to directly account for end effects. In the first phase of the study, the effects of temperature were evaluated over the 50 to 86°F range using 1-inch ring packings at a fixed loading condition. Next, isothermal

Table 3. SUMMARY OF REPORTED PILOT-SCALE STUDIES SELECTED FOR THE TEST DATA BASE

| Study | VOCs Investigated | Packing Size & Type | Packing Height (ft) | Column Diameter (inches) | Water Temp. ($^{o}$F) | Loading Rates | | Air to Water Ratios (vol / vol) |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Air (cfm/ sq ft) | Water (gpm/ sq ft) | |
| 1) Gossett *et al.* [23] | Tetrachloroethylene<br>1,1,1-Trichloroethane<br>Trichloroethylene<br>Chloroform<br>Methylene Chloride | 5/8", 1", 2" Pall Rings<br>1" Saddles<br>2" Tri-Packs | 8 | 17.5 | 50-86 | 15-164 | 15-34 | 5-84 |
| 2) Cummins - Louisiana Site [9] | Benzene<br>Toulene | 1" Saddles | 18 | 24 | 68 | 47-181 | 9-66 | 8-88 |
| 3) Cummins - Multiple Sites [12] | Trichloroethylene | 1" Saddles | 18 | 24 | 55 (avg.) | 42-115 | 10-63 | 5-80 |
| 4) Gross & TerMaath [24] | Trichloroethylene | 1" Pall Rings | 8 | 7.5 | 50-86 | 21 | 21 | 7.5 |
| 5) Malcolm Pirnie (Raczko Report) [48] | Trichloroethylene | 1" Saddles | 10 | 12 | 55 | 37-140 | 9-64 | 7-103 |
| 6) Malcolm Pirnie - Connecticut Site [27] | Trichloroethylene | 1" Saddles<br>1" & 2" Tellerettes | 10 | 12 | 54 | 15-108 | 13-36 | 5-60 |
| 7) Malcolm Pirnie (Cline Report) [6] | Trichloroethylene | 1" Saddles | 9.5 | 12 | 79 | 56-191 | 17-46 | 10-47 |
| 8) Malcolm Pirnie - Pennsylvania Site [27] | Tetrachloroethylene<br>1,1,1-Trichloroethane<br>Trichloroethylene | 1" Saddles | 10 | 12 | 57 | 31-95 | 25-38 | 7-26 |
| 9) Byers & Morton [4] | Tetrachloroethylene<br>Trichloroethylene<br>Trans-1,2-Dichloroethane | 1/2" Ceramic Saddles | 8 | 4 | 43 & 68 | 45-112 | 7-22 | 15-100 |
| 10) Umphres *et al.* [64] | Chloroform<br>Bromodichloromethane<br>Dichlorobromomethane<br>Bromoform | 1" Saddles | 1.75 to 7.67 | 12 | 55 | 53-214 | 4-16 | 100 |

studies were conducted using several types of packings (rings, saddles, and Tri-Packs) of varying nominal sizes. An extensive range of operating conditions were evaluated in this second phase. Several series of experiments were conducted under constant air loading rates, followed by similar tests at constant water loading values. For data analysis, the authors compared actual results with those predicted by the Onda model.

The Gross & TerMaath study [24] reports on the full-scale system designed for trichloroethylene removal at an Air Force installation located in Michigan. In this context, a temperature dependency relationship (covering the range from 50 to 86°F) for the overall mass transfer rate under a single set of loading conditions was presented.

The studies reported by Cummins [9] and Cummins & Westrick [12] represent work conducted by the EPA in test-stripping contaminated water sources on-site using a portable packed column. The 18-foot tower with multiple sampling ports allowed for the establishment of concentration profiles through the depth of the column, directly eliminating end effects. The report by Cummins & Westrick [12] examined trichloroethylene removal at eight sites around the country. By utilizing the same packing and conducting the tests under identical loading conditions, potential site-specific effects on stripping operations were evaluated. The report by Cummins [9] involved a gasoline spill in Louisiana with the resulting major groundwater contaminants being benzene and toluene. Therefore, the stripping of aromatic compounds was investigated. Both studies included comparison of results with predictions by the Onda correlation.

Four on-site studies conducted by Malcolm Pirnie, a consulting engineering firm, were selected from the literature. The report by Raczko et al. [48] examined trichloroethylene removal at two sites. These tests evaluated operational behavior at the extremes of VOC concentration levels encountered in practice. Three separate influent concentration ranges were tested at the sites: 23-34, 1100-2500, and 26,000-28,000 ug/l. The Connecticut site report [27], looking at the stripping of trichloroethylene, compared performance between two different packing configurations, saddles and Tellerettes. The study performed by Cline et al. [6] also investigated the removal of trichloroethylene. Located in Arizona, this site featured an extremely high groundwater temperature of 79°F, representing the highest natural water temperature likely to be encountered in typical practice. The final study reported by this firm [27] involved a Pennsylvania site contaminated with multiple VOCs (trichloroethylene, tetrachloroethylene, and 1,1,1-trichloroethane).

The Byers & Morton study [4] tested spiked tap water containing four VOCs (trichloroethylene, tetrachloroethylene, trans-1,2-dichloroethane, and 1,1,2,2-tetrachloroethane). Experiments were conducted at 43 and 68°F to determine temperature effects on stripping performance. The packing utilized (1/2-inch ceramic saddles) is unique in the data base because of its small nominal size and material of construction.

Finally, the study reported by Umphres et al. [64] examined trihalomethane removal at varying water flows rates while maintaining a constant air to water ratio. The water source was a treated municipal water supply that contained THMs in the 100 to 300 ug/l concentration range. Separate experiments conducted at different packing heights allowed for end effects calculations.

## 3.2 COMPUTER MODEL FORMULATION - INPUT PARAMETERS

### 3.2.1 Introduction

All modeling work was performed on an IBM personal computer system, utilizing the BASIC programming language. Programs were established to read appropriate values from separate data files representing each study considered. One program determined the observed mass transfer values, while a separate program calculated the predicted transfer rates based on the Onda correlation. Each program output provided a list of input and intermediate values used in the various calculations. A third program compared the resulting transfer rates and performed simple statistical analysis (average error and relative standard deviation values). The raw data is contained in Appendix A. The calculation of required input parameters is discussed below, with the specific relations detailed in Appendix B. The actual computer programs along with sample printouts are provided in Appendix C.

### 3.2.2 Henry's Constant

**Introduction:** Previous investigators [4,32] have stressed the need for experimental work to determine accurate Henry's constant values for common VOCs at the low concentration levels encountered in water treatment situations. The relationships presented by Kavanaugh & Trussell [32] and Dilling [14], cited in the work performed by other investigators

[1,2,16,36], were computed from solubility data and the partial pressure of the pure liquid under the given conditions. However, accurate solubility data for the VOCs of concern is often unavailable, and such computations typically require extrapolation from work conducted at high concentrations to the low concentration levels encountered in practice. Such estimations are therefore given only an order-of-magnitude confidence level [55]. In response to this uncertainty, Henry's constants have been used both as a curve-fitting device [9,10,12] and as a possible explanation for differing results from site to site due to changes in water characteristics [2,33]. However, recent experimental work has now apparently established values within reasonable certainty (20%) by separate investigators employing different measurement techniques. This work is summarized and discussed below.

First, however, two preliminary items must be addressed. In the reporting of Henry's constants, four distinct forms may be cited, based upon how the air to water ratio is defined. As the dimensionless stripping factor equals Henry's constant times the air to water ratio, consistent units must be used. Therefore, the following relations can be established:

$$H = H'\left(\frac{\rho_a}{\rho_w}\right)\left(\frac{M_a}{M_w}\right) \qquad \{35\}$$

and

$$H = H''\left(\frac{\rho_a}{\rho_w}\right) \qquad \{36\}$$

and

$$H = H_c\left(\frac{M_w}{\rho_a}\right) \tag{37}$$

where:
$H$ - atm (volume / volume)
$H'$ - atm (mole / mole)
$H''$ - atm (mass / mass)
$H_c$ - atm (volume / mole)
$\rho$ - density
M - molecular weight

Since air to water ratios are normally cited on a volume basis, the Henry's constants based on a volume ratio are recommended as this provides for easy computation of raw data values. Published relationships not utilizing volume units were converted via the above equations for direct comparative purposes.

The second point involves the temperature dependency of Henry's constants. Modeling is typically done with a general relation of the form:

$$\log H = a - \frac{b}{T} \tag{38}$$

where: a,b - constants for the particular compound considered

The temperature dependency of Henry's constant has been found to be quite strong, with values approximately doubling for a 20°F rise [32]. As wide variations will occur over the typical operating range (potentially from 33 to 80°F), it is clear that accurate temperature relationships are needed for design purposes.

**Experimental Procedures:** The most common experimental procedure used is the batch air-stripping method first proposed by Mackay et al. [38]. It was shown that the Henry's constant value could be related to the change in concentration of a given compound when stripped from solution by a gas stream. The governing equation is as follows:

$$\ln\left(\frac{C_t}{C_o}\right) = -\left(\frac{H\,G}{V R_u T}\right) t \qquad \{39\}$$

where $C_t$ - liquid phase concentration at time t

$C_o$ - initial liquid concentration

$R_u$ - universal gas constant

V - column volume

T - system temperature

t - time

A semi-log plot of $C_t / C_o$ versus time yields Henry's constant from the slope obtained. The actual liquid phase concentration values are not required due to the incorporation of the ratio term. Several assumptions were made in the development of this method, the two most important being:

1) The rising air bubbles achieve equilibrium with the liquid before exiting the column.
2) The column contents are completely mixed.

Gossett et al. [23] indicated that these two requirements are at cross purposes. The time available for bubble equilibrium is limited by the height of the column. However, by increasing the column height to satisfy this first assumption, the second assumption of complete mixing becomes harder to adequately meet. This problem is shown to be further exaggerated with increased temperature. Another potential limitation for the batch stripping method noted by Gossett et al. [23] exists in determining individual Henry's constant values from VOC mixtures. The results produced appeared affected by kinetic parameters which should not be the case for equilibrium values. As typical concentrations of total VOCs rarely exceed 1 mg/l, the equilibrium relationship for one VOC should be independent of any other VOCs present, unless chemical reactions have occurred. However, such reactions are unlikely as halogenated organics are considered to be extremely inert compounds [14].

In response to these perceived deficiencies, an alternative method was proposed by Gossett et al. [23]. The Equilibrium Partitioning in Closed Systems (EPICS) procedure relies upon measurement of the ratio of headspace concentrations from two equilibrated bottles containing equal solute masses but possessing different liquid volumes. Knowledge of the actual mass added to the two bottles is not required, nor is the actual headspace concentration needed. Surrogate measures such as gas chromatograph peak heights are sufficient as long as they are linearly related to concentration. Based upon comparative results obtained in the Gossett study, the EPICS method was judged by those investigators to be free from the negative effects previously noted for the batch stripping method.

**Experimental Results:** A summary of the relations obtained from a review of the literature is presented in Table 4. Nicholson et al. [42] and Munz

[41] both followed the basic scheme of Mackay, while Leighton & Calo [34] utilized a slightly more complex procedure based upon batch stripping measurements. Gossett et al. [23] performed both batch and EPICS measurements. Finally, Kavanaugh & Trussell's solubility predictions [32] are presented for comparative purposes. The different relations proposed (excepting Kavanaugh & Trussell) agree within 20% over the 40 to 86°F range (5-30°C) these studies covered.

The relations selected for calculation of Henry's constants are as follows. The Gossett EPICS equations were utilized for nearly all of the compounds considered by that study, namely tetrachloroethylene, trichloroethylene, 1,1,1-trichloroethane, and methylene chloride. The Nicholson relationships were chosen for trihalomethanes as only chloroform was investigated in the Gossett study, while Nicholson and co-workers considered all four major types of trihalomethanes. The equations proposed by Leighton and Calo for benzene and toluene were used since other reliable values were unavailable. Likewise, the relation for trans-1,2-dichloroethane was taken from work performed by Ervin et al. [21] as no other source providing this information was found.

A related question which must be addressed is whether Henry's constant values determined in distilled water hold for varying real world water matrices. Nicholson et al. [42], conducted tests with trihalomethanes using distilled water, natural potable water containing high amounts of salts and organic matter, and water with humic material added. No significant differences in the results for Henry's constants were noted. Indirect support of these findings is given by packed column

Table 4. HENRY'S CONSTANT TEMPERATURE RELATIONSHIPS

| Compound | [32] Kavanaugh & Trussell | | [23] Gossett *et al.* EPICS Method | | [23] Gossett *et al.* Batch Method | | [41] Munz | | [42] Nicholoson *et al.* | | [34] Leighton & Calo | | [21] Ervin *et al.* | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (a) | (b) | (a) | (b) | (a) | (b) | (a) | (b) | (a) | (b) | (a) | (b) | (a) | (b) |
| Tetrachloroethylene | 2017 | 6.775 | 2082 | 6.840 | 1867 | 6.059 | 1900 | 6.250 | | | 1914 | 6.234 | | |
| | [.320, | 1.107] | [.217, | .780] | [.214, | .674] | [.252, | .812] | | | [.216, | .703] | | |
| 1,1,1-Trichloroethane | | | 1710 | 5.577 | 1677 | 5.475 | 1700 | 5.550 | | | 1758 | 5.810 | | |
| | | | [.259, | .742] | [.269, | .756] | [.265, | .753] | | | [.298, | .878] | | |
| Trichloroethylene | 1574 | 4.986 | 2000 | 6.329 | 1730 | 5.357 | 2000 | 6.333 | | | 1878 | 5.909 | | |
| | [.205, | .541] | [.132, | .452] | [.132, | .384] | [.133, | .456] | | | [.138, | .439] | | |
| Trans-1,2-Dichloroethane | | | | | | | | | | | | | 2206 | 7.158 |
| | | | | | | | | | | | | | [.161, | .626] |
| Toluene | | | | | | | | | | | 1492 | 4.427 | | |
| | | | | | | | | | | | [.112, | .281] | | |
| Benzene | 1710 | 5.075 | | | | | | | | | 1577 | 4.646 | | |
| | [.082, | .234] | | | | | | | | | [.092, | .242] | | |
| Methylene Chloride | | | 1679 | 4.703 | 1801 | 5.066 | | | | | | | | |
| | | | [.045, | .126] | [.038, | .114] | | | | | | | | |
| Chloroform | 1871 | 5.495 | 1675 | 4.859 | 1736 | 5.033 | 1800 | 5.234 | 2117 | 6.311 | 1627 | 4.673 | | |
| | [.056, | .178] | [.066, | .186] | [.060, | .174] | [.056, | .169] | [.048, | .176] | [.064, | .175] | | |
| Bromodichloromethane | | | | | | | | | 2122 | 6.051 | | | | |
| | | | | | | | | | [.025, | .093] | | | | |
| Dibromochloromethane | | | | | | | | | 2122 | 5.790 | | | | |
| | | | | | | | | | [.014, | .051] | | | | |
| Bromoform | | | | | | | 1970 | 4.948 | 2322 | 6.181 | | | | |
| | | | | | | | [.0070, | .024] | [.0065, | .027] | | | | |

NOTE:

$$\log H = -\frac{a}{T} + b$$

where:
H = atm (volume/volume)
T = degrees Kelvin

Values in [ ] are predicted Henry's constants at 40 and 80° F (4 and 27° C), respectively.

performance studies involving multiple site testing. Cummins & Westrick [12] conducted studies involving the stripping of trichloroethylene at twelve separate sites across the country using the same pilot test column operated under an identical range of loading conditions. The removals achieved at each location were nearly identical, with slight differences being attributable to water temperature variations between the sites. Bilello & Singley [2], in evaluating the stripping results for chloroform removal from three distinctly different water sources, also concluded that performance was not related to the specific water matrix. Therefore, the effects of water composition on Henry's constant values (and column stripping performance) appear insignificant.

### 3.2.3 Operating Temperature Considerations

An important observation is that the influent air temperature has not been found to significantly affect the performance of a packed column. Gross & TerMaath [24], in evaluating a full-scale stripping system, concluded that removal efficiency was not dependent upon the inlet air temperature, which varied from 15 to 50°F for the data reviewed. In addition, no change in water temperature across the length of the tower was detected. Similar effects were noted by Nyer [43]. Cummins [9] determined from taking air temperature measurements within a pilot column that the air temperature quickly adjusted to that of the water, while the water temperature remained essentially constant. This phenomenon can be explained by the fact that the total thermal mass of water contained in a typical packed tower is much greater than the corresponding thermal mass of the air, resulting in the stripping operation occurring at essentially the temperature of the water. This point was confirmed theoretically by Dyksen et al. [17] via heat balance calculations. Using conservative simplifying assumptions, it was determined that even with an inlet air temperature of 0°F at an air to water ratio of 20, the water temperature would remain within 1°F of the assumed influent temperature of 55°F. Therefore, all air property values were calculated based upon the influent water temperature.

### 3.2.4 Liquid Diffusivity

The Wilke-Chang correlation [69] is widely recommended for liquid diffusivity determinations [31,47,49,63], and was the method of choice for use with the Onda correlation. The relation is an empirical modification of the Stokes-Einstein equation, based on the general observation that:

$$F = \frac{T}{D_L \, \mu_L} \qquad \{40\}$$

where F is the diffusing factor, constant for a given solute-solvent system. The diffusing factor was determined by Wilke and Chang to be a function of both the solute's molar volume and the solvent's effective molecular weight. The resulting correlation is:

$$D_L = 7.4 \times 10^{-15} \frac{(\xi M_B)^{1/2}}{V_A^{0.6}} \left(\frac{T}{\mu_B}\right) \quad \{41\}$$

where:

$D_L$ - liquid diffusivity value ($m^2/\mathrm{sec}$)

$\xi$ - association factor for the solvent

= 2.26 for water (recommended by Hayduk & Laudie [26])

$M_B$ - molecular weight of solvent (g/mole)

$V_A$ - molar volume of solute at normal boiling temperature (liters/mole)

T - temperature in degrees Kelvin

$\mu_B$ - viscosity of solvent ( $(N\,\mathrm{sec})/\mathrm{m}^2$ )

Wilke and Chang reported an average error of 10% for the correlation when water is the solvent [69]. Reid and Sherwood [49] found an 11% error based on their comparison of available methods. A subsequent modification by Hayduk and Laudie, decreasing the association parameter for water from 2.6 to 2.26, reportedly reduced the errors noted using this correlation [26]. This modification, recommended by Treybal [63], was utilized in subsequent calculations.

For estimation of molar volumes, the two common methods are given by LeBas and Schroeder [47]. Both involve simple additive procedures where volume contributions for each element in a compound are summed together. The Schroeder and LeBas methods reportedly produce average errors of less than 5% each [49]. For common VOCs, the two methods yield molar volume predictions within 5% of each other. The LeBas method was chosen based on the recommendation of Reid & Sherwood [49].

### 3.2.5 Gas Diffusivity

Several methods are available for estimation of gas diffusivities. Each approach is based upon the kinetic theory of gases which regards gas molecules as rigid spheres experiencing elastic collisions. From this theory, the following expression has been derived for the binary system of gases A & B [59]:

$$D_G = \frac{b\,T^{3/2}}{P\,d^2}\sqrt{\frac{1}{M_A} + \frac{1}{M_B}} \qquad \{42\}$$

where: $D_G$ - gas diffusivity

b - constant

M - molecular weight for gases A and B

T - temperature in degrees Kelvin

P - total pressure

d - distance between the centers of unlike molecules upon impact

One semi-empirical correlation developed from this general theory which was noted in studies involving the Onda correlation [23,55] is the Hirschfelder method. This approach takes into account the molecular forces between atoms. However, it is a rather complex formulation, involving estimation of gas potential parameters which require a tedious number of calculations.

An alternative method, proposed by Fuller <u>et al.</u> [22], is relatively straightforward to use. The semi-empirical equation, derived from kinetic theory principles and based on a curve fit to available data, is:

$$D_G = \frac{10^{-7}\, T^{1.75}}{P\left[(\Sigma v_A)^{1/3} + (\Sigma v_B)^{1/3}\right]^2} \left(\frac{M_A + M_B}{M_A\, M_B}\right)^{1/2} \qquad \{43\}$$

where: $D_G$ - gas diffusivity value ($m^2$/sec)

v - atomic diffusion volume increment (values given in original work)

M - molecular weight of the gases (g/mole)

T - temperature in Kelvin

P - total pressure (atm)

This correlation was cited in the original work [22] as capable of predicting diffusivities within 7% of experimental values and applicable to both polar and non-polar gases. The method is recommended by Lydersen [37] and Perry & Chilton [47], placing the average error value at 10-12%. Reid and Sherwood, in examining 114 measured values encompassing 65 different binary systems, reported that the Fuller method produced a 6.9% average error, while the Hirschfelder method yielded a 7.5% error on the average [49]. Comparison of Hirschfelder values computed by Roberts et al. [55] for common VOCs at 68°F show differences not exceeding 15% with corresponding Fuller correlation values. The Fuller method was chosen for this study as it appears to be quite accurate while being much easier to work with than the Hirschfelder correlation, particularly for incorporation into the computer programs.

### 3.2.6 Basic Air and Water Properties

The basic properties required included density, viscosity, and surface tension. For incorporation into the computer programs, simple temperature relationships were derived to calculate these values. The specific equations, presented in Appendix B, all produce less than 1% error when compared to actual values as reported by Roberson & Crowe [52] over the range of 0 to 100°F.

### 3.2.7 Packing Parameters

The packing parameters required for the Onda correlation are the total specific surface area and the construction material critical surface tension. The surface area values are readily obtainable from several sources [7,23,25,29,47,63] and are based upon manufacturers' specifications. The critical surface tension values for different materials of construction were provided by Onda et al. [46]. However, this original list is incomplete for the packing materials commonly used today, a point which has not generally been noted. For "plastic" packings, the polyethylene value has been commonly used, although many "plastic" packings are in fact made of polypropylene. The critical surface tension for polypropylene was cited by Gossett et al. [23] and applied in this work. Under typical operating conditions, use of the polyethylene value for cases involving polypropylene packings would result in approximately a 3-7% overestimation of the wetted specific surface area, which directly corresponds to a 3-7% overestimation of the mass transfer rate by the Onda correlation. Therefore, the distinction between "plastic" packing materials is a relevant one to keep in mind.

# CHAPTER 4
# RESULTS AND DISCUSSION

## 4.1 GENERAL ERROR ANALYSIS

### 4.1.1 Introduction

The transfer unit (HTU/NTU) performance model and the Onda mass transfer correlation are both fairly complex relations, and the effects of potential experimental errors are not readily apparent. To gain insight as to the specific impact of certain potential experimental inaccuracies on mass transfer results, the following situations were examined. First, an incorrect stripping factor was considered. As the stripping factor consists of three separate components (Henry's constant times air flow divided by water flow), the overall error can be due to any one of the three. The most likely source for significant miscalculation, however, would be expected in the estimation of Henry's constant, a topic discussed previously in section 3.2.2. The second situation involves imprecise influent and effluent concentration measurements. This case is important to consider as determination of VOC levels in the ug/l range can entail significant measurement inaccuracies. The general error analysis results are presented in graphical form below along with a discussion of the specific evaluations performed and the implications observed from the results.

### 4.1.2 Errors in the Stripping Factor / Henry's Constant

From the pilot studies examined, which were generally found to mimic typical full-scale operating conditions, the portion of the total mass transfer resistance residing in the gas phase (as predicted by the Onda correlation) generally was below 20%. Under such conditions, drastic errors in Henry's constant values do not affect the Onda predicted mass transfer rates to a significant degree. For example, assume the predicted gas-phase resistance is 15% of the total resistance, a reasonable figure. In this case, using relative numbers:

$$r_G = 0.15 \quad r_L = 0.85 \quad r_T = 1.0$$

Now, if the true Henry's constant is in fact only one-half the value used for this calculation, then the gas-phase resistance will be double the figure originally predicted. Therefore:

$$r_G = 0.3 \quad r_L = 0.85 \quad r_T = 1.15$$

Note, however, that this results in only a 15% increase in the total resistance, which translates into a 13% [ 1-(1/1.15) ] decrease in the predicted mass transfer rate. Therefore, under normal conditions, the Onda correlation remains relatively insensitive to even gross inaccuracies in the Henry's constant values used. Furthermore, as previously outlined in section 3.2.2, Henry's constants for many common VOCs have now been established by independent investigators to within approximately 20%. Thus, anticipated errors in Henry's constant appear not to be a significant factor in the Onda correlation predictions.

The real effects of incorrect Henry's constant values surface when used in the transfer unit performance model for calculating "true" mass transfer rates. Reviewing this approach:

$$K_L a = \frac{L}{HTU} \qquad \{44\}$$

and

$$HTU = \frac{Z}{NTU} \qquad \{45\}$$

Therefore:

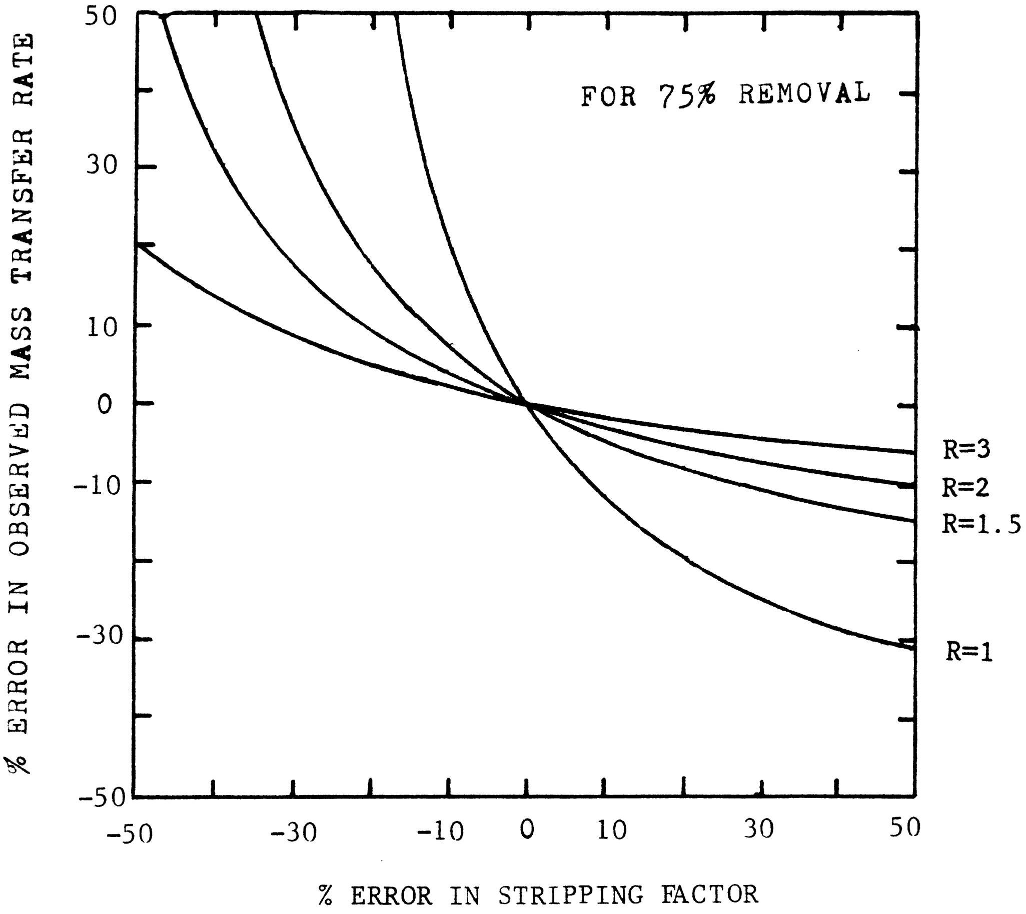
$$K_L a = NTU \frac{Z}{L} \qquad \{46\}$$

Thus, mass transfer rates are directly proportional to NTU values, and any inaccuracies in measured NTU yield equal-value errors in observed transfer rates. The use of inaccurate stripping factors in calculating NTU values (see equation {11}) will result in errors of the opposite sign for measured NTU (and therefore, observed mass transfer rates). Although the specific focus is on Henry's constant, imprecise flow measurements can also significantly contribute to calculation of incorrect stripping factors. In this regard, however, a review of equation {46} reveals that the effects of inaccurate liquid flow values are somewhat mitigated in terms of the resultant error in measured transfer rates. This is because liquid loading affects the mass transfer value both indirectly through

NTU (as part of the stripping factor) and directly (see {46}), but the relationships are such that the two effects offset each other to a certain extent. Therefore, while reasonable care should be taken to establish accurate flow rate information, it is particularly important to do so in determining the air loading rate.

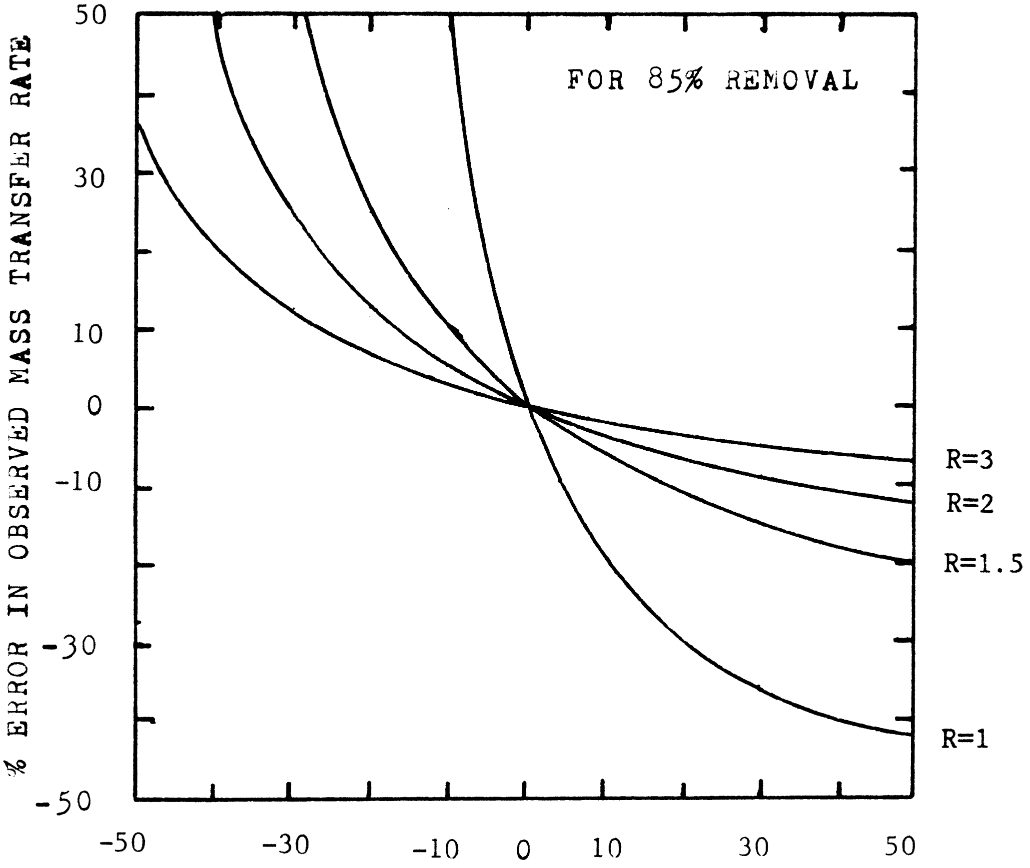
Roberts et al. [54] performed a specific error analysis for inaccurate stripping factor effects on observed transfer rates. Following that graphical presentation, more generalized plots were constructed for this work. Four general situations were considered based upon the assumed removal efficiency of the column (75, 85, 95, and 99% removal). In each case, NTU values were computed using equation {11} for assumed "true" stripping factors of 1, 1.5, 2, and 3. Next, each true stripping factor was incrementally adjusted to simulate experimental error in this term, and a corresponding "erroneous NTU" was calculated. The difference between the "true" and "erroneous" NTU values directly reflect the error which will be seen in the measured mass transfer rate. The results obtained are given below in Figure 7.

From the plots, three items should be noted. First, the resultant error in observed transfer rates depends upon the true stripping factor (R). At lower R values, the calculated NTU becomes very sensitive to inaccurate stripping factors. As an example of this, at 85% removal, a 20% underestimation of the stripping factor results in a 50% overestimation of the mass transfer rate at a true stripping factor of 1.25, but only a 25% overestimation is seen for a true factor of 1.5.



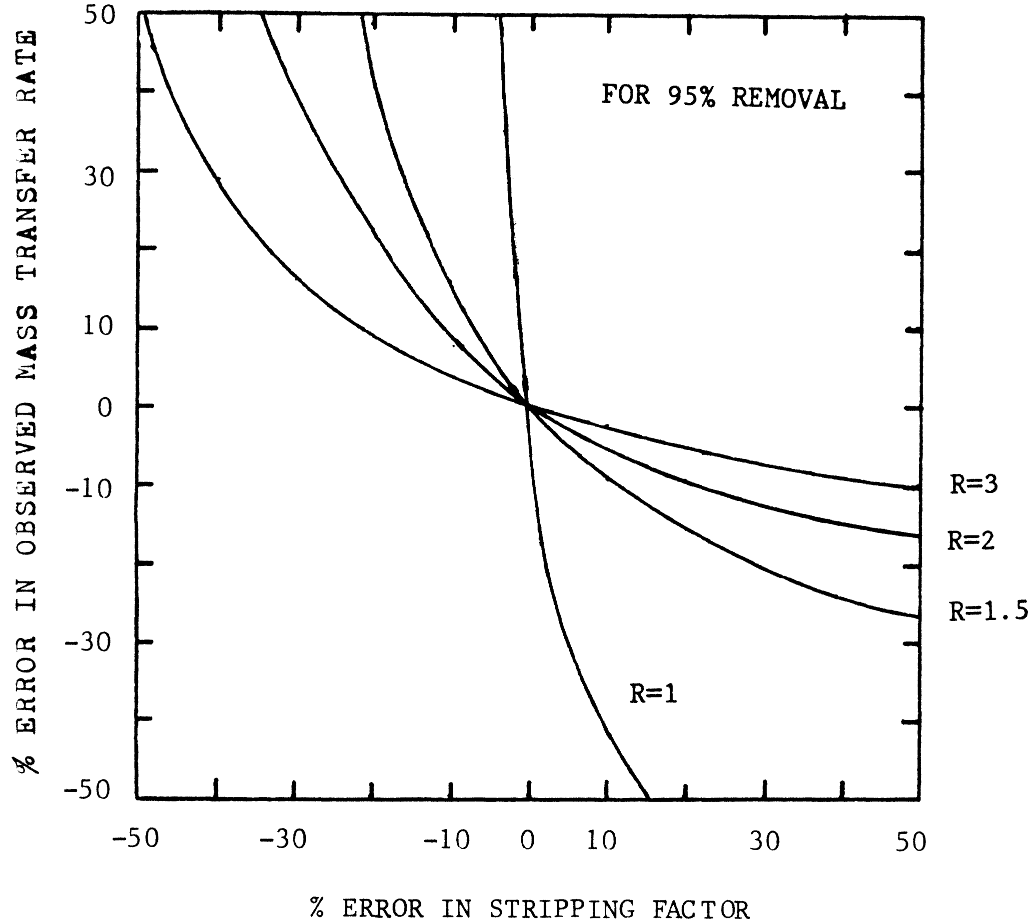
Case (a)

Figure 7. **Sensitivity** of apparent mass transfer **rates** to errors in the estimation of the stripping factor.



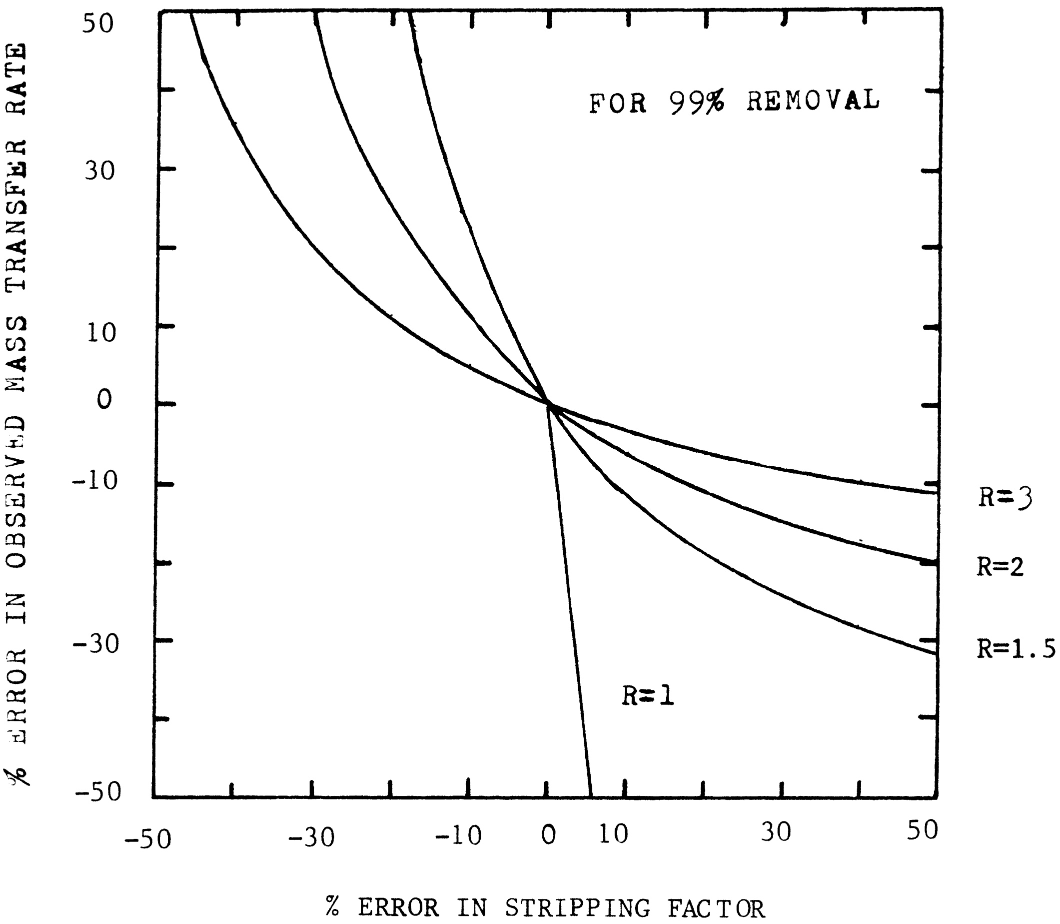
Case (b)

Figure 7 (cont.). Sensitivity of apparent mass transfer rates to errors in the estimation of the stripping factor.



Case (c)

Figure 7 (cont.). Sensitivity of apparent mass transfer rates to errors in the estimation of the stripping factor.



Case (d)

Figure 7 (concluded). Sensitivity of apparent mass transfer rates to errors in the estimation of the stripping factor.

Secondly, the resulting transfer rate error depends upon the recorded removal level, with higher removals yielding increased sensitivity to inaccurate stripping factors. For example, the 20% underestimation of R resulted in a 25% overestimation of true transfer rate at a true stripping factor of 1.5. However, under the same conditions except that the removal value is raised from 85 to 95%, a 43% overestimation of the transfer rate is now noted.

Finally, underestimation of the stripping factor yields exaggerated errors in measured transfer rates compared to corresponding overestimations of true stripping factors. Such errors are particularly magnified at lower true stripping factors. For example, at 95% removal with a true stripping factor of 1.5, a 20% underestimation of R results in a 43% overestimation of observed mass transfer, while a 20% overestimation would result in only a 15% underestimation. Therefore, if experimentally determined Henry's constant relations are lacking, it would actually be conservative to assume higher Henry's constant values. If the value assumed is too low, highly overestimated observed transfer rates may be calculated.

From the results presented, one simple method available to minimize the effects of uncertainties in Henry's constant is to operate the column at sufficiently high stripping factors (above 2 or 3). This allows for more accurate NTU determinations and correspondingly, more accurate mass transfer values. In reviewing the plots, error sensitivity in observed mass transfer rates is pronounced for true stripping factors below 1.5, while a true stripping factor of 3 produced relatively accurate observed transfer rates despite even gross errors in the assumed stripping factor. Therefore, if the calculated stripping factor is less than 1.5, caution should be exercised in evaluating the results. On the other hand, if the assumed stripping factor is 3 or above, the observed transfer rate computed should be in good agreement with the true transfer rate. Given a relatively accurate Henry's constant value (say within 20% as attributed to the relations utilized in this study), a minimum calculated stripping factor of 2 will yield an observed transfer rate within a corresponding 20% accuracy of the true transfer rate.

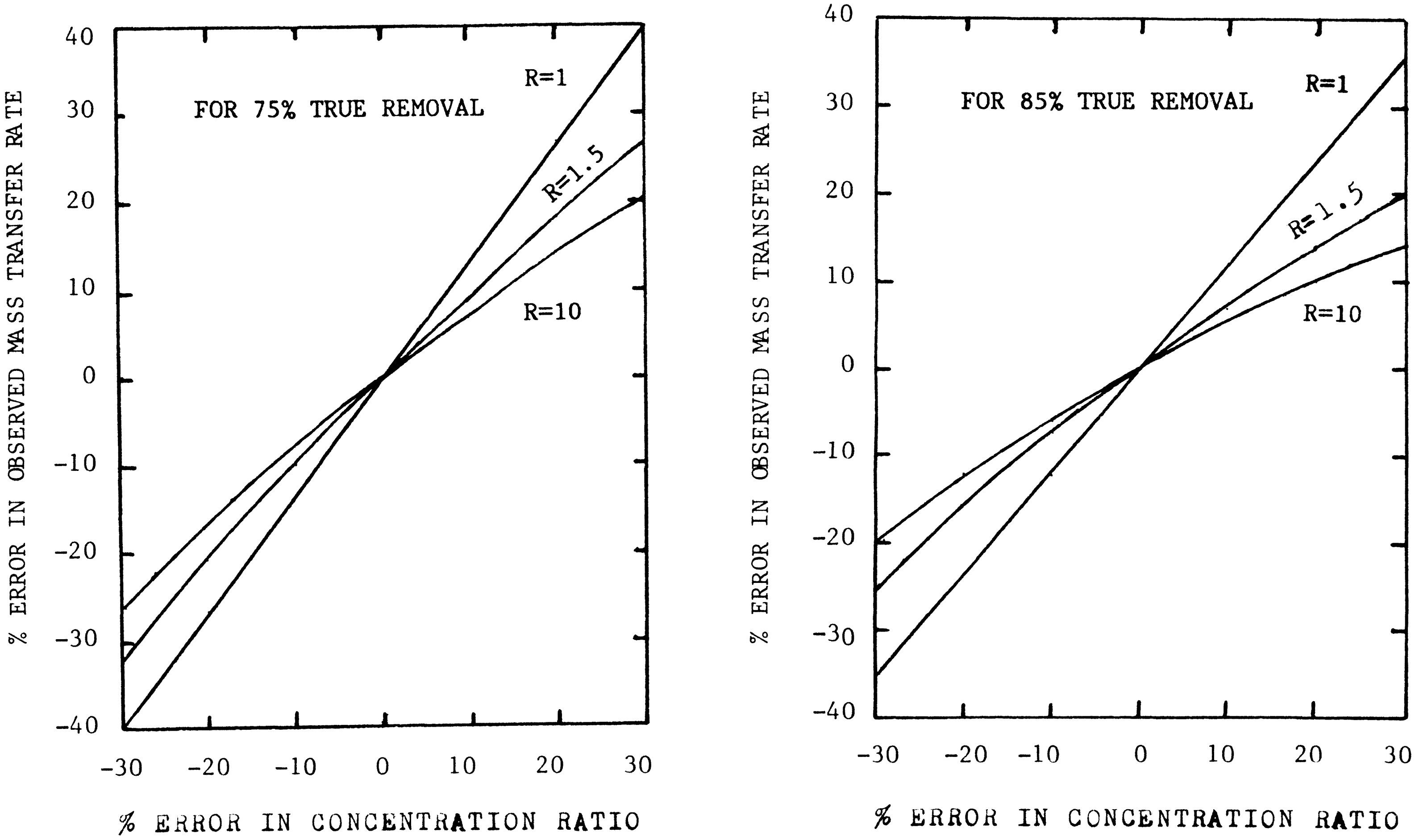
This knowledge may help explain Roberts and co-workers previous findings [50,54] that the Onda relation appears to underpredict relative gas phase resistance. A high relative gas-phase resistance occurs under low air to water operating ratios which, in turn, produce low stripping factors. However, under such conditions, the greatest potential errors in observed mass transfer rates due to inaccurate stripping factors occur. Specifically, the use of overestimated stripping factors result in the underestimation of observed mass transfer rates which would then appear to indicate that the Onda model overpredicted actual performance. Such overestimated stripping factors were in fact utilized by Roberts <u>et al.</u> [50,54], as the Henry's constant values cited are from 15 to 60% above those accepted as relatively accurate for this study. Therefore, the apparent deficiency with the Onda gas-phase correlation may in this case be actually due to the use of inaccurate Henry's constant values. This again points out the critical need for accurate determinations of Henry's constant relations.

### 4.1.3 Errors in Concentration Measurements

In considering concentration measurements, an important point to be made is that the calculation of observed transfer rates requires only the effluent to influent concentration ratio. Therefore, actual concentration levels do not necessarily need to be accurately determined since only this relative ratio is needed. Thus, calibration errors, if equally applied to both measurements, will have no effect on the transfer rate obtained.

As an indication of typical errors encountered in VOC concentration measurements, the quality control data reported by Cummins [9] is used. This work cited a duplicate sample analysis relative error of 10%, while the relative difference between results from two independent labs was 20 to 25%. Therefore, a similar error range of 30% was employed for calculation of the resulting effects on "observed" versus "true" mass transfer rates. The general procedure utilized in looking at the effects of inaccurate stripping factors (section 4.1.2) was also applied to this case.

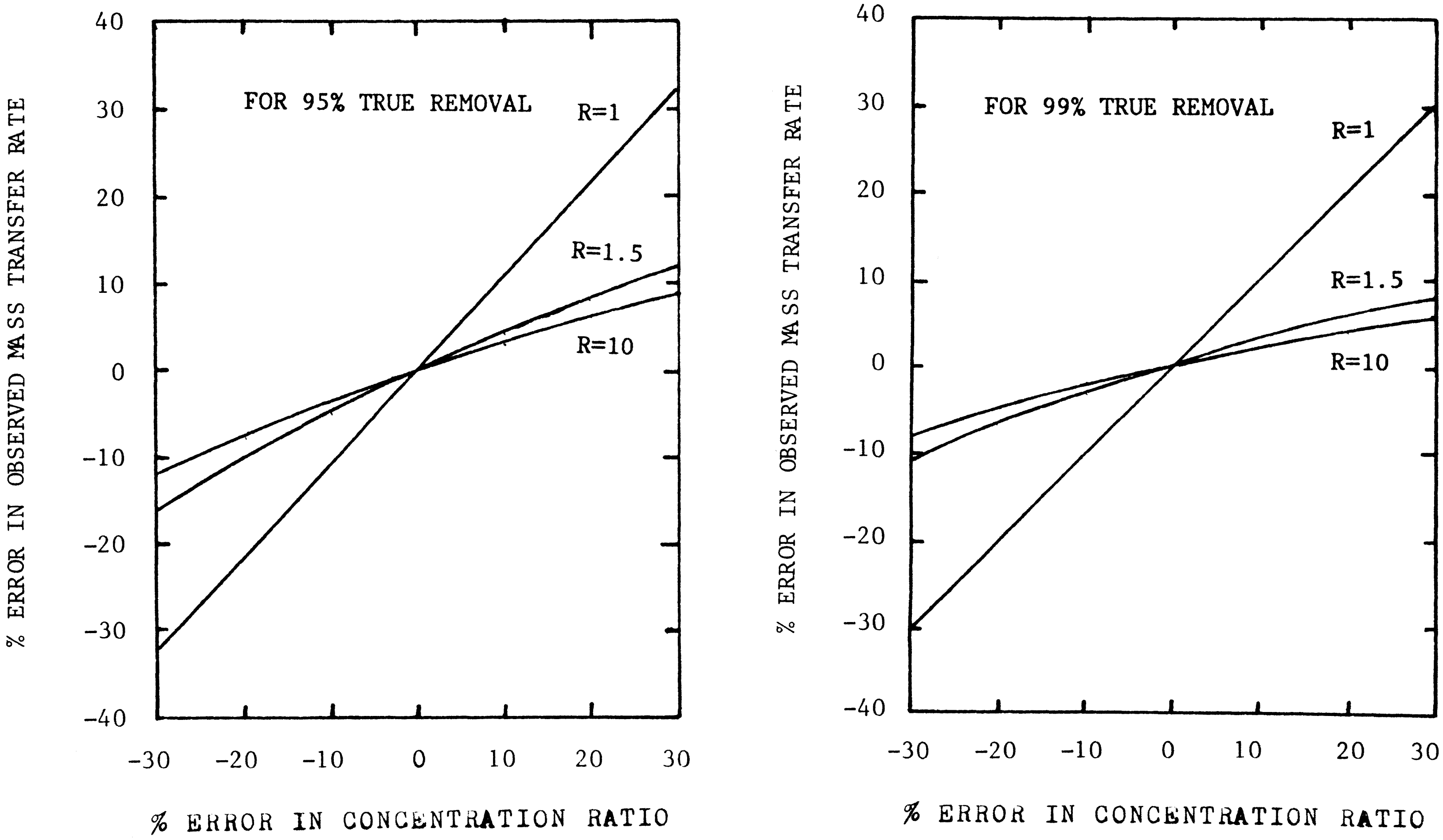
The results from this analysis are presented in four graphs comprising Figure 8. At a given removal level, observed transfer rate errors due to inaccurate concentration measurements are relatively constant for true stripping factors above 1.5, and the relative magnitude of this error in transfer rates does not exceed that noted for the concentration ratio alone. Below an R of 1.5, however, transfer rate error values rapidly increase as the stripping factor is further



Case (a)

Case (b)

Figure 8. Concentration measurement error effects on apparent mass transfer rates



Case (c)

Case (d)

Figure 8 (concluded). Concentration measurement error effects on apparent mass transfer rates decreased. Finally, under similar conditions except that the true removal level is increased, the resulting error in the observed transfer rate will slightly decrease, particularly for stripping factors above 1.5.

### 4.1.4 Summary of Error Analysis

The results indicate that errors in the parameters investigated (the stripping factor and the influent/effluent concentration ratio) will significantly affect the observed performance values given by the transfer unit approach, while Onda model predictions remain relatively unaffected. The errors in observed mass transfer rates become quite significant below true stripping factors of 1.5. Therefore, the results obtained under such operating conditions may be suspect owing to this sensitivity. This point is offered as an explanation for Roberts *et al.* [54] caution that stripping factors below 1 produce unexpected results and should not be used. Fortunately, normal economic operation dictates a minimum stripping factor of 2 with an optimum range of 3 to 5 (see section 3.1.1.4 for details). For data evaluation, as long as the true stripping factor is reasonably judged to be above 1.5 (say a minimum estimated value of 2), it is felt that any errors between observed and predicted mass transfer rates can be attributed to the Onda predictive correlation itself (or other factors such as channeling effects) rather than due to inaccurate measurement of either the stripping factor or VOC concentration.

## 4.2 ONDA MODEL RESULTS

### 4.2.1 Introduction

A summary of the ten studies selected from the available literature with a detailed breakdown of the corresponding operating conditions evaluated by each was previously presented in Table 3. The specific results obtained for observed and Onda-predicted mass transfer rates are provided below in a series of tables appearing within the discussion of the results for each respective study.

A few points concerning the specific use of certain studies should be noted. First, for the study by Gossett et al. [23], the measured mass transfer rates presented by the authors were directly utilized since the raw data was not made available to check upon the results provided. It is important to note that the Henry's constant relations used by Gossett et al. (obtained via the EPICS method) to generate their observed mass transfer rates were the same relations adapted in analyzing data from other studies. Thus, consistent performance analysis was maintained for all of the studies considered. Also, the Onda correlation predictions given in the Gossett study were nearly identical to the values calculated in this work, with differences of less than 3% being noted. This was expected since the computational methods employed were essentially identical. The only difference was with the method chosen for calculation of gas diffusivity values, and the two correlations employed produce similar results (see section 3.2.5).

Secondly, the data presented by Cummins [9] and Cummins & Westrick [12] were handled quite differently from those authors' applications to the Onda correlation. The reasons for this are discussed below under the corresponding results section.

Finally, in accounting for end effects with the data provided by Umphres et al. [64], one subset of experimental results was deleted due to apparent anomalous behavior. Therefore, the corrected transfer rates cited in this study differ from the corresponding values presented in the original work.

### 4.2.2 Individual Study Results

#### 4.2.2.1 Gossett Study

**Isothermal Study Results:** The results for this phase of the study performed by Gossett et al. [23] are presented in Tables 5 and 6 below. Table 5 contains the experimental findings conducted under a constant air loading rate while Table 6 includes the constant water loading tests. In reviewing the Onda correlation's performance, the first potential effect considered is the particular VOC being stripped. No distinct overall pattern based on the specific VOC involved could be detected to explain prediction errors. This fact tends to support the accuracy of the Henry's constant relations chosen, as well as the Onda model's behavior predictions for different VOCs which encompass a wide range of relative volatility. In relation to the later point, based on the Henry's constant

Table 5. RESULTS: GOSSETT STUDY [23] - Isothermal Experiments - Constant Air Loading Rate

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 108 | 14.7 | 54.8 | 57.6 | 60.6 | 5 | 39.1 | 1 | Tetrachloroethylene |
| 108 | 19.2 | 42.2 | 78.0 | 74.4 | - 5 | 30.1 | 2 | " |
| 108 | 22.6 | 35.8 | 84.0 | 84.6 | - 1 | 25.6 | 2 | " |
| 108 | 27.0 | 29.9 | 103.2 | 96.6 | - 6 | 21.3 | 2 | " |
| 108 | 30.5 | 26.5 | 108.0 | 105.6 | - 2 | 18.9 | 2 | " |
| 108 | 33.9 | 23.8 | 127.2 | 114.6 | -10 | 17.0 | 2 | " |
| 108 | 14.7 | 54.8 | 65.4 | 62.4 | - 5 | 37.8 | 1 | 1,1,1-Trichloroethane |
| 108 | 19.2 | 42.2 | 84.0 | 76.8 | - 9 | 29.1 | 1 | " |
| 108 | 22.6 | 35.8 | 93.6 | 87.0 | - 7 | 24.7 | 2 | " |
| 108 | 27.0 | 29.9 | 108.0 | 99.6 | - 8 | 20.6 | 2 | " |
| 108 | 30.5 | 26.5 | 117.0 | 108.6 | - 7 | 18.3 | 2 | " |
| 108 | 33.9 | 23.8 | 127.2 | 118.2 | - 7 | 16.4 | 2 | " |
| 108 | 14.7 | 54.8 | 63.0 | 63.6 | 1 | 22.7 | 2 | Trichloroethylene |
| 108 | 19.2 | 42.2 | 81.0 | 77.4 | - 4 | 17.5 | 3 | " |
| 108 | 22.6 | 35.8 | 91.8 | 87.6 | - 5 | 14.9 | 3 | " |
| 108 | 27.0 | 29.9 | 109.8 | 100.2 | - 9 | 12.4 | 3 | " |
| 108 | 30.5 | 26.5 | 116.4 | 109.8 | - 6 | 11.0 | 3 | " |
| 108 | 33.9 | 23.8 | 126.0 | 118.8 | - 6 | 9.9 | 3 | " |
| 108 | 14.7 | 54.8 | 63.0 | 64.8 | 3 | 9.5 | 5 | Chloroform |
| 108 | 19.2 | 42.2 | 78.6 | 78.6 | 0 | 7.3 | 6 | " |
| 108 | 22.6 | 35.8 | 82.8 | 88.8 | 7 | 6.2 | 6 | " |
| 108 | 27.0 | 29.9 | 101.4 | 101.4 | 0 | 5.2 | 7 | " |
| 108 | 30.5 | 26.5 | 109.2 | 110.4 | 1 | 4.6 | 7 | " |
| 108 | 33.9 | 23.8 | 115.8 | 119.4 | 3 | 4.1 | 8 | " |
| 108 | 14.7 | 54.8 | 75.0 | 67.8 | -10 | 6.4 | 7 | Methylene Chloride |
| 108 | 19.2 | 42.2 | 90.0 | 82.2 | - 9 | 4.9 | 8 | " |
| 108 | 22.6 | 35.8 | 97.2 | 93.0 | - 4 | 4.2 | 9 | " |
| 108 | 27.0 | 29.9 | 112.8 | 105.6 | - 6 | 3.5 | 10 | " |
| 108 | 30.5 | 26.5 | 119.4 | 115.2 | - 4 | 3.1 | 10 | " |
| 108 | 33.9 | 23.8 | 120.6 | 124.2 | 3 | 2.8 | 11 | " |

General Notes:
Packing - 5/8" Pall Rings
Water Temp. - 77° F (25° C)

Table 5 (cont.). RESULTS: GOSSETT STUDY [23] - Isothermal Experiments - Constant Air Loading Rate

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 84 | 14.7 | 42.8 | 52.2 | 52.8 | 1 | 30.6 | 2 | Tetrachloroethylene |
| 84 | 19.2 | 32.8 | 64.2 | 64.2 | 0 | 23.4 | 2 | " |
| 84 | 22.6 | 27.8 | 72.6 | 73.2 | 1 | 19.8 | 3 | " |
| 84 | 27.0 | 23.3 | 82.8 | 83.4 | 1 | 16.6 | 3 | " |
| 84 | 30.5 | 20.6 | 93.6 | 91.2 | - 3 | 14.7 | 3 | " |
| 84 | 33.9 | 18.5 | 118.2 | 98.4 | -17 | 13.2 | 3 | " |
| 84 | 14.7 | 42.8 | 57.0 | 54.6 | - 4 | 29.5 | 2 | 1,1,1-Trichloroethane |
| 84 | 19.2 | 32.8 | 75.0 | 66.0 | -12 | 22.6 | 2 | " |
| 84 | 22.6 | 27.8 | 81.6 | 75.0 | - 8 | 19.2 | 3 | " |
| 84 | 27.0 | 23.3 | 95.4 | 85.8 | -10 | 16.1 | 3 | " |
| 84 | 30.5 | 20.6 | 106.2 | 93.6 | -12 | 14.2 | 3 | " |
| 84 | 33.9 | 18.5 | 129.6 | 101.4 | -22 | 12.8 | 3 | " |
| 84 | 14.7 | 42.8 | 57.0 | 54.6 | - 4 | 17.8 | 3 | Trichloroethylene |
| 84 | 19.2 | 32.8 | 72.6 | 66.6 | - 8 | 13.6 | 4 | " |
| 84 | 22.6 | 27.8 | 78.6 | 75.6 | - 4 | 11.5 | 4 | " |
| 84 | 27.0 | 23.3 | 89.4 | 85.8 | - 4 | 9.7 | 5 | " |
| 84 | 30.5 | 20.6 | 98.4 | 94.2 | - 4 | 8.5 | 5 | " |
| 84 | 33.9 | 18.5 | 124.2 | 101.4 | -18 | 7.7 | 5 | " |
| 84 | 14.7 | 42.8 | 54.0 | 54.6 | 1 | 7.4 | 8 | Chloroform |
| 84 | 19.2 | 32.8 | 67.2 | 66.0 | - 2 | 5.7 | 9 | " |
| 84 | 22.6 | 27.8 | 76.2 | 74.4 | - 2 | 4.8 | 10 | " |
| 84 | 27.0 | 23.3 | 76.2 | 84.6 | 11 | 4.0 | 11 | " |
| 84 | 30.5 | 20.6 | 81.0 | 92.4 | 14 | 3.6 | 11 | " |
| 84 | 33.9 | 18.5 | 104.4 | 96.6 | - 5 | 3.2 | 12 | " |
| 84 | 14.7 | 42.8 | 57.6 | 57.0 | - 1 | 5.0 | 11 | Methylene Chloride |
| 84 | 19.2 | 32.8 | 74.4 | 68.4 | - 8 | 3.8 | 13 | " |
| 84 | 22.6 | 27.8 | 72.0 | 76.8 | 7 | 3.2 | 14 | " |
| 84 | 27.0 | 23.3 | 76.8 | 87.0 | 13 | 2.7 | 15 | " |
| 84 | 30.5 | 20.6 | 82.2 | 94.8 | 15 | 2.4 | 15 | " |
| 84 | 33.9 | 18.5 | 105.0 | 102.0 | - 3 | 2.2 | 16 | " |

General Notes: Packing - 1" Pall Rings
Water temp. - 77° F (25° C)

Table 5 (cont.). RESULTS: GOSSETT STUDY [23] - Isothermal Experiments - Constant Air Loading Rate

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 165 | 14.7 | 83.7 | 48.0 | 43.8 | - 9 | 59.7 | 2 | Tetrachloroethylene |
| 165 | 19.2 | 64.4 | 62.4 | 53.4 | -14 | 46.0 | 3 | " |
| 165 | 22.6 | 54.6 | 73.2 | 60.6 | -17 | 39.0 | 3 | " |
| 165 | 27.0 | 45.6 | 78.0 | 69.0 | -12 | 32.5 | 3 | " |
| 165 | 30.5 | 40.5 | 85.8 | 75.0 | -13 | 28.9 | 3 | " |
| 165 | 33.9 | 36.4 | 94.2 | 81.0 | -14 | 26.0 | 3 | " |
| 165 | 14.7 | 83.7 | 52.8 | 45.0 | -15 | 57.8 | 2 | 1,1,1-Trichloroethane |
| 165 | 19.2 | 64.4 | 67.2 | 55.2 | -18 | 44.4 | 3 | " |
| 165 | 22.6 | 54.6 | 74.4 | 61.8 | -17 | 37.7 | 3 | " |
| 165 | 27.0 | 45.6 | 86.4 | 70.8 | -18 | 31.5 | 3 | " |
| 165 | 30.5 | 40.5 | 91.2 | 77.4 | -15 | 27.9 | 3 | " |
| 165 | 33.9 | 36.4 | 100.8 | 83.4 | -17 | 25.1 | 4 | " |
| 165 | 14.7 | 83.7 | 52.8 | 45.6 | -14 | 34.7 | 4 | Trichloroethylene |
| 165 | 19.2 | 64.4 | 67.8 | 55.2 | -19 | 26.7 | 4 | " |
| 165 | 22.6 | 54.6 | 76.2 | 62.4 | -18 | 22.7 | 5 | " |
| 165 | 27.0 | 45.6 | 84.6 | 70.8 | -16 | 18.9 | 5 | " |
| 165 | 30.5 | 40.5 | 90.0 | 77.4 | -14 | 16.8 | 5 | " |
| 165 | 33.9 | 36.4 | 98.4 | 83.4 | -15 | 15.1 | 6 | " |
| 165 | 14.7 | 83.7 | 50.4 | 45.0 | -11 | 14.5 | 9 | Chloroform |
| 165 | 19.2 | 64.4 | 62.4 | 54.6 | -13 | 11.1 | 10 | " |
| 165 | 22.6 | 54.6 | 69.0 | 61.2 | -11 | 9.4 | 11 | " |
| 165 | 27.0 | 45.6 | 81.6 | 69.6 | -15 | 7.9 | 11 | " |
| 165 | 30.5 | 40.5 | 84.6 | 75.6 | -11 | 7.0 | 12 | " |
| 165 | 33.9 | 36.4 | 91.2 | 81.0 | -11 | 6.3 | 13 | " |
| 165 | 14.7 | 83.7 | 56.4 | 46.8 | -17 | 9.8 | 12 | Methylene Chloride |
| 165 | 19.2 | 64.4 | 69.6 | 56.4 | -19 | 7.5 | 14 | " |
| 165 | 22.6 | 54.6 | 75.6 | 63.0 | -17 | 6.4 | 15 | " |
| 165 | 27.0 | 45.6 | 88.8 | 71.4 | -20 | 5.3 | 16 | " |
| 165 | 30.5 | 40.5 | 91.2 | 76.8 | -16 | 4.7 | 17 | " |
| 165 | 33.9 | 36.4 | 98.4 | 82.8 | -16 | 4.3 | 17 | " |

General Notes: Packing - 2" Pall Rings
Water Temp - 77° F (25° C)

Table 5. RESULTS: GOSSETT STUDY [23] - Isothermal Experiments - Constant Air Loading Rate

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 84 | 14.7 | 42.8 | 43.8 | 52.8 | 21 | 30.5 | 2 | Tetrachloroethylene |
| 84 | 19.2 | 32.8 | 52.8 | 64.2 | 22 | 23.4 | 2 | " |
| 84 | 22.6 | 27.8 | 62.4 | 73.2 | 17 | 19.8 | 3 | " |
| 84 | 27.0 | 23.3 | 70.2 | 83.4 | 19 | 16.6 | 3 | " |
| 84 | 30.5 | 20.6 | 67.2 | 91.2 | 36 | 14.7 | 3 | " |
| 84 | 33.9 | 18.5 | 76.8 | 98.4 | 28 | 13.2 | 3 | " |
| 84 | 14.7 | 42.8 | 48.6 | 54.6 | 12 | 29.5 | 2 | 1,1,1-Trichloroethane |
| 84 | 19.2 | 32.8 | 61.8 | 66.0 | 7 | 22.6 | 2 | " |
| 84 | 22.6 | 27.8 | 69.6 | 75.0 | 8 | 19.2 | 3 | " |
| 84 | 27.0 | 23.3 | 78.6 | 85.8 | 9 | 16.1 | 3 | " |
| 84 | 30.5 | 20.6 | 77.4 | 93.6 | 21 | 14.2 | 3 | " |
| 84 | 33.9 | 18.5 | 85.8 | 101.4 | 18 | 12.8 | 3 | " |
| 84 | 14.7 | 42.8 | 48.6 | 54.6 | 12 | 17.8 | 4 | Trichloroethylene |
| 84 | 19.2 | 32.8 | 61.2 | 66.6 | 9 | 13.6 | 4 | " |
| 84 | 22.6 | 27.8 | 70.2 | 75.6 | 8 | 11.5 | 4 | " |
| 84 | 27.0 | 23.3 | 76.8 | 85.8 | 12 | 9.7 | 5 | " |
| 84 | 30.5 | 20.6 | 75.8 | 94.2 | 25 | 8.5 | 5 | " |
| 84 | 33.9 | 18.5 | 84.0 | 101.4 | 21 | 7.7 | 5 | " |
| 84 | 14.7 | 42.8 | 43.8 | 54.6 | 25 | 7.4 | 8 | Chloroform |
| 84 | 19.2 | 32.8 | 56.4 | 66.0 | 17 | 5.7 | 9 | " |
| 84 | 22.6 | 27.8 | 63.6 | 74.4 | 17 | 4.8 | 10 | " |
| 84 | 27.0 | 23.3 | 69.6 | 84.6 | 22 | 4.0 | 11 | " |
| 84 | 30.5 | 20.6 | 76.2 | 92.4 | 21 | 3.6 | 11 | " |
| 84 | 33.9 | 18.5 | 73.2 | 99.6 | 36 | 3.2 | 12 | " |
| 84 | 14.7 | 42.8 | 49.8 | 57.0 | 15 | 5.0 | 11 | Methylene Chloride |
| 84 | 19.2 | 32.8 | 60.6 | 68.4 | 13 | 3.8 | 13 | " |
| 84 | 22.6 | 27.8 | 66.0 | 76.8 | 16 | 3.3 | 14 | " |
| 84 | 27.0 | 23.3 | 72.0 | 87.0 | 21 | 2.7 | 15 | " |
| 84 | 30.5 | 20.6 | 70.2 | 94.8 | 35 | 2.4 | 15 | " |
| 84 | 33.9 | 18.5 | 74.4 | 102.0 | 37 | 2.2 | 16 | " |

General Notes: Packing - 1" Saddles
Water Temp. - $77^{o}$ F ($25^{o}$ C)

Table 5 (cont.). RESULTS: GOSSETT STUDY [23] - Isothermal Experiments - Constant Air Loading Rates

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 108 | 14.7 | 54.8 | 56.4 | 52.2 | - 7 | 39.1 | 5 | Tetrachloroethylene |
| 108 | 19.2 | 42.2 | 66.6 | 63.0 | - 5 | 30.1 | 6 | " |
| 108 | 22.6 | 35.8 | 81.0 | 70.8 | -13 | 25.5 | 6 | " |
| 108 | 27.0 | 29.9 | 86.4 | 81.0 | - 6 | 21.3 | 6 | " |
| 108 | 30.5 | 26.5 | 102.6 | 88.2 | -14 | 18.9 | 7 | " |
| 108 | 33.9 | 23.8 | 111.6 | 95.4 | -15 | 17.0 | 7 | " |
| 108 | 14.7 | 54.8 | 62.4 | 53.4 | -14 | 37.8 | 5 | 1,1,1-Trichloroethane |
| 108 | 19.2 | 42.2 | 70.8 | 64.8 | - 9 | 29.1 | 6 | " |
| 108 | 22.6 | 35.8 | 82.2 | 73.2 | -11 | 24.7 | 6 | " |
| 108 | 27.0 | 29.9 | 90.6 | 83.4 | - 8 | 20.6 | 7 | " |
| 108 | 30.5 | 26.5 | 106.2 | 90.6 | -15 | 18.3 | 7 | " |
| 108 | 33.9 | 23.8 | 113.4 | 98.4 | -13 | 16.4 | 7 | " |
| 108 | 14.7 | 54.8 | 61.8 | 52.8 | -15 | 22.7 | 8 | Trichloroethylene |
| 108 | 19.2 | 42.2 | 70.2 | 64.2 | - 8 | 17.5 | 9 | " |
| 108 | 22.6 | 35.8 | 81.6 | 72.0 | -12 | 14.9 | 10 | " |
| 108 | 27.0 | 29.9 | 88.2 | 81.6 | - 8 | 12.4 | 10 | " |
| 108 | 30.5 | 26.5 | 104.4 | 88.8 | -15 | 11.0 | 11 | " |
| 108 | 33.9 | 23.8 | 111.6 | 96.0 | -14 | 9.9 | 11 | " |
| 108 | 14.7 | 54.8 | 58.2 | 49.8 | -14 | 9.5 | 17 | Chloroform |
| 108 | 19.2 | 42.2 | 66.6 | 59.4 | -10 | 7.3 | 19 | " |
| 108 | 22.6 | 35.8 | 78.6 | 66.6 | -15 | 6.2 | 20 | " |
| 108 | 27.0 | 29.9 | 82.8 | 75.0 | - 9 | 5.2 | 22 | " |
| 108 | 30.5 | 26.5 | 99.0 | 81.0 | -18 | 4.6 | 23 | " |
| 108 | 33.9 | 23.8 | 105.6 | 86.4 | -18 | 4.1 | 24 | " |
| 108 | 14.7 | 54.8 | 64.2 | 49.8 | -22 | 6.4 | 23 | Methylene Chloride |
| 108 | 19.2 | 42.2 | 70.8 | 59.4 | -16 | 4.9 | 26 | " |
| 108 | 22.6 | 35.8 | 82.2 | 65.4 | -20 | 4.2 | 27 | " |
| 108 | 27.0 | 29.9 | 88.2 | 73.2 | -17 | 3.5 | 29 | " |
| 108 | 30.5 | 26.5 | 105.6 | 78.6 | -26 | 3.1 | 30 | " |
| 108 | 33.9 | 23.8 | 112.2 | 84.0 | -25 | 2.8 | 31 | " |

General Notes: Packing - 2" Tri-Packs
Water Temp. - 77°F (25° C)

Table 6. RESULTS: GOSSETT STUDY [23] - Isothermal Experiments - Constant Water Loading Rate

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 15 | 22.6 | 5.0 | 79.8 | 80.4 | 1 | 3.6 | 6 | Tetrachloroethylene |
| 24 | 22.6 | 7.9 | 85.8 | 81.6 | - 5 | 5.6 | 4 | " |
| 36 | 22.6 | 11.9 | 85.8 | 82.8 | - 4 | 8.5 | 3 | " |
| 54 | 22.6 | 17.9 | 89.4 | 83.4 | - 7 | 12.8 | 3 | " |
| 84 | 22.6 | 27.8 | 84.6 | 84.0 | - 1 | 19.8 | 2 | " |
| 108 | 22.6 | 35.7 | 85.2 | 84.6 | - 1 | 25.5 | 2 | " |
| 120 | 22.6 | 39.7 | 91.2 | 84.6 | - 7 | 28.3 | 2 | " |
| 15 | 22.6 | 5.0 | 85.8 | 82.8 | - 4 | 3.4 | 6 | 1,1,1-Trichloroethane |
| 24 | 22.6 | 7.9 | 88.2 | 84.0 | - 5 | 5.4 | 5 | " |
| 36 | 22.6 | 11.9 | 89.4 | 85.2 | - 5 | 8.2 | 4 | " |
| 54 | 22.6 | 17.9 | 97.2 | 85.8 | -12 | 12.4 | 3 | " |
| 84 | 22.6 | 27.8 | 93.6 | 86.4 | - 8 | 19.2 | 2 | " |
| 108 | 22.6 | 35.7 | 93.6 | 87.0 | - 7 | 24.6 | 2 | " |
| 120 | 22.6 | 39.7 | 96.0 | 87.0 | - 9 | 27.4 | 2 | " |
| 15 | 22.6 | 5.0 | 76.8 | 81.0 | 6 | 2.1 | 10 | Trichloroethylene |
| 24 | 22.6 | 7.9 | 81.0 | 83.4 | 3 | 3.3 | 7 | " |
| 36 | 22.6 | 11.9 | 81.6 | 85.2 | 4 | 4.9 | 6 | " |
| 54 | 22.6 | 17.9 | 94.8 | 86.4 | - 9 | 7.4 | 4 | " |
| 84 | 22.6 | 27.8 | 89.4 | 87.0 | - 3 | 11.5 | 3 | " |
| 108 | 22.6 | 35.7 | 91.8 | 87.6 | - 5 | 14.8 | 3 | " |
| 120 | 22.6 | 39.7 | 96.6 | 87.6 | - 9 | 16.5 | 2 | " |
| 24 | 22.6 | 7.9 | 65.4 | 79.2 | 21 | 1.4 | 16 | Chloroform |
| 36 | 22.6 | 11.9 | 76.2 | 82.8 | 9 | 2.1 | 13 | " |
| 54 | 22.6 | 17.9 | 86.4 | 85.2 | - 1 | 3.1 | 10 | " |
| 84 | 22.6 | 27.8 | 81.6 | 86.4 | 7 | 4.8 | 7 | " |
| 108 | 22.6 | 35.7 | 82.8 | 87.6 | 7 | 6.2 | 6 | " |
| 120 | 22.6 | 39.7 | 90.6 | 87.6 | - 2 | 6.9 | 6 | " |
| 36 | 22.6 | 11.9 | 77.4 | 84.0 | 8 | 1.4 | 17 | Methylene Chloride |
| 54 | 22.6 | 17.9 | 85.8 | 88.2 | 3 | 2.1 | 14 | " |
| 84 | 22.6 | 27.8 | 91.8 | 91.2 | - 1 | 3.3 | 10 | " |
| 108 | 22.6 | 35.7 | 97.2 | 93.0 | - 4 | 4.2 | 9 | " |
| 120 | 22.6 | 39.7 | 103.8 | 93.6 | -10 | 4.6 | 8 | " |

General Notes: Packing - 5/8" Pall Rings
Water Temp. - 77° F (25° C)

Table 6 (cont.). RESULTS: GOSSETT STUDY [23] - Isothermal Experiments - Constant Water Loading Rate

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 15 | 22.6 | 5.0 | 64.8 | 68.4 | 6 | 3.6 | 8 | Tetrachloroethylene |
| 60 | 22.6 | 19.8 | 75.0 | 71.6 | - 3 | 14.1 | 3 | " |
| 84 | 22.6 | 27.8 | 72.6 | 72.6 | 0 | 19.8 | 3 | " |
| 135 | 22.6 | 44.6 | 81.0 | 73.2 | -10 | 31.8 | 2 | " |
| 15 | 22.6 | 5.0 | 68.4 | 70.8 | 4 | 3.4 | 8 | 1,1,1-Trichloroethane |
| 60 | 22.6 | 19.8 | 82.8 | 74.4 | -10 | 13.7 | 3 | " |
| 84 | 22.6 | 27.8 | 82.2 | 75.0 | - 9 | 19.2 | 3 | " |
| 135 | 22.6 | 44.6 | 92.4 | 75.6 | -18 | 30.8 | 2 | " |
| 15 | 22.6 | 5.0 | 50.4 | 68.4 | 36 | 2.1 | 13 | Trichloroethylene |
| 60 | 22.6 | 19.8 | 77.4 | 74.4 | - 4 | 8.2 | 6 | " |
| 84 | 22.6 | 27.8 | 79.2 | 75.0 | - 5 | 11.5 | 4 | " |
| 135 | 22.6 | 44.6 | 87.6 | 76.2 | -13 | 18.5 | 3 | " |
| 60 | 22.6 | 19.8 | 64.8 | 72.6 | 12 | 3.4 | 12 | Chloroform |
| 84 | 22.6 | 27.8 | 72.6 | 74.4 | 2 | 4.7 | 10 | " |
| 135 | 22.6 | 44.6 | 75.0 | 76.8 | 2 | 7.7 | 7 | " |
| 60 | 22.6 | 19.8 | 60.6 | 73.8 | 22 | 2.3 | 17 | Methylene Chloride |
| 84 | 22.6 | 27.8 | 71.4 | 76.8 | 2 | 3.3 | 14 | " |
| 135 | 22.6 | 44.6 | 90.0 | 79.8 | -11 | 5.2 | 10 | " |

General Notes: Packing - 1" Pall Rings
Water Temp. - 77° F (25° C)

Table 6 (cont.) RESULTS: GOSSETT STUDY [23] - Isothermal Experiments - Constant Water Loading Rate

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 15 | 22.6 | 5.0 | 60.0 | 54.0 | -10 | 3.6 | 13 | Tetrachloroethylene |
| 24 | 22.6 | 7.9 | 67.2 | 55.8 | -17 | 5.6 | 10 | " |
| 48 | 22.6 | 15.9 | 70.2 | 58.2 | -17 | 11.3 | 6 | " |
| 90 | 22.6 | 29.8 | 69.0 | 59.4 | -14 | 21.3 | 4 | " |
| 165 | 22.6 | 54.6 | 73.2 | 60.6 | -17 | 39.0 | 3 | " |
| 15 | 22.6 | 5.0 | 62.4 | 55.2 | -12 | 3.4 | 14 | 1,1,1-Trichloroethane |
| 24 | 22.6 | 7.9 | 69.6 | 57.6 | -17 | 5.4 | 10 | " |
| 48 | 22.6 | 15.9 | 72.6 | 60.0 | -17 | 11.0 | 6 | " |
| 90 | 22.6 | 29.8 | 73.8 | 61.2 | -18 | 20.6 | 4 | " |
| 165 | 22.6 | 54.6 | 74.4 | 61.8 | -17 | 37.7 | 3 | " |
| 15 | 22.6 | 5.0 | 52.8 | 51.6 | - 2 | 2.1 | 21 | Trichloroethylene |
| 24 | 22.6 | 7.9 | 63.0 | 55.2 | -12 | 3.3 | 16 | " |
| 48 | 22.6 | 15.9 | 70.2 | 58.8 | -16 | 6.6 | 10 | " |
| 90 | 22.6 | 29.8 | 73.8 | 60.6 | -18 | 12.4 | 7 | " |
| 165 | 22.6 | 54.6 | 76.2 | 62.4 | -18 | 22.7 | 5 | " |
| 24 | 22.6 | 7.9 | 46.8 | 47.4 | 1 | 1.4 | 31 | Chloroform |
| 48 | 22.6 | 15.9 | 60.0 | 53.4 | -11 | 2.8 | 22 | " |
| 90 | 22.6 | 29.8 | 65.4 | 58.2 | -11 | 5.2 | 15 | " |
| 165 | 22.6 | 54.6 | 69.0 | 61.2 | -11 | 9.4 | 10 | " |
| 48 | 22.6 | 15.9 | 58.2 | 52.8 | - 9 | 1.9 | 29 | Methylene Chloride |
| 90 | 22.6 | 29.8 | 68.4 | 58.8 | -14 | 3.5 | 21 | " |
| 165 | 22.6 | 54.6 | 75.6 | 63.0 | -17 | 6.4 | 14 | " |

General Notes: Packing - 2" Pall Rings
Water Temp. - 77°F (25°C)

Table 6 (cont.). RESULTS: GOSSETT STUDY [23] - Isothermal Experiments - Constant Water Loading Rates

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 24 | 22.6 | 7.9 | 60.0 | 70.2 | 17 | 5.6 | 6 | Tetrachloroethylene |
| 48 | 22.6 | 15.9 | 67.2 | 72.0 | 7 | 11.3 | 4 | " |
| 60 | 22.6 | 19.8 | 70.2 | 71.6 | 3 | 14.1 | 3 | " |
| 84 | 22.6 | 27.8 | 69.0 | 72.8 | 5 | 19.8 | 3 | " |
| 135 | 22.6 | 44.6 | 73.2 | 73.2 | 0 | 31.8 | 2 | " |
| 24 | 22.6 | 7.9 | 62.4 | 72.0 | 15 | 5.4 | 6 | 1,1,1-Trichloroethane |
| 48 | 22.6 | 15.9 | 69.6 | 73.8 | 6 | 11.0 | 4 | " |
| 60 | 22.6 | 19.8 | 72.6 | 74.4 | 2 | 13.7 | 3 | " |
| 84 | 22.6 | 27.8 | 73.8 | 75.0 | 2 | 19.2 | 3 | " |
| 135 | 22.6 | 44.6 | 74.4 | 75.6 | 2 | 30.8 | 2 | " |
| 24 | 22.6 | 7.9 | 52.8 | 70.8 | 34 | 3.3 | 10 | Trichloroethylene |
| 48 | 22.6 | 15.9 | 63.0 | 73.8 | 17 | 6.6 | 6 | " |
| 60 | 22.6 | 19.8 | 70.2 | 74.4 | 6 | 8.2 | 6 | " |
| 84 | 22.6 | 27.8 | 73.8 | 75.0 | 2 | 11.5 | 4 | " |
| 135 | 22.6 | 44.6 | 76.2 | 76.2 | 0 | 18.5 | 3 | " |
| 24 | 22.6 | 7.9 | 36.6 | 65.4 | 79 | 1.4 | 21 | Chloroform |
| 48 | 22.6 | 15.9 | 46.8 | 70.8 | 51 | 2.8 | 14 | " |
| 60 | 22.6 | 19.8 | 60.0 | 72.6 | 21 | 3.4 | 12 | " |
| 84 | 22.6 | 27.8 | 65.4 | 74.4 | 14 | 4.8 | 10 | " |
| 135 | 22.6 | 44.6 | 69.0 | 76.8 | 11 | 7.7 | 7 | " |
| 48 | 22.6 | 15.9 | 35.4 | 72.0 | 103 | 1.9 | 19 | Methylene Chloride |
| 60 | 22.6 | 19.8 | 58.2 | 73.8 | 27 | 2.3 | 17 | " |
| 84 | 22.6 | 27.8 | 68.4 | 76.8 | 12 | 3.2 | 14 | " |
| 135 | 22.6 | 44.6 | 75.6 | 79.8 | 6 | 5.2 | 10 | " |

General Notes: Packing - 1" Saddles
Water Temp. - 77° F (25° C)

Table 6 (cont.). RESULTS: GOSSETT STUDY [23] - Isothermal Experiments - Constant Water Loading Rates

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 15 | 22.6 | 5.0 | 76.2 | 60.6 | -20 | 3.6 | 20 | Tetrachloroethylene |
| 24 | 22.6 | 7.9 | 77.4 | 64.2 | -17 | 5.6 | 15 | " |
| 48 | 22.6 | 15.9 | 81.6 | 68.4 | -16 | 11.3 | 10 | " |
| 108 | 22.6 | 35.7 | 81.0 | 71.4 | -12 | 25.6 | 6 | " |
| 180 | 22.6 | 59.5 | 81.0 | 72.6 | -10 | 42.5 | 4 | " |
| 15 | 22.6 | 5.0 | 78.0 | 62.4 | -20 | 3.4 | 20 | 1,1,1-Trichloroethane |
| 24 | 22.6 | 7.9 | 79.2 | 66.0 | -17 | 5.4 | 15 | " |
| 48 | 22.6 | 15.9 | 82.2 | 70.2 | -15 | 11.0 | 10 | " |
| 108 | 22.6 | 35.7 | 82.2 | 73.2 | -11 | 24.6 | 6 | " |
| 180 | 22.6 | 59.5 | 83.4 | 74.4 | -11 | 41.1 | 4 | " |
| 15 | 22.6 | 5.0 | 72.0 | 55.8 | -22 | 2.1 | 30 | Trichloroethylene |
| 24 | 22.6 | 7.9 | 75.0 | 61.2 | -18 | 3.3 | 23 | " |
| 48 | 22.6 | 15.9 | 80.4 | 67.2 | -16 | 6.6 | 16 | " |
| 108 | 22.6 | 35.7 | 81.6 | 72.0 | -12 | 14.8 | 10 | " |
| 180 | 22.6 | 59.5 | 82.4 | 74.4 | -10 | 24.7 | 7 | " |
| 15 | 22.6 | 5.0 | 64.2 | 41.4 | -36 | 0.86 | 51 | Chloroform |
| 24 | 22.6 | 7.9 | 68.4 | 48.0 | -30 | 1.4 | 42 | " |
| 48 | 22.6 | 15.9 | 73.8 | 57.6 | -22 | 2.8 | 31 | " |
| 108 | 22.6 | 35.7 | 78.6 | 66.6 | -15 | 6.2 | 20 | " |
| 180 | 22.6 | 59.5 | 76.8 | 70.8 | - 8 | 10.3 | 15 | " |
| 15 | 22.6 | 5.0 | 52.8 | 36.6 | -31 | 0.58 | 60 | Methylene Chloride |
| 24 | 22.6 | 7.9 | 58.2 | 43.8 | -25 | 0.92 | 52 | " |
| 48 | 22.6 | 15.9 | 76.2 | 54.6 | -28 | 1.9 | 40 | " |
| 108 | 22.6 | 35.7 | 82.2 | 65.4 | -20 | 4.2 | 27 | " |
| 180 | 22.6 | 59.5 | 87.6 | 71.4 | -18 | 7.0 | 21 | " |

General Notes: Packing - 2" Tri-Packs
Water Temp. - 77° F (25° C)

relations utilized for this work, the VOCs tested represent a six-fold difference in relative volatility. Since the VOCs were introduced as a mixture, a wide range in stripping factors (0.6 to 60) was obtained. As expected, correlation errors were independent of this factor except potentially for some isolated points with low (<2) values, an area where measurement errors are magnified in the calculation of "observed" mass transfer rates (see section 4.1).

The effects of different packing materials were next examined. In looking at the Pall ring data, which formed the majority of the work, the Onda model produced excellent results. Out of 167 data points, only one predicted value was more than 22% in error. For both the 5/8- and 1-inch rings, there was a definite tendency by the model to underpredict performance, but the absolute magnitude (approximately a -3% average) is practically negligible. For the 2-inch rings, however, this underprediction was more severe. All fifty-two points lie between +1 and -20% in error, with fifty points lying in the -9 to -20% range.

The results for the 2-inch rings become significant upon reviewing the 2-inch Tri-Pack data. Prediction errors for the latter packing fall in the -5 to -36% range. Also, while the average error for the 2-inch rings was -14%, the 2-inch Tri-Packs had a -16% average error. This indicates a potential deficiency in the Onda model for larger nominal packing sizes. However, attempts to account for this behavior by modification of the liquid-phase shape factor coefficient were unsuccessful. The shape factor has essentially the same value (approximately 5.2) for each size of Pall ring considered (including the

2-inch size) and also for the 1-inch saddles, while the 2-inch Tri-Packs value is 7.0. Therefore, any adjustment to the power value associated with the shape factor cannot be effectively used to differentiate the performance predictions for both 2-inch packings from the smaller sizes.

Gossett and his co-authors attempted to explain the 2-inch Tri-Pack behavior by comparing the results to the 1-inch saddles, whose performance was consistently overestimated by the Onda correlation. It was concluded that a fundamental difference in behavior between the two types of packing was responsible for the results. However, as subsequently discussed, such a fundamental difference was not noted in the other studies considered. Therefore, the nominal size explanation offered here seems more likely and reasonable.

The behavior of the 1-inch saddles cannot be easily explained. For fifty-one of the fifty-four points, the correlation error ranged from 0 to +37%, with an average error of +20%. No discernible pattern could be detected from a review of the data. The modified Onda model proposed by Gossett <u>et al.</u> (see section 2.2.3.5) produced a widely scattered plot, indicating that the relative gas-phase resistance was not related to the correlation error values noted for this packing.

A third area of concern lies in the evaluation of loading rate effects. Overall, no clear-cut patterns could be related to predictive errors. For runs conducted under constant liquid loading, the potential pattern of increasing error by the correlation as the air loading is decreased (i.e.- increased relative gas-phase resistance) was seen for both the 2-inch Tri-Packs and 1-inch saddles. However, for the Tri-Packs, the overall effect of only a 10% error increase over a 12-fold decrease in the air flow rate can hardly be deemed significant. Although a more serious error is noted for the saddles, a consistent relationship based on only relative gas-phase resistance is not clearly visible. Since three experimental tests produced gross errors (+50 to +100%), inconsistent with other results noted for this packing, the apparent effects seem exaggerated.

For the constant air flow tests, prediction errors appear independent of the water loading rates. It should be noted that the liquid loading range employed (15 to 34 gpm per square foot) resides comfortably in the middle of the typical design range of 10 to 50 gpm per square foot previously cited (see section 3.1.1.4). Thus, extreme water loading conditions were not investigated.

**Temperature Dependency Study Results:** The specific results obtained based on this data are presented in Table 7. For two of the five compounds tested, namely chloroform and methylene chloride, large positive errors (+70 to +186%) were found for the correlation. Since the test packing was 1-inch Pall rings, relatively close agreement with the Onda predictions would be expected based on the isothermal study results for this packing. However, the compounds in question are the lowest in volatility of those tested and under the operating conditions employed, the corresponding stripping factors did not exceed 1.7. For such low stripping factors, measurement errors become magnified in calculation of observed transfer rates (see section 4.1), and this is offered as a

Table 7. RESULTS: GOSSETT STUDY [23] - Temperature Dependency Experiments

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| | | | | | | | | Tetrachloroethylene: |
| 40 | 33.4 | 8.1 | 54.0 | 53.4 | - 1 | 2.5 | 8 | 50° F (10° C) |
| 40 | 33.4 | 8.1 | 75.0 | 79.8 | 6 | 4.4 | 6 | 68° F (20° C) |
| 40 | 33.4 | 8.1 | 102.0 | 112.2 | 10 | 7.5 | 5 | 86° F (30° C) |
| | | | | | | | | 1,1,1-Trichloroethane: |
| 40 | 33.4 | 8.1 | 61.2 | 55.5 | - 9 | 2.8 | 7 | 50° F (10° C) |
| 40 | 33.4 | 8.1 | 84.0 | 82.2 | - 2 | 4.5 | 6 | 68° F (20° C) |
| 40 | 33.4 | 8.1 | 108.6 | 115.2 | 6 | 6.9 | 5 | 86° F (30° C) |
| | | | | | | | | Trichloroethylene: |
| 40 | 33.4 | 8.1 | 45.0 | 53.4 | 19 | 1.5 | 12 | 50° F (10° C) |
| 40 | 33.4 | 8.1 | 69.0 | 80.4 | 16 | 2.6 | 10 | 68° F (20° C) |
| 40 | 33.4 | 8.1 | 93.6 | 114.0 | 22 | 4.3 | 8 | 86° F (30° C) |
| | | | | | | | | Chloroform: |
| 40 | 33.4 | 8.1 | 23.4 | 49.3 | 110 | 0.71 | 23 | 50° F (10° C) |
| 40 | 33.4 | 8.1 | 42.6 | 74.4 | 75 | 1.1 | 21 | 68° F (20° C) |
| 40 | 33.4 | 8.1 | 66.0 | 106.2 | 70 | 1.7 | 18 | 86° F (30° C) |
| | | | | | | | | Methylene Chloride: |
| 40 | 33.4 | 8.1 | 16.8 | 48.1 | 186 | 0.48 | 30 | 50° F (10° C) |
| 40 | 33.4 | 8.1 | 28.8 | 73.2 | 154 | 0.76 | 27 | 68° F (20° C) |
| 40 | 33.4 | 8.1 | 47.4 | 105.6 | 123 | 1.2 | 24 | 86° F (30° C) |

General Notes: Packing - 1" Pall Rings

possible explanation for the gross errors noted. Using the remaining data for the other three compounds, no discernible pattern of prediction errors associated with temperature changes could be seen. The range of testing covered, 50 to 86°F, represents most groundwater temperature situations, although colder conditions could be encountered in surface water treatment situations.

**Modified Onda Relation:** The results reported by Gossett et al. [23] for the values of "a" and "b" in the modified Onda equations (see section 2.2.3.5) are presented in Table 8; a typical definition plot is given in Figure 9. As noted in the original report, the plots generally have wide scatter to them. Furthermore, the lack of agreement among the various packings is disturbing. It was hoped that the "a" and "b" values would be nearly constant for the different sizes of Pall rings, indicating that such modifications would apply to a particular packing configuration, regardless of its nominal size. Of concern also is that entirely different results were obtained for separate studies involving the same packing, namely the 1-inch Pall rings. Although the temperature dependency study itself had apparent problems, even the data which appears in reasonable agreement with expectations does not match the results obtained from the isothermal study. Finally, the results for the 1-inch saddles and the 2-inch Tri-Packs yield correlation constant values drastically different from their original ones and even more so from each other. However, as subsequently detailed, these proposed modifications are not consistent with the results seen in other studies. Therefore, as conceded by the

Table 8. Reported Adjustment Values for the Modified Onda Correlation From Gossett and Co-workers [23]

| Packings (all plastic) | a | b |
|---|---|---|
| 5/8 inch Pall Rings | 1.09 | 0.49 |
| 1 inch Pall Rings[1] | 1.14 | 0.47 |
| 1 inch Pall Rings[2] | 1.85 | 0.14 |
| 2 inch Pall Rings | 1.22 | 0.78 |
| 1 inch Saddles | 0.95 | 0.33 |
| 2 inch Tri-Packs | 1.08 | 2.22 |

1 - from isothermal study (77°F or 25°C)
2 - from temperature dependency study (50-86°F or 10-30°C)

NOTE: See equation {31} in text.
a - modifies Onda liquid-phase relation
b - modifies Onda gas-phase relation
See typical defining plot - Figure 9

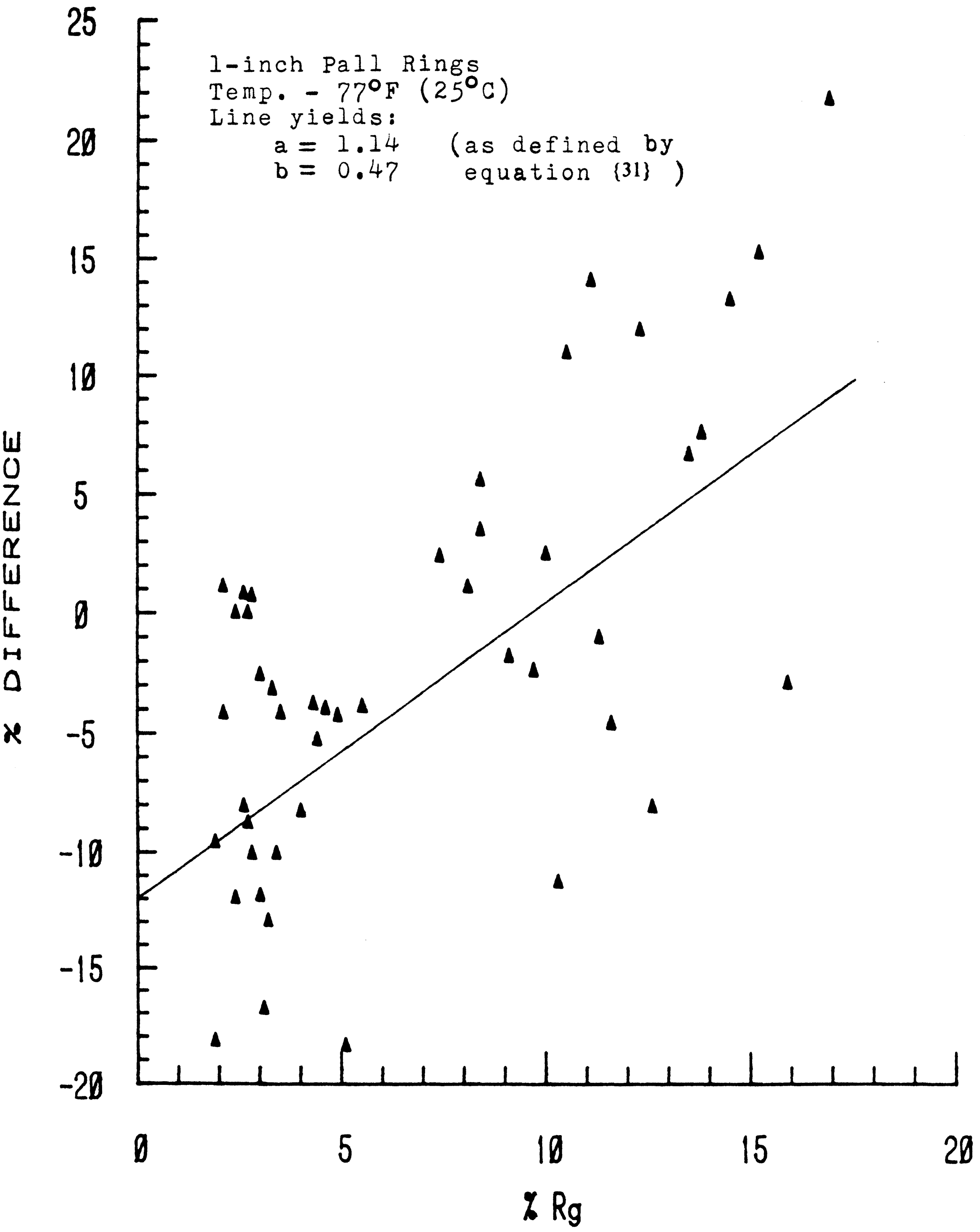


Figure 9. Typical definition plot reported for proposed adjustment factors to the Onda equations. After Gossett <u>et al.</u> [23].

authors of the original report, no simple alteration of the individual gas- and liquid-phase mass transfer relations by constant factors appears to consistently improve the predictive ability of the Onda correlation.

#### 4.2.2.2 Cummins Studies

For the studies considered [9,10,12], sampling was conducted at two or three foot intervals within the packed column to determine a concentration profile down the length of the column. This procedure eliminated the need to correct for end effects. In the original work, the top of packing concentration values were not directly measured, but were "determined" based on the procedure described below.

The data analysis utilized by the original investigators involved adjusting both top-of-packing concentrations and Henry's constant values to obtain a minimum deviation from the profile prediction offered by the Onda model. First, using Henry's constants conforming to solubility predictions, a best-fit value for the top of packing concentration was calculated such that the relative standard deviation between the "observed" and predicted profiles was minimized. Next, various values for Henry's constant were selected and the process repeated. A plot of the assumed Henry's constant values versus the corresponding profile standard deviations yielded a minimum point. The Henry's constant value corresponding to this minimum point was assumed to be the true value. The Henry's constants reported based on this analysis [9,10,12] are from 40 to 60% less than the corresponding values judged to be reasonably accurate and used for the calculations performed in this study. As Henry's constant relations appear well-established by recent experimental work (see section 3.2.2), the use of these "best-fit" values could not be justified. Indeed, the values do not lead to improved performance by the Onda model based on data from the other studies considered.

Furthermore, the validity of the analysis procedure utilized is suspect. The concept of obtaining a best-fit Henry's constant by itself is not extremely questionable. Assuming that the Onda correlation is reasonably accurate, either an estimate of true Henry's constant values can be made in lieu of reliable data or a check performed on reported values. However, the adjustment of the top of packing concentrations seems unjustifiable, an apparent case of hedging one's bets that the Onda model itself is accurate.

In reviewing the Louisiana site study [9], which provided the raw data and details of the author's analysis (both of which are provided in Appendix A), the best-fit top-of-packing concentrations generally do not reasonably conform with the established column profiles. Since the first samples were taken at a packing depth of 0.5 feet, the actual top of the packing concentration would be expected to lie slightly above this value. However, the top-of-packing concentrations cited were both significantly above and below the 0.5-foot values, more so than could be reasonably attributed to analytical measurement errors alone. In addition, wide variations in the top-of-packing concentration reported were seen based upon the results presented for the solubility-predicted Henry's constant versus the best-fit Henry's constant value. Finally, a total of fifteen experimental tests were completed on-site during a two day time frame. Over such a short period, significantly changing influent concentrations of VOCs would not be expected, and this was generally confirmed by the 0.5-foot depth concentrations. However, the top of packing values calculated by this analysis procedure did not reflect this apparent fact.

Because of such questions, the raw data presented in the Louisiana site report was reworked for this evaluation using the end effects analysis procedure suggested by equation {34}. Linear regressions were performed on the profile data to yield a best-fit NTU versus packing depth equation for each experiment. In this regard, the 0.5-foot depth samples were assumed to be the top of the packing concentration values. Since only the slope of the line obtained is required (representing 1/HTU), this assumption had no effect on the results. Details of the actual analysis are provided in Appendix A.

The Onda prediction results for the Louisiana site study are presented in Table 9 below. The results for the correlation show a pattern of increasing positive error as the air to water ratio increases, from a slight negative error at high ratios (a -10% average for ratios exceeding 75/1) up to a larger positive error at low ratios (a +20% average for ratios less than 17/1). An important consideration is that the increase in the air to water ratio was achieved via an increase in the air loading coupled with a decrease in the water loading. Therefore, individual loading effects on model prediction errors could not be easily differentiated. However, this work serves to test two column operating extremes. The low liquid loading, high air to water ratio case produces

Table 9 . RESULTS: CUMMINS STUDY [9] - Louisiana Site Investigation

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 106.4 | 9.2 | 87.0 | 32.7 | 29.8 | - 9 | 18.9 | 4 | Toluene |
| 84.9 | 14.1 | 45.0 | 39.7 | 40.9 | 3 | 9.8 | 5 | " |
| 74.8 | 22.1 | 25.3 | 50.1 | 56.6 | 13 | 5.5 | 6 | " |
| 64.7 | 29.5 | 16.4 | 61.3 | 69.3 | 13 | 3.6 | 8 | " |
| 47.1 | 44.2 | 8.0 | 71.6 | 90.2 | 26 | 1.7 | 12 | " |
| 155.6 | 13.3 | 87.7 | 47.3 | 39.7 | -16 | 19.0 | 2 | " |
| 126.0 | 20.6 | 45.8 | 47.2 | 54.8 | 16 | 9.9 | 4 | " |
| 102.4 | 30.9 | 24.8 | 69.2 | 73.3 | 6 | 5.4 | 6 | " |
| 88.9 | 39.7 | 16.7 | 65.6 | 87.2 | 33 | 3.6 | 7 | " |
| 57.3 | 54.5 | 7.9 | 82.7 | 105.8 | 28 | 1.7 | 11 | " |
| 181.2 | 17.7 | 76.9 | 47.4 | 49.3 | 4 | 16.7 | 3 | " |
| 165.0 | 28.0 | 44.1 | 72.9 | 69.3 | - 5 | 9.6 | 4 | " |
| 128.0 | 38.3 | 25.0 | 78.5 | 86.3 | 10 | 5.4 | 6 | " |
| 102.4 | 48.7 | 15.8 | 95.7 | 101.4 | 6 | 3.4 | 7 | " |
| 74.8 | 66.3 | 8.4 | 85.2 | 123.5 | 45 | 1.8 | 10 | " |
| 106.4 | 9.2 | 87.0 | 35.8 | 31.5 | -12 | 15.9 | 3 | Benzene |
| 84.9 | 14.1 | 45.0 | 50.8 | 43.2 | -15 | 8.2 | 6 | " |
| 74.8 | 22.1 | 25.3 | 55.5 | 59.6 | 7 | 4.6 | 7 | " |
| 64.7 | 29.5 | 16.4 | 68.6 | 72.8 | 6 | 3.0 | 9 | " |
| 47.1 | 44.2 | 8.0 | 91.4 | 94.1 | 3 | 1.5 | 13 | " |
| 155.6 | 13.3 | 87.7 | 44.8 | 42.1 | - 6 | 16.0 | 4 | " |
| 126.0 | 20.6 | 45.8 | 60.9 | 57.9 | - 5 | 8.4 | 5 | " |
| 102.4 | 30.9 | 24.8 | 71.5 | 77.2 | 8 | 4.5 | 7 | " |
| 88.9 | 39.7 | 16.7 | 67.4 | 91.7 | 36 | 3.1 | 8 | " |
| 57.3 | 54.5 | 7.9 | 91.3 | 110.5 | 21 | 1.4 | 13 | " |
| 181.2 | 17.7 | 76.9 | 61.4 | 52.2 | -15 | 14.1 | 4 | " |
| 165.0 | 28.0 | 44.1 | 82.2 | 73.2 | -11 | 8.1 | 5 | " |
| 128.0 | 38.3 | 25.0 | 85.8 | 91.0 | 6 | 4.6 | 6 | " |
| 102.4 | 48.7 | 15.8 | 97.8 | 106.6 | 9 | 2.9 | 8 | " |
| 74.8 | 66.3 | 8.4 | 116.3 | 129.1 | 11 | 1.5 | 12 | " |

General Notes: Packing - 1" Saddles
Water Temp. - 68° F (20° C)

the highest removal values obtainable for a given system, while operation at high liquid loading and low air to water ratios yields the lowest removal efficiencies. Economical design practice would tend to fall in the region between these two extremes.

From a predictive standpoint, the Onda model handled the situation of low liquid loading and high air to water ratios reasonably well. Although it would result in underestimation of actual compound removal, the error is not serious, judging by the fact that the mass transfer rate was underestimated by less than 20%. However, the results for operation under high liquid loading combined with low air to water ratios raises some concern. The Onda correlation was given an accuracy of 20% in the original work [46]. If a corresponding safety factor of 0.8 is chosen for design purposes, then the average 20% overestimation by the Onda model would barely be taken into account under such conditions. Therefore, the packed column so-designed could offer only limited flexibility in regards to handling larger liquid loadings or increased influent concentrations without a reduction in performance. As operation at high liquid loading and low air to water ratios can offer economical operation, such effects are particularly important to consider.

The multiple site study [12] results presented in Table 10 support the general findings observed for the Louisiana site investigation. However, very large positive errors (+100 to +200%) are seen for the high water loading, low air to water ratio cases. This poses a potential serious limitation on the use of the correlation. However, several points tend to discount the results indicated. First, and most importantly, the

Table 10. RESULTS: CUMMINS STUDY [12] - Multiple Site Investigation

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 112 | 10.5 | 80 | 28.9 | 25.7 | -11 | 16.9 | 3 | |
| 101 | 16.8 | 45 | 40.6 | 36.6 | -10 | 9.5 | 4 | |
| 84 | 25.2 | 25 | 47.1 | 49.1 | 4 | 5.3 | 5 | |
| 67 | 33.6 | 15 | 46.7 | 60.0 | 28 | 3.2 | 6 | |
| 50 | 47.1 | 8 | 39.5 | 75.0 | 92 | 1.7 | 10 | |
| 42 | 63.0 | 5 | 32.0 | 90.6 | 183 | 1.1 | 12 | |

General Notes:
Packing - 1" Saddles
VOC Stripped - Trichloroethylene
Water Temp. - 55° F (12.5° C)

NOTE: Measured values are based on average removals achieved at eight separate sites.

measured transfer rates were computed from average removal values cited in the original article. These values were generated based on the data analysis procedure previously concluded to be suspect. Indeed, a review of the calculated top-of-packing concentrations presented in the Louisiana site report (and reproduced in Appendix A) reveal an explanation for the results obtained from the multiple-site study. In all cases, the top-of-packing concentrations were reduced when the best-fit Henry's constant value was used as compared to when the solubility-predicted Henry's constant was employed. The greatest impact was seen for the lowest air to water ratio test conditions, where the top-of-packing concentrations decreased 30 to 50%. The use of such reduced concentration values which may well be significantly less than true values would result in lower computed removal efficiencies than had actually occurred. In turn, these inaccurately low removal values will yield "observed" transfer rates which underestimate the true rates. Therefore, the corresponding Onda predictions would appear to overestimate transfer rates, particularly at low air to water ratios. Such an observation is indeed noted from the results presented in Table 10.

A further indication that the "observed" transfer rates computed from the information provided in the multiple-site report are inaccurate is revealed upon comparing the measured results given by the multiple-site and Louisiana site studies. For the multi-site investigation, as the air to water ratio decreased, the corresponding observed transfer rates increased at first, but then significantly decreased for the lowest two air to water ratios. As the Onda correlation predicted a steady increase in the transfer rate, large positive errors were noted. For the Louisiana site study, however, this predicted continual increase in measured transfer rates as the air to water ratio decreased was indeed evident in the observed results. As the tests conducted in both studies involved column operation under similar loading conditions, consistent general mass transfer behavior should have been found. Again, it appears that the multiple-site report data is suspect and should be discounted. Therefore, the prediction errors for high liquid loading, low air to water ratios noted from the Louisiana site investigation are believed more indicative of the Onda correlation's accuracy than the exaggerated error seen in the multi-site study where inaccurate data analysis appears to be responsible for the gross errors noted between "observed" and predicted transfer rates.

#### 4.2.2.3 Gross & TerMaath Study

This study [24] investigated trichloroethylene removal using 1-inch Pall rings. The results for a particular air and water loading rate were fitted to a general temperature dependency relation for the overall mass transfer rate, given as:

$$K_L a = \exp\left(8.518 - \frac{2515}{T}\right) \qquad \{47\}$$

where: $K_L a$ - overall mass transfer rate (1/minute)

T - degrees Kelvin

Table 11 RESULTS: GROSS & TERMAATH STUDY [24]

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 21 | 21 | 7.5 | 34.7 | 32.9 | - 5 | 1.0 | 11 | 40° F ( 4° C) |
| 21 | 21 | 7.5 | 49.2 | 52.2 | 6 | 1.9 | 9 | 60° F (16° C) |
| 21 | 21 | 7.5 | 68.0 | 78.9 | 16 | 3.4 | 7 | 80° F (27° C) |

General Notes: Packing - 1" Pall Rings
VOC Stripped - Trichloroethylene

NOTE: Measured values are calculated at selected temperatures from the general temperature equation given in the original work (see equation {47} in text).

The expression is valid over the range of 50 to 86°F. The Henry's constant values used by the researchers to generate this relation were taken from Gossett et al. [23] and represent the same values for TCE employed in evaluating the data from other studies.

Predicted transfer rates were computed for comparison with the results given by the above expression at temperature values of 40 , 60, and 80°F. This served to span the normal operating water temperature range encountered in practice. The results presented in Table 11 show the Onda correlation to slightly overpredict the effects due to temperature variations. However, the resultant errors are relatively small in magnitude (well within the 20% accuracy originally placed on the correlation), and therefore they can be attributed to experimental inaccuracies. Thus, for this data, temperature considerations were adequately handled by the Onda model without significant prediction errors.

#### 4.2.2.4 Malcolm Pirnie Study - Raczko Report

This study [48] evaluated the potential effects of influent VOC concentration on performance. Two sites were investigated. The first, located in Pennsylvania, contained very low levels (20 to 30 ug/liter) of trichloroethylene while the second site, in New Jersey, provided groundwater with high TCE levels of 1000 to 2500 ug/liter, along with samples from a contaminated pit which contained an extreme value of approximately 27,000 ug/liter. The pilot tests conducted covered the

Table 12. RESULTS: MALCOLM PIRNIE STUDY [48] - Raczko Report

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 48.4 | 19.1 | 18.9 | 36.9 | 38.4 | 4 | 4.1 | 7 | Penns. Influent= |
| 48.4 | 25.5 | 14.2 | 48.4 | 47.4 | - 2 | 3.1 | 8 | Site 23-34 ug/l |
| 48.4 | 28.0 | 12.9 | 47.0 | 50.8 | 8 | 2.8 | 9 | " " |
| 56.0 | 31.8 | 13.2 | 60.5 | 56.1 | - 7 | 2.9 | 8 | " " |
| 66.2 | 38.2 | 13.0 | 69.5 | 64.6 | - 7 | 2.8 | 8 | " " |
| 135.0 | 12.7 | 79.3 | 27.5 | 29.3 | 7 | 17.2 | 3 | N.J. Influent= |
| 61.1 | 25.5 | 18.0 | 59.8 | 47.9 | -20 | 3.9 | 7 | Site 1100-2500 |
| 132.4 | 25.5 | 38.9 | 43.1 | 49.3 | 14 | 8.4 | 4 | " ug/l |
| 36.9 | 38.2 | 7.2 | 83.5 | 62.3 | -25 | 1.6 | 12 | " " |
| 76.4 | 38.2 | 15.0 | 72.5 | 65.1 | -10 | 3.3 | 7 | " " |
| 140.1 | 38.2 | 27.4 | 63.2 | 66.6 | 5 | 5.9 | 5 | " " |
| 127.3 | 43.3 | 22.0 | 61.4 | 72.8 | 19 | 4.8 | 5 | " " |
| 122.2 | 50.9 | 18.0 | 95.8 | 81.8 | -15 | 3.9 | 6 | " " |
| 112.0 | 63.7 | 13.2 | 79.5 | 95.6 | 20 | 2.9 | 7 | " " |
| 63.7 | 8.9 | 53.4 | 22.2 | 22.0 | - 1 | 11.6 | 4 | " Influent= |
| 140.1 | 10.2 | 102.8 | 28.9 | 24.8 | -14 | 22.3 | 3 | " 26,000-28,000 ug/l |

General Notes:
Packing - 1" Saddles
VOC Stripped - Trichloroethylene
Water Temp. - 55° F (12.5° C)

entire range of typical operating conditions. Thus, this study provides a strong test for the Onda model.

Correlation predictions show excellent agreement with measured results as indicated in Table 12 above. Seven positive errors were noted, averaging +11%, while nine negative errors at an average of -11% were found, yielding a balanced error distribution. Of the errors noted, no relation could be attributed to the corresponding relative gas-phase resistance values. In addition, the wide range of influent concentration levels had no apparent effect on column performance. This was expected since general mass transfer theory holds that actual concentration levels do not affect fundamental transfer behavior. Finally, no water matrix effects on performance were noted between the two separate sites that the study investigated.

In conducting their own data analysis, the original authors (Raczko _et al._) presented a graph of the measured transfer rates versus those predicted by the Sherwood-Holloway correlation. The results showed the Sherwood-Holloway model to be in serious error, overestimating transfer rates by approximately 67%. Therefore, the superiority of the Onda correlation over that offered by Sherwood and Holloway was again demonstrated.

#### 4.2.2.5 Malcolm Pirnie Study - Connecticut Site Report

This study [27] compared the performance of two distinct packing types, namely saddle versus Tellerette configurations. Also, a limited amount of additional testing with 2-inch Tellerettes sought to ascertain any performance differences between common 1- and 2-inch nominal size packings. Since two separate wells were investigated, influent TCE levels ranged from 17 to 140 ug/l. The study fairly well tested the typical design operating conditions, particularly by employing economical stripping factors in the 3 to 5 range.

From the results presented in Table 13, there was no general indication that correlation errors were related to the percentage of gas-phase resistance. Two large underestimations (~40%) did occur when the gas-phase resistance was very high (~35% of total resistance). However, upon further review, these cases also involved a stripping factor of only 1.0. Therefore, the apparent correlation errors may actually be due to the magnification of experimental measurement inaccuracies noted for such low stripping factors. In support of this contention, one additional experimental run produced a -46% prediction error when the stripping factor was also 1.0, but the gas-phase resistance for this case was only 14% of the total resistance.

Overall, the Onda correlation offered excellent predictive agreement with the results obtained. Neglecting the three points discussed above, the predictions yielded ten positive errors, averaging +9%, and thirteen negative errors, averaging -9%. Therefore, this study indicates that the Onda model can provide highly accurate predictions for design. In addition, the correlation handled two different packing configurations equally well, without any adjustment necessary. Likewise, local water quality and influent VOC levels had no effects on the results.

Table 13. RESULTS: MALCOLM PIRNIE STUDY [27] - Connecticut Site Report

| Loading Conditions | | | Mass Transfer Rates | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes | |
| 54.7 | 20.4 | 20.1 | 38.8 | 39.6 | 2 | 4.1 | 7 | Well #1 | 1-inch |
| 81.5 | 20.4 | 29.9 | 42.1 | 40.2 | - 5 | 6.1 | 5 | " | Saddles |
| 108.2 | 16.6 | 48.9 | 37.4 | 34.7 | - 7 | 10.0 | 4 | " | " |
| 81.5 | 30.6 | 19.9 | 60.6 | 54.2 | -11 | 4.1 | 6 | " | " |
| 40.7 | 20.4 | 15.0 | 33.5 | 39.0 | 16 | 3.1 | 8 | Well #2 | " |
| 67.5 | 20.4 | 24.8 | 35.3 | 39.9 | 13 | 5.1 | 6 | " | " |
| 40.7 | 20.4 | 15.0 | 38.9 | 39.0 | 0 | 3.1 | 8 | Combined | " |
| 67.5 | 20.4 | 24.8 | 40.2 | 39.9 | - 1 | 5.1 | 6 | Wells | " |
| 54.7 | 20.4 | 20.1 | 37.3 | 38.2 | 2 | 4.1 | 5 | Well #1 | 1-inch |
| 81.5 | 20.4 | 29.9 | 39.9 | 38.6 | - 3 | 6.1 | 4 | " | Tellerettes |
| 108.2 | 16.6 | 48.9 | 40.6 | 33.3 | -18 | 10.0 | 3 | " | " |
| 101.9 | 15.3 | 49.9 | 30.8 | 31.3 | 2 | 10.2 | 3 | " | " |
| 50.9 | 15.3 | 24.9 | 29.1 | 30.8 | 6 | 5.1 | 5 | " | " |
| 67.5 | 20.4 | 24.8 | 39.7 | 38.4 | - 3 | 5.1 | 5 | " | " |
| 40.7 | 20.4 | 15.0 | 41.6 | 37.7 | - 9 | 3.1 | 7 | Well #2 | " |
| 67.5 | 20.4 | 24.8 | 45.7 | 38.4 | -16 | 5.1 | 5 | " | " |
| 40.7 | 20.4 | 15.0 | 40.9 | 37.7 | - 8 | 3.1 | 7 | Combined | " |
| 67.5 | 20.4 | 24.8 | 43.6 | 38.4 | -12 | 5.1 | 5 | Wells | " |
| 101.9 | 30.6 | 24.9 | 42.8 | 52.4 | 22 | 5.1 | 4 | " | " |
| 16.6 | 25.5 | 4.9 | 77.4 | 41.8 | -46 | 1.0 | 14 | " | " |
| 101.9 | 12.7 | 59.8 | 23.1 | 27.3 | 18 | 12.3 | 3 | " | " |
| 16.6 | 25.5 | 4.9 | 57.5 | 34.7 | -40 | 1.0 | 37 | " | 2-inch |
| 50.9 | 25.5 | 15.0 | 39.2 | 40.7 | 4 | 3.1 | 17 | " | Tellerettes |
| 85.3 | 25.5 | 25.1 | 41.8 | 42.5 | 2 | 5.1 | 12 | " | " |
| 24.2 | 35.7 | 5.1 | 72.8 | 45.7 | -37 | 1.0 | 34 | " | " |
| 15.0 | 35.7 | 15.0 | 64.0 | 52.8 | -18 | 3.1 | 16 | " | " |
| 108.2 | 31.8 | 25.4 | 52.6 | 50.5 | - 4 | 5.2 | 11 | " | " |

General Notes: VOC Stripped - Trichloroethylene
Water Temp. - 57$^{\circ}$ F (13$^{\circ}$ C)

Finally, the 2-inch Tellerette's performance was accurately modeled, unlike the distinct underprediction found for 2-inch packings in the Gossett study.

#### 4.2.2.6 Malcolm Pirnie Study - Cline Report

This study [6] investigated the removal of trichloroethylene using 2-inch Tri-Packs. As the contamination site is located in Arizona, the groundwater temperature encountered (79°F) represents the highest natural operating temperature likely to be confronted in practice. Typical loading conditions were tested, although the stripping factor range was very high with respect to economical design values. Only one run was conducted where the stripping factor was less than 6 while a range of 3 to 5 is normally optimal for design purposes.

The results presented in Table 14 indicate a definite overprediction by the Onda model. Prediction errors ranged from +2 to +34%, yielding an average of +15%. This is in direct contrast with the Gossett study results, where the correlation underpredicted mass transfer rates by an average of 16% for 2-inch Tri-Packs. One possible explanation for the overestimation of transfer rates seen with the Cline data lies in potential channeling effects. The test column used was twelve inches in diameter, which yields a column diameter to nominal packing size ratio of only 6 to 1. To avoid channeling effects, the absolute minimum value cited is 8 to 1 [63]. As detailed in section 3.1.1.2, channeling leads to reduced column performance, thereby causing overprediction by the Onda

Table 14. RESULTS: MALCOLM PIRNIE STUDY [6] - Cline Report

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 101.9 | 16.6 | 46.0 | 58.8 | 60.4 | 3 | 20.1 | 10 | |
| 84.0 | 17.8 | 35.3 | 47.2 | 62.8 | 33 | 15.4 | 12 | |
| 127.3 | 20.4 | 46.8 | 60.1 | 71.1 | 18 | 20.4 | 10 | |
| 86.6 | 21.6 | 29.9 | 55.5 | 72.3 | 30 | 13.1 | 13 | |
| 85.3 | 25.5 | 25.1 | 60.5 | 80.9 | 34 | 11.0 | 14 | |
| 75.1 | 28.0 | 20.1 | 75.5 | 85.3 | 13 | 8.8 | 16 | |
| 101.9 | 30.6 | 24.9 | 91.5 | 93.2 | 2 | 10.9 | 14 | |
| 101.9 | 31.8 | 23.9 | 88.0 | 95.9 | 9 | 10.4 | 14 | |
| 114.6 | 33.1 | 25.9 | 92.9 | 99.5 | 7 | 11.3 | 13 | |
| 91.7 | 34.4 | 19.9 | 93.4 | 100.1 | 7 | 8.7 | 16 | |
| 76.4 | 39.5 | 14.5 | 94.9 | 107.9 | 14 | 6.3 | 19 | |
| 127.3 | 40.7 | 23.4 | 98.0 | 115.9 | 18 | 10.2 | 14 | |
| 191.0 | 40.7 | 35.1 | 113.5 | 119.4 | 5 | 15.3 | 10 | |
| 56.0 | 42.0 | 10.0 | 92.8 | 108.2 | 17 | 4.4 | 24 | |
| 178.3 | 45.8 | 29.1 | 120.4 | 129.0 | 7 | 12.7 | 11 | |

General Notes: Packing - 2" Tri-Packs
VOC Stripped - Trichloroethylene
Water Temp. - $79^{o}$ F ($26^{o}$ C)

correlation. It should be pointed out, however, that redistribution rings were present at regular intervals within the test column, and these rings should have mitigated a good portion of the potential channeling effects.

No dependence of prediction error on percent gas-phase resistance was noted. A slight (~10%) increase in error was seen for operation at the lower end of the liquid loading rates tested. However, the actual loading values in question are around 20 gpm per square foot, which is not extremely low with respect to the typical design range.

#### 4.2.2.7 Malcolm Pirnie Study - Pennsylvania Site Report

This study [27] tested water contaminated with a mixture of three VOCs. Liquid loading rates were maintained in the middle of the typical operating range, while a reasonable range of stripping factors was employed.

The evaluation results given in Table 15 show a consistent overestimation of transfer rates by the Onda correlation, with prediction errors ranging from -12% to +48% which yielded an overall average error of +20%. One encouraging point was that predictions for each VOC (tetrachloroethylene, trichloroethylene, and 1,1,1-trichloroethane) produced similar average errors (+16%, +22%, and +20% respectively), indicating that the particular VOC involved did not have a bearing on the resulting correlation error. No relationship between prediction error and percent gas-phase resistance was detected. Nearly all of the work was conducted at two moderate liquid loading rates (22.5 and 31.8 gpm per

Table 15. RESULTS: MALCOLM PIRNIE STUDY [27] - Pennsylvania Site Report

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 38.2 | 25.5 | 11.2 | 37.4 | 48.9 | 31 | 2.6 | 9 | Trichloroethylene |
| 63.7 | 25.5 | 18.7 | 38.1 | 50.2 | 32 | 4.3 | 6 | " |
| 68.8 | 25.5 | 20.2 | 40.7 | 50.4 | 24 | 4.6 | 6 | " |
| 85.3 | 25.5 | 25.1 | 56.6 | 50.8 | -10 | 5.8 | 5 | " |
| 89.1 | 25.5 | 26.2 | 38.4 | 50.9 | 33 | 6.0 | 5 | " |
| 30.6 | 31.8 | 7.2 | 47.8 | 56.5 | 18 | 1.7 | 12 | " |
| 59.8 | 31.8 | 14.1 | 59.1 | 58.9 | 0 | 3.2 | 7 | " |
| 80.2 | 31.8 | 18.8 | 40.4 | 59.7 | 48 | 4.3 | 6 | " |
| 94.5 | 31.8 | 22.4 | 49.8 | 60.1 | 21 | 5.1 | 5 | " |
| 71.3 | 38.2 | 14.0 | 56.2 | 67.8 | 21 | 3.2 | 7 | " |
| 38.2 | 25.5 | 11.2 | 49.6 | 47.8 | - 3 | 4.3 | 5 | Tetrachloroethylene |
| 63.7 | 25.5 | 18.7 | 40.2 | 48.5 | 21 | 7.2 | 4 | " |
| 68.8 | 25.5 | 20.2 | 42.6 | 48.6 | 15 | 7.8 | 4 | " |
| 85.3 | 25.5 | 25.1 | 37.9 | 48.8 | 30 | 9.7 | 3 | " |
| 89.1 | 25.5 | 26.2 | 42.1 | 48.9 | 16 | 10.1 | 3 | " |
| 30.6 | 31.8 | 7.2 | 51.2 | 55.7 | 10 | 2.8 | 7 | " |
| 42.0 | 31.8 | 9.9 | 44.2 | 56.4 | 28 | 3.8 | 6 | " |
| 59.8 | 31.8 | 14.1 | 64.7 | 57.1 | -12 | 5.5 | 4 | " |
| 80.2 | 31.8 | 18.8 | 49.4 | 57.5 | 18 | 7.2 | 4 | " |
| 94.5 | 31.8 | 22.4 | 41.1 | 57.8 | 42 | 8.6 | 3 | " |
| 71.3 | 38.2 | 14.0 | 60.7 | 65.5 | 9 | 5.4 | 4 | " |
| 38.2 | 25.5 | 11.2 | 39.3 | 49.6 | 28 | 4.7 | 5 | 1,1,1-Trichloroethane |
| 63.7 | 25.5 | 18.7 | 37.3 | 50.3 | 36 | 7.8 | 3 | " |
| 68.8 | 25.5 | 20.2 | 42.7 | 50.4 | 19 | 8.4 | 3 | " |
| 85.3 | 25.5 | 25.1 | 46.1 | 44.5 | 11 | 10.4 | 3 | " |
| 89.1 | 25.5 | 26.2 | 40.4 | 50.7 | 26 | 10.9 | 3 | " |
| 30.6 | 31.8 | 7.2 | 56.0 | 57.9 | 4 | 3.0 | 6 | " |
| 42.0 | 31.8 | 9.9 | 44.9 | 58.6 | 31 | 4.1 | 5 | " |
| 59.8 | 31.8 | 14.1 | 63.1 | 59.3 | - 6 | 5.9 | 4 | " |
| 80.2 | 31.8 | 18.8 | 50.1 | 59.6 | 19 | 7.8 | 3 | " |
| 94.5 | 31.8 | 22.4 | 40.8 | 59.8 | 48 | 9.3 | 3 | " |
| 71.3 | 38.2 | 14.0 | 63.7 | 68.0 | 8 | 5.8 | 4 | " |

General Notes: Packing - 1" Saddles
Water Temp. - 57° F (13° C)

square foot), while the air to water ratio was varied over a limited range of 7 to 27. Despite such a narrow range of test conditions, a relatively wide scatter in observed transfer rates can be noted for experiments conducted under very similar loading conditions. Also, scatter is visible in the observed rates for a given experiment among the three VOCs tested. Therefore, it is clearly apparent that significant random errors in measuring true mass transfer rates must be anticipated when reviewing the results from pilot-scale packed column studies.

#### 4.2.2.8 Byers & Morton Study

This study [4] was unique in several respects. First, the test packing utilized was 1/2-inch ceramic saddles. Such small nominal-sized packings are not normally chosen in practice since the associated large pressure drops result in high operational costs. Also, ceramic packing material is not typically selected for water treatment applications, being much more expensive than corresponding plastic packings. Secondly, spiked distilled water was tested rather than the actual contaminated water source. This neglected any possible water matrix effects. Finally, the study specifically sought to examine temperature effects by conducting tests at 43 and 68°F.

A total of four VOCs were tested (trans-1,2-dichloroethane, tetrachloroethylene, trichloroethylene, and 1,1,2,2-tetrachloroethane), although only data for the first three of these was evaluated since Henry's constant values for the fourth compound were not available. In

Table 16. RESULTS: BYERS & MORTON STUDY [4]

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 47.0 | 20.7 | 17.0 | 59.0 | 90.0 | 53 | 5.4 | 15 | Trichloroethylene:<br>68° F (20° C) |
| 70.5 | 21.5 | 24.6 | 67.1 | 95.4 | 42 | 7.8 | 11 | " |
| 82.8 | 22.4 | 27.7 | 74.8 | 99.4 | 33 | 8.8 | 10 | " |
| 47.0 | 20.7 | 17.0 | 64.0 | 90.1 | 41 | 11.2 | 8 | Tetrachloroethylene:<br>68° F (20° C) |
| 70.5 | 21.5 | 24.6 | 71.6 | 94.4 | 32 | 11.7 | 6 | " |
| 82.8 | 22.4 | 27.7 | 83.9 | 98.0 | 17 | 12.1 | 6 | " |
| 47.0 | 20.7 | 17.0 | 65.0 | 99.4 | 53 | 7.2 | 10 | Trans-1,2-Dichloroethane:<br>68° F (20° C) |
| 70.5 | 21.5 | 24.6 | 69.7 | 104.7 | 50 | 10.5 | 8 | " |
| 44.6 | 7.1 | 46.9 | 24.4 | 23.5 | - 4 | 6.8 | 13 | Trichloroethylene:<br>43° F (6° C) |
| 66.9 | 8.2 | 61.4 | 30.6 | 26.7 | -13 | 8.9 | 10 | " |
| 44.6 | 21.5 | 15.5 | 53.2 | 51.0 | - 4 | 2.2 | 21 | " |
| 66.9 | 20.7 | 24.2 | 54.4 | 51.9 | - 5 | 3.5 | 16 | " |
| 77.5 | 20.7 | 28.0 | 63.7 | 52.6 | -17 | 4.1 | 14 | " |
| 44.6 | 7.1 | 46.9 | 24.7 | 23.3 | - 6 | 11.2 | 2 | Tetrachloroethylene:<br>43° F (6° C) |
| 66.9 | 8.2 | 61.4 | 31.4 | 26.3 | -16 | 14.6 | 6 | " |
| 111.5 | 8.3 | 100.9 | 37.1 | 26.9 | -27 | 24.1 | 4 | " |
| 44.6 | 21.5 | 15.5 | 52.1 | 51.8 | - 1 | 3.7 | 12 | " |
| 66.9 | 20.7 | 24.2 | 52.4 | 51.9 | - 1 | 5.8 | 9 | " |
| 77.5 | 20.7 | 28.0 | 62.8 | 52.3 | -17 | 6.7 | 8 | " |
| 44.6 | 7.1 | 46.9 | 26.4 | 25.7 | - 3 | 8.4 | 9 | Trans-1,2-Dichloroethane:<br>43° F (6° C) |
| 66.9 | 8.2 | 61.4 | 31.8 | 29.1 | - 8 | 10.9 | 7 | " |
| 44.6 | 21.5 | 15.5 | 56.2 | 56.4 | 0 | 2.8 | 14 | " |
| 66.9 | 20.7 | 24.2 | 57.1 | 56.9 | 0 | 4.3 | 11 | " |
| 77.5 | 20.7 | 28.0 | 67.1 | 57.6 | -14 | 5.0 | 10 | " |

General Notes: Packing - 1/2" Ceramic Saddles looking at the results presented in Table 16, a severe problem with predicted temperature variation effects on transfer rates is indicated. At 43°F, the Onda model consistently underestimated mass transfer values, yielding negative errors ranging from 0 to -27% with an average of -9%. In stark contrast, at 68°F the correlation clearly overestimated transfer rates, with positive errors occurring in the range from +17 to +53%, giving an average of +40%. The results were consistent for each of the three VOCs evaluated.

#### 4.2.2.9 Umphres Study

In conducting tests at four separate packing heights, the data from this study [64] lent itself to the end effects analysis procedure described in section 3.1.1.1 for computing observed transfer rates. The details of this analysis are provided in Appendix A. The results for the observed rates along with corresponding correlation predictions are given in Table 17. The Onda model predicted transfer rates within 20% of measured rates for each of the four trihalomethanes tested. Such reasonable results tend to support the accuracy of the Henry's constant relations given by Nicholson et al. [42] and utilized in this evaluation.

An extremely high air to water ratio was required to produce reasonable stripping factors for removal of the low-volatile compounds. Also, very low water flow rates were tested (4, 8, and 16 gpm per square foot). Therefore, the extreme operating situation of low liquid loading and high air to water ratios was investigated. These results do not

Table 17. RESULTS: UMPHRES STUDY [64]

| Loading Conditions | | | Mass Transfer Rates | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm per sq ft) | Water Rate (gpm per sq ft) | Air to Water Ratio (vol / vol) | Measured (1/hrs) | Onda Prediction (1/hrs) | % Difference | Stripping Factor | % Gas Resistance | Specific Notes |
| 214 | 16 | 100 | 32.1 | 37.1 | 16 | 8.1 | 6 | Chloroform |
| 107 | 8 | 100 | 18.9 | 21.6 | 14 | 8.1 | 6 | " |
| 53 | 4 | 100 | 11.9 | 12.5 | 5 | 8.1 | 8 | " |
| 214 | 16 | 100 | 32.0 | 34.8 | 9 | 4.3 | 10 | Bromodichloromethane |
| 107 | 8 | 100 | 18.8 | 20.0 | 6 | 4.3 | 12 | " |
| 53 | 4 | 100 | 12.5 | 11.4 | - 9 | 4.3 | 14 | " |
| 214 | 16 | 100 | 28.9 | 31.7 | 10 | 2.3 | 18 | Dibromochloromethane |
| 107 | 8 | 100 | 17.9 | 18.0 | 1 | 2.3 | 20 | " |
| 53 | 4 | 100 | 12.2 | 10.1 | -17 | 2.3 | 23 | " |
| 214 | 16 | 100 | 32.1 | 26.6 | -17 | 1.2 | 31 | Bromoform |
| 107 | 8 | 100 | 15.6 | 14.8 | - 5 | 1.2 | 34 | " |
| 53 | 4 | 100 | 9.4 | 8.1 | -14 | 1.2 | 38 | " |

General Notes:
Packing - 1" Saddles
Water Temp. - 55° F (12.5° C)

indicate any enhanced performance over that predicted by the Onda model, unlike what was tentatively identified from the results of the Cummins studies.

The testing of low-volatile trihalomethanes also produced cases of large relative gas-phase resistance, values for which ranged from 6 to 38% of the total resistance. Even under such conditions, no association of correlation error values with the relative gas-phase resistance is seen.

### 4.2.3 General Data Base Results

#### 4.2.3.1 VOC Effects

Specific VOC considerations are represented in the Onda correlation by diffusivity and Henry's constant values. Diffusivity values appear accurately modeled by established semi-empirical correlations (see sections 3.2.4 & 3.2.5 for details). As the particular values for common VOCs are quite similar (less than a 20% difference), previously raised questions concerning the exact dependency of mass transfer rates on diffusivity (i.e. - whether $k \propto D^{1/2}$ or $k \propto D^{2/3}$ is more appropriate) could not be effectively evaluated. Although it is still felt that a $k \propto D^{2/3}$ dependency would be more appropriate, following combined film-penetration theory and general experimental results, the practical differences between the two are insignificant for VOC stripping applications. Thus, no justification can be put forth for modifying the Onda relation in this regard.

On the other hand, reliable Henry's constant values were not previously well established. The defining relations selected from the literature (see section 3.2.2) were experimentally determined and corroborated among different investigators within approximately 20%. In addition, particular water source characteristics, VOC mixtures, and absolute concentration levels were confirmed as not significantly affecting the Henry's constants obtained for water treatment situations.

Therefore, it was not anticipated that mass transfer correlation errors would be found attributable to any of these factors.

In reviewing the overall data base results, only the Pennsylvania site investigation conducted by Malcolm Pirnie produced results which could potentially be attributed to one of the above factors, namely reduced performance due to water matrix effects. Such water characteristic effects would reasonably be expected to appear in the results of other studies since in nearly all of these other cases, the contaminated water source was tested on-site. However, no such effects were indicated. Also, nothing highly unusual was noted for the Pennsylvania site in question with regard to water characteristics. Thus, it is felt that other unknown factors are responsible for the consistent correlation overpredictions which occurred for that particular study.

For five of the ten studies evaluated, the contaminated water contained a mixture of VOCs. In every case, similar transfer results were noted for each specific VOC considered. Consistent correlation errors which potentially could be attributed to VOC interactions were not found.

Finally, testing reported by Raczko et al. encompassed a wide range of influent concentrations (20 to 27,000 ug/l of TCE). The consistently accurate Onda model predictions confirm that absolute concentration levels do not play a role in column performance.

#### 4.2.3.2 Loading Rate Effects

**Extreme Operating Conditions:** The results from the Cummins studies indicated an area of concern existed for the Onda correlation under extreme operating conditions. Each of the two situations cited are considered below in light of the results provided from the results of the other studies evaluated.

At low liquid loading and high air to water ratios (less than 20 gpm per square foot and exceeding 75 to 1, respectively), a slight (~10%) enhancement of performance over that predicted by the correlation was noted from Cummins work. This can be explained by a significant increase in the wetted packing surface area through air flow turbulence effects along with longer liquid-air contact time due to increased liquid hold-up under such operating conditions. However, the Umphres study evaluation refutes this observation. For that work, even at a water flow rate of only 4 gpm per square foot and an air to water ratio of 100 to 1, no clear-cut enhanced performance phenomenon was noted. Thus, the apparent enhancement effect viewed in the Cummins studies may actually be due to random error, especially since the resultant correlation error value of -10% is well within the normal accuracy of 20% originally attributed to the Onda model [46]. Therefore, the correlation adequately handles such an extreme operating condition well outside the normal range of design.

The second extreme situation, involving high liquid loading and low air to water ratios (above 40 gpm per square foot and less than 17 to 1, respectively) yielded decreased column performance compared to that predicted by the Onda relation for the Cummins studies. This could be explained by a predominance of thick sheet flow through the column and relatively little turbulence generated within the large water mass. However, even in the Cummins studies themselves, these effects were not entirely consistent. Furthermore, isolated experiments in the various Malcolm Pirnie studies conducted under similar operating conditions do not display convincing evidence that the effects are not actually due to random errors or other factors. Again, the correlation errors seen under such operating conditions (around +20%) are within the stated accuracy of the Onda model. Thus, this extreme case also appears to be reasonably predicted by the Onda relations.

**Gas-Phase Resistance:** The Gossett study, expanding upon the assertation of Roberts and co-workers [50,54] that gas-phase resistance was underestimated by the Onda correlation, sought to directly link transfer rate prediction errors to relative gas-phase resistance values using equation {31}. Such a general trend was noted for the results cited [23], although there is considerable scatter to the defining plots. Furthermore, the suggested correlation adjustment values varied greatly and were dependent upon the actual packing type considered (see Table 8). The original report [23] did not find the data convincing enough to recommend such adjustments.

A review of the results obtained in evaluating data from other studies show that no similar patterns can be established, even though the relative gas-phase resistance predicted by the correlation ranged up to

40% of the total resistance. The adjustment values computed by Gossett et al. would not improve the predictive capabilities of the Onda correlation for the studies considered. Thus, gas-phase resistance predictions do not appear to be a particular area of concern for the Onda model.

#### 4.2.3.3 Packing Material Effects

The Gossett study results indicated an underestimation of transfer rates by the Onda correlation for 2-inch packing sizes on the order of 15%. In addition, a review of the defining correlation plot for the Onda liquid-phase relation previously presented in Figure 4 also reveals an apparent underestimation of the transfer coefficient on the order of 15-20% for the 2-inch packings represented in the defining data base. Therefore, a deficiency in the Onda model for larger packing sizes is strongly suggested.

However, data evaluated from two other studies do not support these observations, although perhaps not totally convincingly. First, the performance results from the Malcolm Pirnie investigation of a Connecticut site location yielded good agreement with Onda correlation predictions, although only six experimental tests were conducted with 2-inch packings. Of these six tests, two yielded observed transfer rates substantially underestimated by the correlation (~ -40% error), but these results were dismissed due to operation at a stripping factor of only 1.0. However, perhaps some of this error could be attributed to the 2-inch packing size. Secondly, the Malcolm Pirnie study conducted by Cline *et al.* at an Arizona site using 2-inch Tri-Packs produced observed transfer rates that were *over*estimated by the Onda model. The pilot scale system utilized, however, was found vulnerable to channeling effects, and such effects decrease column performance. Therefore, if these effects were severe enough, the "true" transfer rates (i.e. - those for a system properly designed to prevent channeling) might actually be lower than those predicted by the correlation.

Due to the conflicting evidence cited, no conclusions can be put forth concerning this matter. Further investigative studies involving larger packing sizes ( 2-inch and up) are required to resolve this point. In any case, the apparent correlation errors are not severe (approximately -15%) and would provide an additional safety factor for design purposes.

The results obtained for one specific packing type (1-inch saddles) must also be discussed. Data from both the Gossett study and the Malcolm Pirnie investigation of the Pennsylvania site showed the Onda model overpredicted transfer rates by approximately 20%. This is in contrast to five other studies examined that tested this specific packing and did not find any such systematic overestimation by the correlation. No other potential factors considered could be found to explain these divided results.

Finally, significant differences based upon the specific packing configuration (saddles, Tellerettes, Pall rings, or Tri-Packs) were not clearly evident from the overall results. In particular, the data collected from the Malcolm Pirnie study of the Connecticut site showed consistently accurate predictions by the Onda model for different packing configurations (saddles and Tellerettes). Therefore, packing effects seem to be adequately modeled based on gross parameters (nominal size and specific surface area) without regard to specific configurations.

#### 4.2.3.4 Temperature Effects

Three of the studies evaluated specifically examined temperature effects. Two of the studies, one by Gossett et al. and the other by Gross and TerMaath, did not indicate any significant problems with the temperature dependency predictions given by the Onda correlation. The third study, by Byers & Morton, did indicate large prediction errors, however, with a 9% average underestimation at 43°F and a 40% average overestimation at 68° F. These results were consistently seen for each of three VOCs considered.

A further review of the Byers & Morton study in the context of other results obtained is necessary to evaluate its significance. The 43°F data is within reasonable accuracy expectations for the Onda model with only a single experiment producing an underestimation by the correlation exceeding 17%. The data taken at 68°F is of more concern due to the relatively large overestimations found using the Onda relations. However, such results are clearly not consistent with the other two temperature dependency studies cited above where water temperatures up to 86° F were evaluated. In addition, both the Gossett isothermal study and the Malcolm Pirnie study reported by Cline et al. involved water temperatures around 78° F, while the original correlation comparison study by Roberts et al. was conducted 68° F; no similar pattern of large transfer rate overestimations attributable to temperature effects could be seen for any of this work. Thus, it is felt that other unknown factors contributed to the results found by Byers & Morton at 68°F, and the Onda correlation in fact adequately accounts for temperature effects.

### 4.2.4 Summary of Onda Model Evaluation

A basic statistical analysis was performed encompassing all 449 data points evaluated. In 202 instances, the Onda correlation overpredicted mass transfer rates on the average of +20%, while underpredicting transfer values in 241 cases with a corresponding average of -11%. The relative standard deviation for the data is 25%. In reviewing the individual studies, the Cummins & Westrick multiple-site study data was deemed suspect due to the questionable analysis procedure used by those investigators in generating the reported column removal efficiency values (see section 4.2.2.2). Likewise, the temperature dependency study performed by Gossett et al. produced some inconsistent results which were attributed to column operation under extremely low stripping factors (see section 4.2.2.1). Therefore, all results obtained using suspect data from these two studies were removed with new statistics performed on the remaining results. In this case, with a total of 437 points evaluated, the Onda model overestimated transfer rates 192 times (with a corresponding +16% average), while underestimating the values 239 times (by a corresponding -11% average). The relative standard deviation computed was 17%. Thus, the deletion of only 12 suspect data points had a profound affect on the accuracy measures calculated for the correlation.

In reviewing the overall results, with consideration of variable and sometimes conflicting findings which could not be easily resolved, it is felt that the proper accuracy value for the Onda mass transfer correlation should be placed at 30% rather than the 20% cited in the original work. Based on the relative standard deviation of 17% cited, this would correspond to approximately a 90% design confidence limit. Indeed, in reviewing the original defining correlation plots previously presented in Figure 4, such an error boundary accounts for a significantly greater percentage of observations cited. Thus, it appears that the application of packed column technology to low-level VOC stripping of contaminated drinking water sources can be modeled using the chemical engineering-based Onda mass transfer correlation within a similar accuracy found for various chemical engineering systems. Given the complex nature of packed column operation, the formulation of a generalized correlation for a priori prediction of mass transfer rates accurate to within ±30% is actually quite remarkable.

Within the context of this study, several identified areas of concern for the Onda model were evaluated, most notably: gas-phase resistance predictions, performance differences between distinct packing configurations, extreme operating conditions (high liquid loading/low air to water ratios and low liquid loading/high air to water ratios), temperature effects, and underestimation of performance for larger packings sizes ($\geq 2$ inches). Although further investigation into each of these areas is encouraged, only the last effect (larger packings) is deemed potentially significant to require modification of the correlation mainly because the apparent deficiency is noted in the original defining data base for the correlation.

# CHAPTER 5

# CONCLUSIONS

In reviewing the modeling of packed column performance, the crucial design area identified involved the prediction of mass transfer rates. Accurate predictions for transfer values are critical since the required column height is directly proportional to the assumed mass transfer rate. Therefore, the first phase of this study evaluated mass transfer correlations available in the chemical engineering literature based upon general theoretical considerations and previous experimental studies which applied packed column technology to water treatment situations. From this initial screening, the following conclusions were reached:

1) The Sherwood and Holloway correlation appears applicable only as a data-fitting relation for a given set of experimental test results. However, noted theoretical limitations with the model indicate that even such curve-fitting may be questionable. In particular, the assumption that gas-phase resistance is negligible does not appear valid for common VOCs encountered in water treatment applications.

2) The Shulman correlation was found to have no foreseeable design applications since crucial effective interfacial area values are available only for obsolete packing materials. In addition, theoretical deficiencies were noted in the model's original derivation.

3) The Onda correlation offers _a priori_ estimation of mass transfer rates for a wide variety of design situations. The correlation accounts for gas-phase resistance and appears theoretically sound. In a direct comparison test performed by Roberts and co-workers, the Onda correlation was clearly found to be the most accurate of the three proposed models.

Based on these results, the Onda correlation was selected as the most promising model available, meriting further evaluation. In conjunction with the subsequent specific evaluation, two conclusions were reached in related areas investigated, namely:

1) Predicted Henry's constant values, previously of questionable accuracy for dilute solutions of VOCs, are now more firmly established, with 20% variation seen in proposed temperature relationships reported by independent investigators utilizing different measurement techniques. In addition, compound interactions, concentration level effects, and water matrix effects were found not to significantly alter the applicable relations.
2) Experimental measurement errors are magnified in the results for observed mass transfer rates when column operation is conducted under stripping factor less than 1.5. Therefore, apparent transfer rates noted under such conditions should be viewed with caution when compared to predicted rates. A recommended minimum apparent stripping factor of 2 was put forth for accurate evaluation of proposed transfer rate

correlations. This is not a serious limitation since a stripping factor of 2 also represents the minimum operating point for economical design based upon reported optimization study results.

A test data base was established from reported pilot-scale studies that investigated treatment of low-level VOCs from water supplies. Predicted and measured mass transfer rates were computed with the results analyzed in terms of various identified performance factors. The following conclusions were reached in regards to the noted accuracy of the Onda model:

1) The Onda correlation produced a 17% standard deviation in predicting mass transfer for the 437 points ultimately evaluated. Based upon a 90% confidence interval for design, the standard deviation cited corresponds to an accuracy value ± 30%. This value reasonably coincides with the apparent accuracy of the model originally noted for chemical engineering systems, indicating a direct correspondence between the two distinct areas of application.

2) Compound interactions, concentration level effects, and water matrix effects were found not to significantly affect the accuracy of predicted column mass transfer rates. This is consistent with the noted absence of such effects in the determination of appropriate Henry's constant values.

3) The Onda model adequately handled the following specific areas of concern identified in this evaluation:

   - a) Gas-phase resistance predictions.
   - b) Performance differences between distinct packing configurations.
   - c) Extreme column operating conditions.
   - d) Temperature effects.

4) A particular area requiring further investigation involves potential underestimation of performance by the correlation for larger ($\geq 2$ inches) nominal packing sizes.

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## APPENDIX A - Experimental Data

Table A-1. REPORTED EXPERIMENTAL DATA - Cummins Study [9]
Louisiana Site Investigation

| Loading Conditions | | | Assumed Top-of-Packing Conc. (ug/l) based on assumed Henry's Constant | |
|---|---|---|---|---|
| Air Rate (cfm) | Water Rate (gpm) | Air to Water Ratio (vol / vol) | Solubility H | Modified H |
| Benzene: | | | | |
| 334 | 29 | 87.0 | 110 | 100 |
| 267 | 44 | 45.0 | 110 | 92 |
| 235 | 69 | 25.3 | 200 | 144 |
| 203 | 93 | 16.4 | 251 | 168 |
| 148 | 139 | 8.0 | 416 | 261 |
| 489 | 42 | 87.7 | 80 | 72 |
| 396 | 65 | 45.8 | 158 | 128 |
| 322 | 97 | 24.8 | 212 | 163 |
| 279 | 125 | 16.7 | 354 | 245 |
| 180 | 171 | 7.9 | 413 | 266 |
| 569 | 56 | 76.9 | 101 | 91 |
| 518 | 88 | 44.1 | 159 | 131 |
| 402 | 120 | 25.0 | 335 | 253 |
| 322 | 153 | 15.8 | 385 | 268 |
| 235 | 208 | 8.4 | 338 | 235 |
| Toluene: | | | | |
| 334 | 29 | 87.0 | 35.2 | 31.9 |
| 267 | 44 | 45.0 | 38.8 | 32.1 |
| 235 | 69 | 25.3 | 66.9 | 42.4 |
| 203 | 93 | 16.4 | 86.2 | 49.3 |
| 148 | 139 | 8.0 | 150. | 77.2 |
| 489 | 42 | 87.7 | 27.2 | 24.3 |
| 396 | 65 | 45.8 | 65.9 | 49.1 |
| 322 | 97 | 24.8 | 72.2 | 49.9 |
| 279 | 125 | 16.7 | 139. | 83.3 |
| 180 | 171 | 7.9 | 142. | 76.1 |
| 569 | 56 | 76.9 | 37.4 | 33.3 |
| 518 | 88 | 44.1 | 53.6 | 44.0 |
| 402 | 120 | 25.0 | 114. | 76.9 |
| 322 | 153 | 15.8 | 124. | 75.0 |
| 235 | 208 | 8.4 | 121. | 72.4 |

Notes: Governing Henry's Constant Values (on a volume basis):
Benzene: Solubility H = 0.20
Modified (best-fit) H = 0.135

Toluene: Solubility H = 0.23
Modified (best-fit) H = 0.129

NOTE: Illustrates results of data analysis performed by Cummins. A different analysis method was adapted for this evaluation (see Table A-3).

Table A-2. Experimental Data: Cummins Study [9] - Louisiana Site Investigation

| Loading Conditions | | | Sample Concentration (ug/l) at Given Sample Port Location From Top of Packing (feet) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm) | Water Rate (gpm) | Air to Water Ratio (vol / vol) | 0.5 | 3.5 | 6.5 | 9.5 | 12.5 | 15.5 | 17.5 |
| Benzene: | | | | | | | | | |
| 334 | 29 | 87.0 | 130 | 31 | 6.4 | 1.4 | 0.5 | --- | --- |
| 267 | 44 | 45.0 | 150 | 34 | 11 | 3.5 | 0.9 | --- | --- |
| 235 | 69 | 25.3 | 160 | 57 | 23 | 17 | 5.5 | 2.4 | 1.8 |
| 203 | 93 | 16.4 | 170 | 85 | 38 | 44 | 16 | 7.9 | 4.0 |
| 148 | 139 | 8.0 | 280 | 230 | 200 | --- | 78 | 49 | 32 |
| 489 | 42 | 87.7 | 110 | 22 | 6.2 | 1.6 | 0.5 | --- | --- |
| 396 | 65 | 45.8 | 130 | 46 | 21 | 7.1 | 2.4 | 1.0 | 0.5 |
| 322 | 97 | 24.8 | 130 | 77 | 34 | 20 | 11 | 4.0 | 2.9 |
| 279 | 125 | 16.7 | 150 | --- | 79 | 47 | 33 | 20 | 13 |
| 180 | 171 | 7.9 | 210 | --- | 170 | 180 | 140 | 64 | 70 |
| 569 | 56 | 76.9 | 120 | 29 | 12 | 3.3 | 0.8 | --- | --- |
| 518 | 88 | 44.1 | 130 | 47 | 30 | 11 | 4.2 | 1.0 | 0.7 |
| 402 | 120 | 25.0 | 160 | 120 | 69 | 36 | 17 | 8.0 | 5.8 |
| 322 | 153 | 15.8 | 120 | --- | 140 | 93 | 31 | 27 | 13 |
| 235 | 208 | 8.4 | 280 | 230 | 170 | 110 | 75 | 49 | 41 |
| Toluene: | | | | | | | | | |
| 334 | 29 | 87.0 | 34 | 9.1 | 2.1 | 0.7 | --- | --- | --- |
| 267 | 44 | 45.0 | 44 | 11 | 3.4 | 1.6 | --- | --- | --- |
| 235 | 69 | 25.3 | 52 | 18 | 8.6 | 5.8 | 1.7 | 0.8 | 0.9 |
| 203 | 93 | 16.4 | 51 | 26 | 13 | 18 | 4.7 | 3.0 | 1.5 |
| 148 | 139 | 8.0 | 84 | 64 | 55 | 58 | 33 | 16 | 12 |
| 489 | 42 | 87.7 | 34 | 7.7 | 2.3 | 0.6 | --- | --- | --- |
| 396 | 65 | 45.8 | 42 | 16 | 6.6 | 3.1 | 1.3 | 0.6 | 0.5 |
| 322 | 97 | 24.8 | 51 | 27 | 12 | 6.5 | 3.8 | 1.2 | 1.1 |
| 279 | 125 | 16.7 | 57 | --- | 48 | 13 | 11 | 9.3 | 5.6 |
| 180 | 171 | 7.9 | 73 | --- | --- | 48 | 36 | 25 | 18 |
| 569 | 56 | 76.9 | 39 | 9.7 | 3.9 | 1.6 | --- | --- | --- |
| 518 | 88 | 44.1 | 50 | 18 | 8.8 | 3.4 | 1.3 | --- | --- |
| 402 | 120 | 25.0 | 39 | --- | 26 | 13 | 7.0 | 3.1 | 1.8 |
| 322 | 153 | 15.8 | 44 | --- | --- | 25 | 9.6 | 8.1 | 4.6 |
| 235 | 208 | 8.4 | 81 | 66 | 52 | 37 | 25 | 19 | 15 |

General Notes:
Packing - 1" Saddles
Water Temp. - 68°F (20°C)
Column Depth - 18 feet
Column Diameter - 2 feet

Table A-3. DATA ANALYSIS (END EFFECTS) - Cummins Study [9] - Louisiana Site Investigation

| Loading Conditions | | | Number of Transfer Units at Indicated Depth | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm) | Water Rate (gpm) | Air to Water Ratio (vol / vol) | 3.0' | 6.0' | 9.0' | 12.0' | 15.0' | 17.0' | 1/HTU (1/ft) | HTU (ft) | Correlation Coefficient |
| Benzene: | | | | | | | | | | | |
| 334 | 29 | 87.0 | 1.48 | 3.15 | 4.77 | 5.86 | ---- | ---- | 0.619 | 1.62 | .996 |
| 267 | 44 | 45.0 | 1.58 | 2.84 | 4.13 | 5.68 | ---- | ---- | 0.673 | 1.49 | .999 |
| 235 | 69 | 25.3 | 1.12 | 2.21 | 2.58 | 4.00 | 5.05 | 5.42 | 0.969 | 1.03 | .992 |
| 203 | 93 | 16.4 | 0.77 | 1.80 | 1.60 | 3.01 | 4.03 | 5.04 | 1.045 | 0.96 | .966 |
| 148 | 139 | 8.0 | 0.21 | 0.38 | ---- | 1.88 | 2.87 | 3.83 | 1.181 | 0.85 | .979 |
| 489 | 42 | 87.7 | 1.62 | 2.88 | 4.23 | 5.39 | ---- | ---- | 0.722 | 1.38 | .999 |
| 396 | 65 | 45.8 | 1.09 | 1.95 | 3.17 | 4.39 | 5.38 | 6.17 | 0.827 | 1.21 | .999 |
| 322 | 97 | 24.8 | 0.55 | 1.49 | 2.13 | 2.88 | 4.15 | 4.56 | 1.060 | 0.94 | .995 |
| 279 | 125 | 16.7 | ---- | 0.70 | 1.35 | 1.81 | 2.58 | 3.11 | 1.443 | 0.69 | .995 |
| 180 | 171 | 7.9 | ---- | ---- | 0.16 | 0.47 | 1.74 | 1.57 | 1.464 | 0.68 | .928 |
| 569 | 56 | 76.9 | 1.48 | 2.42 | 3.81 | 5.34 | ---- | ---- | 0.705 | 1.42 | .995 |
| 518 | 88 | 44.1 | 1.08 | 1.57 | 2.71 | 3.81 | 5.46 | 5.87 | 0.831 | 1.20 | .990 |
| 402 | 120 | 25.0 | 0.30 | 0.91 | 1.67 | 2.59 | 3.54 | 4.13 | 1.090 | 0.92 | .997 |
| 322 | 153 | 15.8 | ---- | ---- | 0.20 | 1.31 | 1.48 | 2.43 | 1.220 | 0.82 | .959 |
| 235 | 208 | 8.4 | 0.21 | 0.58 | 1.23 | 1.91 | 2.76 | 3.15 | 1.401 | 0.71 | .995 |
| Toluene: | | | | | | | | | | | |
| 334 | 29 | 87.0 | 1.35 | 2.88 | 4.04 | ---- | ---- | ---- | 0.680 | 1.47 | .997 |
| 267 | 44 | 45.0 | 1.45 | 2.74 | 3.58 | ---- | ---- | ---- | 0.859 | 1.16 | .992 |
| 235 | 69 | 25.3 | 1.14 | 2.00 | 2.47 | 3.93 | 4.87 | 4.72 | 1.082 | 0.92 | .981 |
| 203 | 93 | 16.4 | 0.73 | 1.58 | 1.17 | 2.91 | 3.52 | 4.47 | 1.172 | 0.85 | .949 |
| 148 | 139 | 8.0 | 0.30 | 0.48 | 0.41 | 1.20 | 2.46 | 3.03 | 1.513 | 0.66 | .924 |
| 489 | 42 | 87.7 | 1.52 | 2.77 | 4.18 | ---- | ---- | ---- | 0.688 | 1.45 | .999 |
| 396 | 65 | 45.8 | 1.02 | 2.00 | 2.84 | 3.82 | 4.70 | 4.90 | 1.066 | 0.94 | .996 |
| 322 | 97 | 24.8 | 0.67 | 1.59 | 2.31 | 2.95 | 4.36 | 4.46 | 1.089 | 0.92 | .992 |
| 279 | 125 | 16.7 | ---- | 0.12 | 1.69 | 1.90 | 2.12 | 2.78 | 1.484 | 0.67 | .926 |
| 180 | 171 | 7.9 | ---- | ---- | 0.48 | 0.87 | 1.44 | 2.02 | 1.611 | 0.62 | .987 |
| 569 | 56 | 76.9 | 1.47 | 2.45 | 3.42 | ---- | ---- | ---- | 0.915 | 1.09 | .999 |
| 518 | 88 | 44.1 | 1.06 | 1.84 | 2.89 | 3.96 | ---- | ---- | 0.937 | 1.07 | .998 |
| 402 | 120 | 25.0 | ---- | 0.38 | 1.08 | 1.73 | 2.62 | 3.22 | 1.190 | 0.84 | .997 |
| 322 | 153 | 15.8 | ---- | ---- | 0.61 | 1.79 | 2.01 | 2.77 | 1.236 | 0.81 | .966 |
| 235 | 208 | 8.4 | 0.22 | 0.50 | 0.95 | 1.55 | 2.00 | 2.42 | 1.896 | 0.53 | .995 |

End effects equation: $(NTU)_{\text{Measured}} = \frac{1}{HTU}(Z) + (NTU)_{\text{End Effects}}$

Table A-4. EXPERIMENTAL DATA - Cummins & Westrick Study [12]
Multiple Site Investigation

| Loading Conditions | | | |
|---|---|---|---|
| Air Rate (cfm) | Water Rate (gpm) | Air to Water Ratio (vol / vol) | Removal |
| 353 | 33.0 | 80 | 99.72 |
| 318 | 52.8 | 45 | 99.31 |
| 265 | 79.2 | 25 | 97.3 |
| 212 | 106 | 15 | 91.6 |
| 158 | 148 | 8 | 74 |
| 132 | 198 | 5 | 54 |

General Notes:

Packing - 1" Saddles
VOC Stripped - Trichloroethylene
Water Temp. - 55°F (avg.)
Column Height - 18 feet
Column Diameter - 2 feet

NOTE: Removal values are based on average achieved at eight separate sites. No absolute concentrations provided.

Table A-5. EXPERIMENTAL DATA: Malcolm Pirnie Study [27]
Pennsylvania Site Investigation

| Loading Conditions | | | Concentration (ug/l) | | |
|---|---|---|---|---|---|
| Air Rate (cfm) | Water Rate (gpm) | Air to Water Ratio (vol / vol) | Influent | Effluent | Percent Removal |
| Trichloroethylene: | | | | | |
| 30 | 20 | 11.2 | 145 | 33.2 | 77 |
| 50 | 20 | 18.7 | 161 | 31.3 | 81 |
| 54 | 20 | 20.2 | 178 | 30.7 | 83 |
| 67 | 20 | 25.1 | 333 | 28.4 | 92 |
| 70 | 20 | 26.2 | 156 | 28.2 | 82 |
| 24 | 25 | 7.2 | 157 | 41.8 | 73 |
| 47 | 25 | 14.1 | 230 | 34.4 | 85 |
| 63 | 25 | 18.8 | 126 | 30.8 | 76 |
| 75 | 25 | 22.4 | 220 | 38.4 | 83 |
| 47 | 30 | 14.0 | 166 | 35.5 | 79 |
| Tetrachloroethylene: | | | | | |
| 30 | 20 | 11.2 | 15.1 | 1.9 | 87 |
| 50 | 20 | 18.7 | 11.6 | 1.9 | 84 |
| 54 | 20 | 20.2 | 13.7 | 2.0 | 85 |
| 67 | 20 | 25.1 | 10.3 | 1.8 | 83 |
| 70 | 20 | 26.2 | 11.8 | 1.7 | 86 |
| 24 | 25 | 7.2 | 12.9 | 2.6 | 80 |
| 33 | 25 | 9.9 | 12.9 | 2.9 | 78 |
| 47 | 25 | 14.1 | 19.5 | 2.1 | 89 |
| 63 | 25 | 18.8 | 10.7 | 1.8 | 83 |
| 75 | 25 | 22.4 | 10.0 | 2.2 | 78 |
| 47 | 30 | 14.0 | 12.9 | 2.2 | 83 |
| 1,1,1-Trichloroethane: | | | | | |
| 30 | 20 | 11.2 | 26.0 | 4.8 | 82 |
| 50 | 20 | 18.7 | 22.3 | 4.1 | 82 |
| 54 | 20 | 20.2 | 20.9 | 3.0 | 86 |
| 67 | 20 | 25.1 | 23.3 | 2.8 | 88 |
| 70 | 20 | 26.2 | 24.7 | 3.8 | 85 |
| 24 | 25 | 7.2 | 23.3 | 4.0 | 83 |
| 33 | 25 | 9.9 | 20.8 | 4.5 | 78 |
| 47 | 25 | 14.1 | 35.1 | 3.9 | 89 |
| 63 | 25 | 18.8 | 19.7 | 3.2 | 84 |
| 75 | 25 | 22.4 | 17.2 | 3.8 | 78 |
| 47 | 30 | 14.0 | 23.3 | 3.6 | 85 |

General Notes:
Packing - 1" Saddles
Packing Depth - 10 feet
Column Diameter - 12 inches
Water Temp. - 57° F

Table A-6. EXPERIMENTAL DATA: Malcolm Pirnie Study [48]
Raczko Report

| Loading Conditions | | | TCE Concentration (ug/l) | | |
|---|---|---|---|---|---|
| Air Rate (cfm) | Water Rate (gpm) | Air to Water Ratio (vol / vol) | Influent | Effluent | Percent Removal |
| Pennsylvania Site: | | | | | |
| 38 | 15 | 19 | 33.7 | 4.3 | 87 |
| 38 | 20 | 14 | 32.0 | 4.7 | 86 |
| 38 | 22 | 13 | 23.2 | 4.3 | 82 |
| 44 | 25 | 13 | 31.0 | 4.7 | 85 |
| 52 | 30 | 13 | 34.2 | 5.6 | 84 |
| New Jersey Site (Production Well): | | | | | |
| 106 | 10 | 79 | 1879 | 141 | 93 |
| 48 | 20 | 18 | 2150 | 188 | 91 |
| 104 | 20 | 39 | 1777 | 249 | 86 |
| 29 | 30 | 7.2 | 1960 | 351 | 82 |
| 60 | 30 | 15 | 2522 | 363 | 86 |
| 110 | 30 | 27 | 1080 | 167 | 85 |
| 100 | 34 | 22 | 2120 | 438 | 79 |
| 96 | 40 | 18 | 1827 | 250 | 86 |
| 88 | 50 | 13 | 2015 | 547 | 73 |
| New Jersey Site (Contaminated Pit): | | | | | |
| 110 | 8 | 103 | 27636 | 899 | 97 |
| 50 | 7 | 53 | 25667 | 1377 | 95 |

General Notes:
Packing - 1" Saddles
Packing Depth - 10 feet
Column Diameter - 12 inches
VOC Stripped - Trichloroethylene
Water Temp. - 55° F (12.5° C)

Table A-7. EXPERIMENTAL DATA: Malcolm Pirnie Study [27]
Connecticut Site Investigation

| Loading Conditions | | | | | |
|---|---|---|---|---|---|
| Air Rate (cfm) | Water Rate (gpm) | Air to Water Ratio (vol / vol) | TCE Concentration (ug/l) Influent | TCE Concentration (ug/l) Effluent | Percent Removal |
| Well #1 (1-inch saddles): | | | | | |
| 43 | 16 | 20 | 49.3 | 6.9 | 86 |
| 64 | 16 | 30 | 51.7 | 5.7 | 89 |
| 85 | 13 | 50 | 52.1 | 3.0 | 94 |
| 64 | 24 | 20 | 66.2 | 8.0 | 88 |
| Well #2 (1-inch saddles): | | | | | |
| 32 | 16 | 15 | 22.9 | 4.2 | 82 |
| 53 | 16 | 25 | 22.6 | 3.3 | 85 |
| Combined Wells (1-inch saddles): | | | | | |
| 32 | 16 | 15 | 53.3 | 7.7 | 86 |
| 53 | 16 | 25 | 47.4 | 5.4 | 89 |
| Well #1 (1-inch Tellerettes): | | | | | |
| 43 | 16 | 20 | 49.3 | 6.9 | 86 |
| 64 | 16 | 30 | 51.7 | 5.7 | 89 |
| 85 | 13 | 50 | 52.1 | 3.0 | 94 |
| 80 | 12 | 50 | 135.1 | 12.7 | 91 |
| 40 | 12 | 25 | 113.7 | 13.9 | 88 |
| 53 | 16 | 25 | 140.1 | 16.4 | 88 |
| Well #2 (1-inch Tellerettes): | | | | | |
| 32 | 16 | 15 | 17.2 | 2.2 | 87 |
| 53 | 16 | 25 | 18.5 | 1.6 | 91 |
| Combined Wells (1-inch Tellerettes): | | | | | |
| 32 | 16 | 15 | 36.4 | 4.8 | 87 |
| 53 | 16 | 25 | 40.5 | 3.9 | 90 |
| 80 | 24 | 25 | 69.6 | 14.4 | 79 |
| 13 | 20 | 5 | 114.5 | 23.6 | 79 |
| 80 | 10 | 60 | 101.2 | 11.7 | 88 |
| Combined Wells (2-inch Tellerettes): | | | | | |
| 13 | 20 | 5 | 101.3 | 26.3 | 74 |
| 40 | 20 | 15 | 97.7 | 19.8 | 80 |
| 67 | 20 | 25 | 111.6 | 17.9 | 84 |
| 19 | 28 | 5 | 109.3 | 29.4 | 73 |
| 56 | 28 | 15 | 111.2 | 17.8 | 84 |
| 85 | 25 | 25 | 111.2 | 17.6 | 84 |

General Notes:
VOC Stripped - Trichloroethylene
Packing Depth - 10 feet
Column Diameter - 12 inches
Water Temp. - 57° F (13° C)

Table A-8. EXPERIMENTAL DATA: Malcolm Pirnie Study [6]
Cline Report

| Loading Conditions | | | TCE Concentration (ug/l) | | |
|---|---|---|---|---|---|
| Air Rate (cfm) | Water Rate (gpm) | Air to Water Ratio (vol / vol) | Influent | Effluent | Percent Removal |
| 80 | 13 | 46.0 | 40 | 0.7 | 98.3 |
| 66 | 14 | 35.3 | 36 | 1.8 | 95.0 |
| 100 | 16 | 46.8 | 35 | 1.2 | 96.6 |
| 68 | 17 | 29.9 | 32 | 1.8 | 94.4 |
| 67 | 20 | 25.1 | 31 | 2.2 | 92.9 |
| 59 | 22 | 20.1 | 36 | 1.9 | 94.7 |
| 80 | 24 | 24.9 | 33 | 1.2 | 96.4 |
| 80 | 25 | 23.9 | 34 | 1.6 | 95.3 |
| 90 | 26 | 25.9 | 43 | 1.9 | 95.6 |
| 72 | 27 | 19.9 | 31 | 1.6 | 94.8 |
| 60 | 31 | 14.5 | 40 | 3.1 | 92.3 |
| 100 | 32 | 23.4 | 36 | 2.5 | 93.1 |
| 150 | 32 | 35.1 | 42 | 1.8 | 95.7 |
| 44 | 33 | 10.0 | 35 | 3.7 | 89.4 |
| 140 | 36 | 29.1 | 38 | 2.0 | 94.7 |

General Notes: Packing - 2" Tri-Packs
Packing Depth - 9.5 feet
Column Diameter - 12 inches
VOC Stripped - Trichloroethylene
Water Temp. - 79° F (26° C)

Table A-9. EXPERIMENTAL DATA - Byers & Morton Study [4]

| Loading Conditions | | | Concentration (ug/l) | | |
|---|---|---|---|---|---|
| Air Rate (cfm) | Water Rate (gpm) | Air to Water Ratio (vol / vol) | Influent | Effluent | Percent Removal |
| PCE (43°F): | | | | | |
| 3.8 | 1.80 | 17.0 | 7 | 0.4 | 94 |
| 5.7 | 1.87 | 24.6 | 7 | 0.3 | 96 |
| 6.7 | 1.95 | 27.7 | 7 | 0.2 | 97 |
| TCE (43°F): | | | | | |
| 3.8 | 1.80 | 17.0 | 172 | 14 | 92 |
| 5.7 | 1.87 | 24.6 | 172 | 10 | 94 |
| 6.7 | 1.95 | 27.7 | 172 | 8 | 95 |
| Trans 1,2-DCE (43°F): | | | | | |
| 3.8 | 1.80 | 17.0 | 103 | 6 | 94 |
| 5.7 | 1.87 | 24.6 | 103 | 5 | 95 |
| PCE (68°F): | | | | | |
| 3.8 | 0.62 | 46.9 | 15.3 | 0.6 | 96 |
| 5.7 | 0.71 | 61.4 | 15.3 | 0.4 | 97 |
| 9.5 | 0.72 | 100.9 | 15.3 | 0.2 | 99 |
| 3.8 | 1.87 | 15.5 | 15.3 | 2.0 | 87 |
| 5.7 | 1.80 | 24.2 | 15.3 | 1.6 | 89 |
| 6.6 | 1.80 | 28.0 | 15.3 | 1.0 | 93 |
| TCE (68°F): | | | | | |
| 3.8 | 0.62 | 46.9 | 342 | 16 | 95 |
| 5.7 | 0.71 | 61.4 | 342 | 11 | 97 |
| 3.8 | 0.72 | 15.5 | 342 | 54 | 84 |
| 5.7 | 1.80 | 24.2 | 342 | 39 | 89 |
| 6.6 | 1.80 | 28.0 | 342 | 26 | 92 |
| Trans 1,2-DCE (68°F): | | | | | |
| 3.8 | 0.62 | 46.9 | 264 | 9 | 97 |
| 5.7 | 0.71 | 61.4 | 264 | 7 | 97 |
| 3.8 | 0.72 | 15.5 | 264 | 34 | 87 |
| 5.7 | 1.80 | 24.2 | 264 | 25 | 90 |
| 6.6 | 1.80 | 28.0 | 264 | 16 | 94 |

General Notes: Packing - 1/2" Ceramic Saddles
Column Height - 8 feet
Column Diameter - 4 inches

Table A-10. EXPERIMENTAL DATA - Umphres Study [64]

| Loading Conditions | | | Removals at Indicated Packing Depths (%) | | | |
|---|---|---|---|---|---|---|
| Air Rate (cfm) | Water Rate (gpm) | Air to Water Ratio (vol / vol) | 1.75' | 3.75' | 5.75' | 7.67' |
| Chloroform: | | | | | | |
| 168 | 12.6 | 100 | 62 | 72 | 84 | 84 |
| 84 | 6.3 | 100 | 56 | 77 | 88 | 91 |
| 42 | 3.1 | 100 | 67 | 80 | 91 | 95 |
| Bromodichloromethane: | | | | | | |
| 168 | 12.6 | 100 | 57 | 71 | 80 | 78 |
| 84 | 6.3 | 100 | 54 | 76 | 83 | 90 |
| 42 | 3.1 | 100 | 59 | 80 | 89 | 94 |
| Dibromochloromethane: | | | | | | |
| 168 | 12.6 | 100 | 49 | 60 | 74 | 65 |
| 84 | 6.3 | 100 | 40 | 66 | 74 | 83 |
| 42 | 3.1 | 100 | 47 | 69 | 83 | 88 |
| Bromoform: | | | | | | |
| 168 | 12.6 | 100 | 39 | 52 | 64 | 50 |
| 84 | 6.3 | 100 | 31 | 56 | 61 | 69 |
| 42 | 3.1 | 100 | 44 | 61 | 70 | 75 |

General Notes:
Packing - 1" Saddles
Column Diameter - 12 inches
Water Temp. - 55° F
Specific concentration values not given in original work.

Table A-11. DATA ANALYSIS (END EFFECTS) - Umphres Study [64]

| Loading Conditions | | | Number of Transfer Units At Indicated Packing Depths | | | | | |
|---|---|---|---|---|---|---|---|---|
| Air Rate (cfm) | Water Rate (gpm) | Air to Water Ratio (vol / vol) | 1.75' | 3.75' | 5.75' | 7.67' | 1/HTU (1/ft) | HTU (ft) |
| Chloroform: | | | | | | | | |
| 168 | 12.6 | 100 | 1.0 | 0.9 | 0.8 | 0.6 | 0.25 | 4.0 |
| 84 | 6.3 | 100 | 0.9 | 0.8 | 0.6 | 0.4 | 0.29 | 3.45 |
| 42 | 3.1 | 100 | 1.2 | 1.0 | 0.7 | 0.8 | 0.37 | 2.7 |
| Bromodichloromethane: | | | | | | | | |
| 168 | 12.6 | 100 | 1.4 | 1.4 | 1.1 | 1.1 | 0.25 | 4.0 |
| 84 | 6.3 | 100 | 1.6 | 1.6 | 1.3 | 1.2 | 0.29 | 3.45 |
| 42 | 3.1 | 100 | 1.7 | 1.8 | 1.5 | 1.5 | 0.39 | 2.55 |
| Dibromochloromethane: | | | | | | | | |
| 168 | 12.6 | 100 | 2.0 | 1.9 | 1.7 | 1.6 | 0.225 | 4.4 |
| 84 | 6.3 | 100 | 2.3 | 2.0 | 1.7 | 1.5 | 0.28 | 3.6 |
| 42 | 3.1 | 100 | 2.7 | 2.6 | 2.4 | 2.2 | 0.38 | 2.6 |
| Bromoform: | | | | | | | | |
| 168 | 12.6 | 100 | 1.9 | 1.7 | 1.3 | 0.9 | 0.25 | 4.0 |
| 84 | 6.3 | 100 | 2.6 | 2.6 | 2.3 | 1.9 | 0.24 | 4.2 |
| 42 | 3.1 | 100 | 3.3 | 3.3 | 2.9 | 2.5 | 0.29 | 3.45 |

General Notes:
Packing - 1" Saddles
Column Diameter - 12 inches
Water Temp. - 55° F
Specific concentration values not given by original work.

End effects equation:

$$(NTU)_{\text{Measured}} = \left(\frac{1}{HTU}\right)(Z) + (NTU)_{\text{End Effects}}$$

## APPENDIX B - Required Input Parameters: Values & Calculations

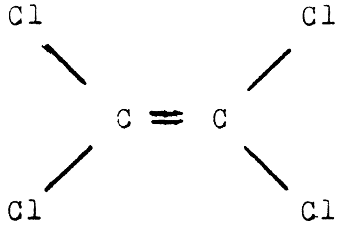
| Section | Description |
|---|---|
| B-1 | Structural Formulas of VOCs Investigated |
| B-2 | Liquid Diffusivity Calculations - Wilke-Chang Correlation |
| B-3 | Gas Diffusivity Calculations - Fuller Correlation |
| B-4 | Basic Air & Water Property Calculations |
| B-5 | Packing Parameter Values |

# APPENDIX B.1

## INPUT PARAMETERS - Structural Formulas of VOCs

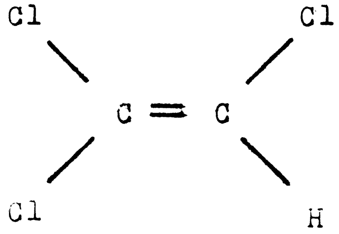
### Halogenated Aliphatic Hydrocarbons

Tetrachloroethylene (Perchloroethylene):



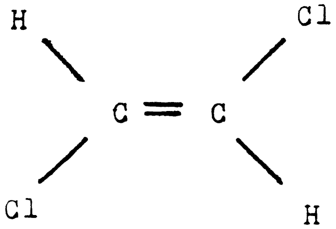
MW = 166

Trichloroethylene:



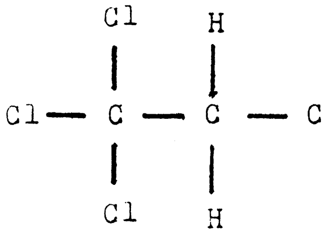
MW = 131

Trans 1,2-Dichloroethylene:



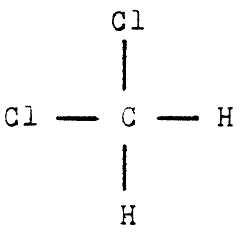
MW = 97

1,1,1-Trichloroethane (Methyl Chloroform):



MW = 133

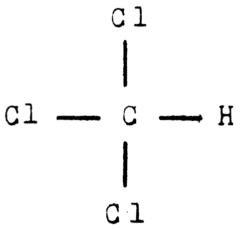
Dichloromethane (Methylene Chloride):



$$\begin{array}{ccccc} & & \mathrm{Cl} & & \\ & & | & & \\ \mathrm{Cl} & - & \mathrm{C} & - & \mathrm{H} \\ & & | & & \\ & & \mathrm{H} & & \end{array}$$

MW = 85

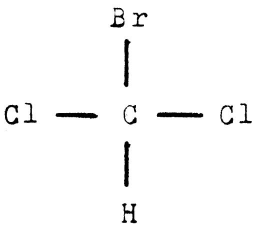
Trichloromethane (Chloroform):



$$\begin{array}{ccccc} & & \mathrm{Cl} & & \\ & & | & & \\ \mathrm{Cl} & - & \mathrm{C} & - & \mathrm{H} \\ & & | & & \\ & & \mathrm{Cl} & & \end{array}$$

MW = 119

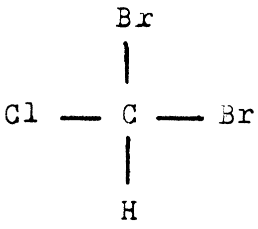
Bromodichloromethane:



$$\begin{array}{ccccc} & & \mathrm{Br} & & \\ & & | & & \\ \mathrm{Cl} & - & \mathrm{C} & - & \mathrm{Cl} \\ & & | & & \\ & & \mathrm{H} & & \end{array}$$

MW = 164

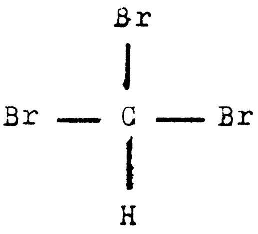
Dibromochloromethane:



$$\begin{array}{ccccc} & & \mathrm{Br} & & \\ & & | & & \\ \mathrm{Cl} & - & \mathrm{C} & - & \mathrm{Br} \\ & & | & & \\ & & \mathrm{H} & & \end{array}$$

MW = 208

Tribromomethane (Bromoform):

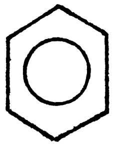


$$\begin{array}{ccccc} & & \mathrm{Br} & & \\ & & | & & \\ \mathrm{Br} & - & \mathrm{C} & - & \mathrm{Br} \\ & & | & & \\ & & \mathrm{H} & & \end{array}$$

MW = 253

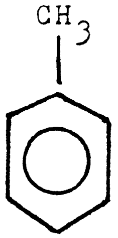
## Monocyclic Aromatics

Benzene:



MW = 78

Toluene (Methyl Benzene):



MW = 92

# APPENDIX B.2

## ONDA MODEL INPUTS - Liquid Diffusivity - Wilke-Chang correlation [69]

$$D_L = 7.4x10^{-15} \frac{(\xi M_B)^{1/2}}{V_A^{0.6}} \left(\frac{T}{\mu_B}\right)$$

where: $D_L$ - liquid diffusivity, $m^2/\mathrm{sec}$

$\xi$ - association factor for the solvent

= 2.26 for water (recommended by Hayduk & Laudie [26])

$M_B$ - molecular weight of solvent, g/mole

= 18.0 for water

$V_A$ - molal volume of solute at normal boiling temperature, liter/mole

T - temperature, degrees Kelvin

$\mu_B$ - viscosity of solvent, $(N\ \mathrm{sec})/m^2$

The required molar volume increments at the normal boiling point as formulated by LeBas [54]:

| | (liter/mole)<br>$V_{B(i)}$ |
|---|---|
| Bromine | 27.0 |
| Carbon | 14.8 |
| Chlorine | 24.6 |
| Hydrogen | 3.7 |
| Oxygen | 7.4 |
| Aromatic Ring | -15.0 |

From the above, the following results were obtained for the VOCs investigated:

|  | (liter/mole) $V_B$ | a | a' |
|---|---|---|---|
| Tetrachloroethylene | 128 | 25.7 | 5.81 |
| 1,1,1-Trichloroethane | 115 | 25.1 | 5.67 |
| Trichloroethylene | 107 | 28.6 | 6.46 |
| Trans-1,2-Dichloroethane | 86 | 32.6 | 7.37 |
| Toluene | 118 | 26.9 | 6.09 |
| Benzene | 96 | 30.5 | 6.90 |
| Methylene Chloride | 71 | 36.4 | 8.19 |
| Chloroform | 92 | 31.2 | 7.06 |
| Bromodichloromethane | 95 | 30.8 | 6.95 |
| Dibromochloromethane | 97 | 30.3 | 6.85 |
| Bromoform | 100 | 29.9 | 6.75 |

where a and a' represent coefficients for the following reduced temperature equations used in the computer programs:

$$D_L = a \times 10^{-16} \frac{T}{\mu_B} \qquad D'_L = a' \times 10^{-16} \frac{T}{\mu'_B}$$

with: $D_L$ in $m^2/\text{sec}$
$\mu_B$ in $(N\ \text{sec})/m^2$

$D'_L$ in $ft^2/\text{sec}$
$\mu'_B$ in $(\text{lb sec})/ft^2$

# APPENDIX B.3

## ONDA MODEL INPUTS - Gas Diffusivity - Fuller correlation [22]

$$D_G = \frac{10^{-7}\, T^{1.75}}{P\left[(\Sigma v_A)^{1/3} + (\Sigma v_B)^{1/3}\right]^2} \left(\frac{M_A + M_B}{M_A M_B}\right)^{1/2}$$

where: $D_G$ - gas diffusivity, $m^2/\text{sec}$

v - atomic diffusion volume increment (values given in original work)

M - molecular weight of system gases, g/mole

T - temperature in Kelvin

P - total pressure (atm)

The atomic diffusion volumes from the original work are:

| | $V_{(i)}$ |
|---|---|
| Air | 20.1 |
| Carbon | 16.5 |
| Chlorine | 19.5 |
| Hydrogen | 1.98 |
| Aromatic ring | -20.2 |

From the above, the following results were obtained for the VOCs investigated:

| | (1/mole)<br>$V_A$ | (g/mole)<br>$M_A$ | a | $a'$ |
|---|---|---|---|---|
| Tetrachloroethylene | 111 | 166 | 3.55 | 38.2 |
| 1,1,1-Trichloroethane | 97 | 133 | 3.83 | 41.2 |
| Trichloroethylene | 94 | 131 | 3.90 | 42.0 |
| Trans-1,2-Dichloroethane | 76 | 97 | 4.38 | 47.2 |
| Toluene | 111 | 92 | 3.76 | 40.5 |
| Benzene | 91 | 78 | 4.18 | 45.0 |
| Methylene Chloride | 60 | 85 | 4.90 | 52.8 |
| Chloroform | 77 | 119 | 4.26 | 45.9 |
| * Bromodichloromethane | -- | 164 | 4.11 | 44.2 |
| * Dibromochloromethane | -- | 208 | 3.96 | 42.6 |
| * Bromoform | -- | 253 | 3.81 | 41.0 |

where a and $a'$ represent coefficients for the following reduced temperature-dependent equations used in the computer programs:

$$D_G = a \times 10^{-10} (T)^{1.75} \qquad D'_G = a' \times 10^{-10} (T)^{1.75}$$

with: $D_G$ in $m^2/\text{sec}$
$D'_G$ in $ft^2/\text{sec}$

NOTE: Since the Fuller equation connot be used to estimate bromide-containing compounds (since no atomic diffusion volume value is available), values cited by Roberts and Levy [53] based upon the Hirschfelder method were used to formulate the necessary relations.

# APPENDIX B.4

## ONDA MODEL INPUTS - Basic Air & Water Properties

The following correlations were formulated based on a air temperature range from 0 to 100°F with values obtained from Roberson and Crowe [52]. Errors of less than 1% were noted over this range using these equations:

### Air Density:

Metric:

$$\rho = -4.5 \, x \, 10^{-3} (T) \; + \; 1.30$$

where:

$\rho$ - $kg / m^3$
T - ° Celcius

English:

$$\rho = -5.0 \, x \, 10^{-6} (T) \; + \; 2.68 \, x \, 10^{-3}$$

where:

$\rho$ - $kg / m^3$
T - ° Farenhite

### Air Viscosity:

Metric:

$$\mu = 5.0 \, x \, 10^{-8} (T) \; + \; 1.71 \, x \, 10^{-5}$$

where:

$\mu$ - $(N \text{ sec}) / m^2$
T - ° Celcius

English:

$$\mu = 5.5 \, x \, 10^{10} (T) \; + \; 3.40 \, x \, 10^{-7}$$

where:

$\mu$ - $(\text{lb sec}) / ft^2$
T - ° Farenhite

The following correlations were formulated based on a water temperature range from 32 to 100°F with values obtained from Roberson and Crowe [52]. Errors of less than 1% were noted over this range using these equations:

Water Density:

Metric: 1000 $kg/m^3$

English: 1.94 $slugs/ft^3$

NOTE - essentially constant over the range considered.

Water Viscosity:

Metric:

$$\frac{1}{\mu^{1/2}} = 0.4\,(T) + 23.65$$

where:

$\mu$ - $(N \sec)/m^2$
T - ° Celcius

English:

$$\frac{1}{\mu^{1/2}} = 1.5\,(T) + 116$$

where:

$\mu$ - $(\mathrm{lb} \sec)/ft^2$
T - ° Farenhite

Water Surface Tension:

Metric:

$$\sigma = -1.40 \times 10^{-4}\,(T) + 7.58 \times 10^{-2}$$

where:

$\sigma$ - $N/m$
T - ° Celcius

English:

$$\sigma = 5.6 \times 10^{-6}\,(T) + 5.38 \times 10^{-3}$$

where:

$\sigma$ - $\mathrm{lb}/ft$
T - ° Farenhite

# APPENDIX B.5

## ONDA MODEL INPUTS - Packing Parameters

### Basic Packing Properties - [23,29,47,63]

| Packings | (inches) Nominal Diameter | (1/ft) Specific Surface Area | Onda Shape Factor |
|---|---|---|---|
| Pall Rings (polypropylene) | 5/8 | 104 | 5.42 |
| | 1 | 63 | 5.25 |
| | 2 | 31 | 4.88 |
| Saddles (polypropylene) | 1 | 63 | 5.25 |
| Saddles (ceramic) | 1/2 | 142 | 5.92 |
| Tellerettes (polyethylene) | 1 | 55 | 4.58 |
| | 2 | 36 | 6.00 |
| Tri-Packs (polypropylene) | 2 | 42 | 7.00 |

NOTE: The shape factor is the dimensionless term represented by the nominal size of the packing times the packing's specific surface area.

### Critical Surface Tension for Different Packing Materials [23,47]

| Packing Material | Critical Surface Tension (N/m) | Critical Surface Tension (lb/ft) |
|---|---|---|
| Ceramic | 0.061 | 0.00418 |
| Polyethylene | 0.033 | 0.00226 |
| Polypropylene | 0.0285 | 0.00195 |

## APPENDIX C - Computer Model Programs & Sample Outputs

| Section | Description |
|---|---|
| C-1 | Computer Program - Transfer Unit Approach to Evaluating Column Performance (English Units Version) |
| C-2 | Sample Output - Transfer Unit Evaluation |
| C-3 | Computer Program - Onda Correlation Predictions of Mass Transfer Rates (English Units Version) |
| C-4 | Sample Output - Onda Model Predictions |

# APPENDIX C-1

## Computer Program - Transfer Unit Column Performance Model

```
1  REM HTU/NTU design approach -- English units version (lb,ft,sec)
2  REM Input file must be named "Exp.Dat"
3  REM Format required for input file (separate lines except as noted):
4  REM Test Conditions Data (type in once at top of file):
5  REM    Particular VOC considered  (type in " ")
6  REM    Henry's constant (atm * ft¢3 water / ft¢3 air)
7  REM    Column diameter & height (ft) (put on same line in given order)
8  REM    Type in:  0 if air flow is at actual operating temp.
9  REM              1 if air flow is based on standard temp. of 32 F (0 C)
10 REM        If air flow is based on standard temp. of 32 F, input the
11 REM        actual operating temp. on next line, otherwise leave blank.
12 REM Experimental Results (repeat as necessary):
13 REM    VOC input & output concentrations (ppb) (same line, given order)
14 REM    Water & air flow rates (gpm & cfm) (same line, given order)
20 OPEN "EXP.DAT" FOR INPUT AS #1
22 LET COUNT=1
24 REM Program inputs necessary basic values:
25 INPUT#1,VOC$
30 INPUT#1,Hc
35 INPUT#1,D,Z
40 INPUT#1,StanCond
42 IF StanCond=0 THEN 45
44 INPUT#1,GTEMP
45 REM Print out governing experimental conditions:
46 FOR Q=1 TO 15
50 LPRINT
55 NEXT Q
60 LPRINT "    HTU/NTU DESIGN APPROACH -- DATA ANALYSIS"
65 LPRINT "    ----------------------------------------"
70 LPRINT
75 LPRINT
80 LPRINT
85 LPRINT "        BASIC PARAMETER VALUES:"
90 LPRINT "        -----------------------"
95 LPRINT
100 LPRINT
105 LPRINT "        VOC PROPERTIES:"
110 LPRINT "               ";VOC$
115 LPRINT "               HENRY'S CONSTANT=";Hc;"Atm*(Ft¢3 water/Ft¢3 air)"
120 LPRINT
125 LPRINT
130 LPRINT "        COLUMN DIMENSIONS:"
135 LPRINT "               DIAMETER=";D;"Ft"
140 LPRINT "               HEIGHT=";Z;"Ft"
145 FOR Q=16 TO 50
150 LPRINT
155 NEXT Q
```

NOTE: The "¢" symbol represents the "^" (power) symbol in BASIC.

```
157 REM Program inputs experimental test results:
160 INPUT#1,INF,EFF
165 INPUT#1,Lgpm,G
180 LET GDENSITY=((0.-0.000005)*GTEMP)+0.00268
185 LET Gstd=G
190 LET G=Gstd*(0.00252/GDENSITY)
195 LET P=1-(EFF/INF)
200 LET L=Lgpm/7.48
202 REM Calculate basic column performance parameters:
205 LET R=Hc*(G/L)
210 LET NTU=(R/(R-1.))*LOG(((INF/EFF)*(R-1.)+1.)/R)
215 LET HTU=Z/NTU
220 LET LFLUX=L/((3.1416/4.)*(D¢2))
222 REM Calculate observed mass transfer rate:
225 LET KLa=(LFLUX/HTU)/60.
230 LET GFLUX=G/((3.1416/4.)*(D¢2))
232 REM Print column performance results for each set of experimental data:
235 LPRINT " RUN # ";COUNT
240 LPRINT " --------"
242 LPRINT
245 LET COUNT=COUNT+1
250 LPRINT "   COLUMN OPERATING CONDITIONS:"
255 LPRINT "          WATER FLOW RATE= ";
260 LPRINT USING "##.#";L;
265 LPRINT                 " CFM";"     or  ";Lgpm;"gal/min"
270 LPRINT "          AIR FLOW RATE=   ";
275 LPRINT USING "###.#";G;
280 LPRINT                   " CFM"
285 IF StanCond=0 THEN 295
290 LPRINT "          AIR FLOW RATE=";Gstd;"SCFM  (at 32 F  or  0 C)"
295 LPRINT
300 LPRINT "          WATER FLUX= ";
305 LPRINT USING "##.##";LFLUX;
310 LPRINT                 " (Ft¢3/Min)/Ft¢2";"     or  ";
315 LPRINT USING "##.#";LFLUX*7.48;
320 LPRINT                       "(gal/min)/Ft¢2"
325 LPRINT "          AIR FLUX=    ";
330 LPRINT USING "###.#";GFLUX;
335 LPRINT                " (Ft¢3/Min)/Ft¢2"
340 LPRINT "          AIR TO WATER VOLUME RATIO= ";
345 LPRINT USING "###.#";G/L;
350 LPRINT                   " Ft¢3/Ft¢3"
355 LPRINT
365 LPRINT "   COLUMN PERFORMANCE:"
370 LPRINT "          VOC INFLUENT CONCENTRATION=";INF;"ppb"
375 LPRINT "          VOC EFFLUENT CONCENTRATION=";EFF;"ppb"
380 LPRINT "          VOC REMOVAL= ";
385 LPRINT USING "##.#";P*100.;
390 LPRINT                     " %"
400 LPRINT
```

```
405 LPRINT "   COMPUTED DESIGN PARAMETERS:"
410 LPRINT "          R= ";
415 LPRINT USING "###.#";R;
420 LPRINT                 "            Stripping Factor"
425 LPRINT "          NTU= ";
430 LPRINT USING "##.#";NTU;
435 LPRINT                 "           Number of Transfer Units"
440 LPRINT "          HTU= ";
445 LPRINT USING "##.#";HTU;
450 LPRINT                 " Ft        Height of a Transfer Unit"
455 LPRINT
460 LPRINT "          KLa= ";
465 LPRINT USING "#.###¢¢¢¢";KLa;
470 LPRINT                   " 1/Secs       or   ";
475 LPRINT USING "###.#";KLa*3600.;
480 LPRINT                       " 1/Hrs"
485 FOR QQ=1 TO 10
490 LPRINT
495 NEXT QQ
500 IF StanCond=1 THEN 510
505 LPRINT
525 REM Check if all experimental data from input file has been evaluated:
555 IF EOF(1) THEN 600
560 GOTO 160
600 CLOSE#1
1000 END
```

# APPENDIX C-2

## Sample Output - Transfer Unit Evaluation Computer Program

```
HTU/NTU DESIGN APPROACH -- DATA ANALYSIS
----------------------------------------


     BASIC PARAMETER VALUES:
     -----------------------


     VOC PROPERTIES:
             TCE
             HENRY'S CONSTANT= .3 Atm*(Ft^3 water/Ft^3 air)


     COLUMN DIMENSIONS:
             DIAMETER= 1 Ft
             HEIGHT= 10 Ft
```

## Sample Output (cont.) - Transfer Unit Evaluation

```
RUN #  4
--------

 COLUMN OPERATING CONDITIONS:
        WATER FLOW RATE=  3.3 CFM       or    25 gal/min
        AIR FLOW RATE=    41.4 CFM

        WATER FLUX=  4.26 (Ft^3/Min)/Ft^2      or   31.8(gal/min)/Ft^2
        AIR FLUX=     52.7 (Ft^3/Min)/Ft^2
        AIR TO WATER VOLUME RATIO=  12.4 Ft^3/Ft^3

 COLUMN PERFORMANCE:
        VOC INFLUENT CONCENTRATION= 31 ppb
        VOC EFFLUENT CONCENTRATION= 4.7 ppb
        VOC REMOVAL= 84.8 %

 COMPUTED DESIGN PARAMETERS:
        R=   3.7                Stripping Factor
        NTU=  2.2               Number of Transfer Units
        HTU=  4.5 Ft            Height of a Transfer Unit

        KLa= 0.158E-01 1/Secs         or     56.9 1/Hrs
```

# APPENDIX C-3

## Computer Program - Onda Correlation

```
1  REM Onda mass transfer equation -- English units version (lb,ft,sec)
2  REM Input file must be named "Exp.Dat"
3  REM Format required for input file (separate lines except as noted):
4  REM General Test Conditions (type in once at top of file):
5  REM    VOC to be considered (type in " ")
6  REM        Acceptable VOCs & required input names:
7  REM              Tetratchloroethylene     (input as "PCE")
8  REM              Trichloroethylene        (input as "TCE")
9  REM              1,1,1-Trichloroethane    (input as "1,1,1-TCE")
10 REM              Trans 1,2-Dichloroethane (input as "Trans 1,2-DCE")
11 REM              Methylene Chloride       (input as given)
12 REM              Benzene                  (input as given)
13 REM              Toluene                  (input as given)
14 REM              Chloroform               (input as given)
15 REM              Bromodichloromethane     (input as given)
16 REM              Dibromochloromethane     (input as given)
17 REM              Bromoform                (input as given)
18 REM    Water temp. & air temp. ( F) (put on same line in given order):
19 REM    Packing type (i.e. - Pall rings, Intallox saddles) (type in " "):
20 REM    Packing material - ceramic, polyethylene,polypropylene, PVC
21 REM       Note for  plastic' packings:
22 REM            Intallox saddles & Pall rings - polyproplyene
23 REM            Tellerettes - polyethylene
24 REM        Type in:   1  for ceramic
25 REM                   2  for polyethylene
26 REM                   3  for polypropylene
27 REM                   4  for PVC
28 REM    Nominal packing size (inches) & specific surface area (1/ft)
29 REM            (same line, given order)
30 REM    Henry's constant (atm * ft¢3 / ft¢3)
31 REM    Column dia (ft)
32 REM    Type in:  0  if the air flow is based actual operating temperature
33 REM              1  if the air flow is based on standard temp. of 32 F
34 REM Specific Test Conditions (repeat as necessary):
35 REM    Water flow rate (gal/min)
36 REM    Air flow rate (ft¢3/min)
40 OPEN "EXP.DAT" FOR INPUT AS #1
42 LET COUNT=1
44 REM Program inputs particular VOC to be considered:
46 INPUT#1,VOC$
48 REM Program inputs temp (F) to compute basic water/air properties:
50 INPUT#1,LTEMP,GTEMP
52 REM Compute temp. dependent water/air properties:
54 LET LDENSITY=1.94
56 LET LVISCOS=(1./(1.5*LTEMP+116.))¢2
58 LET LTEN=((0.-0.0000056)*LTEMP)+0.00538
60 LET GDENSITY=((0.-0.000005)*GTEMP)+0.00268
65 LET GVISCOS=(0.0000000055*GTEMP)+0.000000340
```

NOTE: The "¢" symbol represents the "∧" (power) symbol in BASIC.

```
70 REM Compute Diffusion Coefficients:
71 REM    Liquid diffusion value based on Wilke-Chang Correlation.
73 REM    Gas diffusion value based on method of Fuller et al.
75 REM    Equations presented are the reduced forms of the general equations.
81 IF VOC$="Methylene Chloride" THEN 85
83 GOTO 89
85 LET LCOEF=(8.19E-16)
87 LET GCOEF=(4.90E-9)
89 IF VOC$="Trans 1,2-DCE" THEN 93
91 GOTO 100
93 LET LCOEF=(7.365E-16)
95 LET GCOEF=(4.72E-9)
100 IF VOC$="Benzene" THEN 110
105 GOTO 120
110 LET LCOEF=(6.90E-16)
115 LET GCOEF=(4.50E-9)
120 IF VOC$="Toluene" THEN 130
125 GOTO 145
130 LET LCOEF=(6.09E-16)
140 LET GCOEF=(4.05E-9)
145 IF VOC$="TCE" THEN 155
150 GOTO 165
155 LET LCOEF=(6.46E-16)
160 LET GCOEF=(4.20E-9)
165 IF VOC$="PCE" THEN 175
170 GOTO 185
175 LET LCOEF=(5.81E-16)
180 LET GCOEF=(3.82E-9)
185 IF VOC$="1,1,1-TCE" THEN 195
190 GOTO 205
195 LET LCOEF=(6.21E-16)
200 LET GCOEF=(4.12E-9)
205 IF VOC$="Chloroform" THEN 215
210 GOTO 225
215 LET LCOEF=(7.06E-16)
220 LET GCOEF=(4.59E-9)
225 IF VOC$="Bromodichloromethane" THEN 230
228 GOTO 234
230 LET LCOEF=(6.95E-16)
232 LET GCOEF=(4.42E-9)
234 IF VOC$="Dibromochloromethane" THEN 238
236 GOTO 242
238 LET LCOEF=(6.85E-16)
240 LET GCOEF=(4.26E-9)
242 IF VOC$="Bromoform" THEN 246
244 GOTO 250
246 LET LCOEF=(6.75E-16)
248 LET GCOEF=(4.10E-9)
250 LET LCelcius=(LTEMP-32.)/1.8
252 LET GCelcius=(GTEMP-32.)/1.8
254 LET LDIFF=LCOEF*(LCelcius+273.)/LVISCOS
256 LET GDIFF=GCOEF*((GCelcius+273.)¢1.75)
```

```
258 REM Progran inputs packing parameters:
260 INPUT#1,TYPE$
262 INPUT#1,MATERIAL
264 IF MATERIAL=1 THEN CRTTEN=0.00418
265 IF MATERIAL=1 THEN MATERIAL$="Ceramic"
266 IF MATERIAL=2 THEN CRTTEN=0.00226
267 IF MATERIAL=2 THEN MATERIAL$="Polyethylene"
268 IF MATERIAL=3 THEN CRTTEN=0.00195
269 IF MATERIAL=3 THEN MATERIAL$="Polypropylene"
270 IF MATERIAL=4 THEN CRTTEN=0.00274
271 IF MATERIAL=4 THEN MATERIAL$="PVC"
285 INPUT#1,SIZE,SURFAREA
290 LET PACKSIZE=SIZE/12.
295 REM Program inputs Henry's constant value:
300 INPUT#1,Hc
305 LET H=Hc*(LDENSITY/GDENSITY)*(28.8/18.)
310 REM Program inputs column diameter:
315 INPUT#1,D
317 REM Program inputs whether gas flow rates are for standard conditions:
319 INPUT#1,StanCond
320 REM Print out general test condition data:
323 FOR Q=1 TO 10
325 LPRINT
330 NEXT Q
335 LPRINT "ONDA MODEL PREDICTIONS"
340 LPRINT "----------------------"
345 LPRINT
350 LPRINT
355 LPRINT
360 LPRINT "   BASIC PARAMETER VALUES:"
365 LPRINT "   -----------------------"
370 LPRINT
375 LPRINT
380 LPRINT "   VOC PROPERTIES:"
385 LPRINT "          ";VOC$
390 LPRINT "          Hc= ";
395 LPRINT USING "#.##";Hc;
400 LPRINT                 " Atm*(Ft¢3 water/Ft¢3 air)"
405 LPRINT "          H= ";
410 LPRINT USING "####";H;
415 LPRINT                " Atm*(mole water/mole air)"
420 LPRINT
425 LPRINT
430 LPRINT "   COLUMN PACKING PROPERTIES:"
435 LPRINT "          PACKING TYPE  -- ";TYPE$
440 LPRINT "          MATERIAL  -- ";MATERIAL$
445 LPRINT "          CRITICAL SURFACE TENSION=";CRTTEN;"Lb/Ft"
450 LPRINT "          PACKING SIZE=";SIZE;"Inches"
455 LPRINT "          SPECIFIC TOTAL SURFACE AREA=";SURFAREA;"Ft¢2/Ft¢3"
465 LPRINT
470 LPRINT
475 LPRINT "   COLUMN DIMENSIONS:"
480 LPRINT "          COLUMN DIAMETER=";D;"Ft"
485 LPRINT
490 LPRINT
```

```
495 LPRINT "   WATER PROPERTIES:"
500 LPRINT "         TEMPERATURE=";LTEMP;"F"
505 LPRINT "         DENSITY=";LDENSITY;"Slugs/Ft¢3"
510 LPRINT "         VISCOSITY= ";
515 LPRINT USING "#.###¢¢¢¢";LVISCOS;
520 LPRINT                       " Lb*Sec/Ft¢2"
525 LPRINT "         SURFACE TENSION= ";
530 LPRINT USING "#.#####";LTEN;
535 LPRINT                 " Lb/Ft"
540 LPRINT "         DIFFUSION COEFFICIENT FOR ";VOC$;" = ";
545 LPRINT USING "#.##¢¢¢¢";LDIFF;
550 LPRINT                   " Ft¢2/Sec"
555 LPRINT
560 LPRINT
565 LPRINT "   AIR PROPERTIES:"
570 LPRINT "         TEMPERATURE=";GTEMP;"F"
575 LPRINT "         DENSITY= ";
580 LPRINT USING "#.###¢¢¢¢";GDENSITY;
585 LPRINT                        " Slugs/Ft¢3"
590 LPRINT "         VISCOSITY= ";
595 LPRINT USING "#.###¢¢¢¢";GVISCOS;
600 LPRINT                      " Lb*Sec/Ft¢2"
605 LPRINT "         DIFFUSION COEFFICIENT FOR ";VOC$;" = ";
610 LPRINT USING "#.##¢¢¢¢";GDIFF;
615 LPRINT                      " Ft¢2/Sec"
620 FOR Q=11 TO 27
625 LPRINT
630 NEXT Q
645 REM Program inputs specific experimental conditions (flow values):
650 INPUT#1,Lgpm
655 INPUT#1,G
660 REM Calculate predicted specific wetted surface area of the packing:
665 LET L=Lgpm/7.48
670 LET LgpmLOAD=Lgpm/((3.1416/4.)*(D¢2))
675 LET LLOAD=L/((3.1416/4.)*(D¢2))
680 LET LFLUX=(LLOAD*LDENSITY)/60.
685 LET Re=LFLUX/(SURFAREA*LVISCOS)
690 LET Fr=(LFLUX¢2*SURFAREA)/(LDENSITY¢2*32.2)
695 LET We=(LFLUX¢2/(LDENSITY*LTEN*SURFAREA))
700 LET WETAREA=SURFAREA*(1.-EXP((0.-1.45)*((CRTTEN/LTEN)¢.75)*(Re¢.1)*
(Fr¢(0.-.05))*(We¢.2)))
702 REM Calculate predicted liquid-side mass transfer coefficient:
705 LET a=(LDENSITY/(LVISCOS*32.2))¢0.33333
710 LET LRe=LFLUX/(WETAREA*LVISCOS)
715 LET LSc=LVISCOS/(LDENSITY*LDIFF)
720 LET Shape=SURFAREA*PACKSIZE
725 LET kL=.0051*(LRe¢0.66667)*(LSc¢(0.0-0.5))*(Shape¢0.4)/a
730 REM Calculate predicted gas-phase mass transfer coefficient:
736 IF StanCond=0 THEN 750
740 LET Gstd=G
745 LET G=Gstd*(0.00252/GDENSITY)
750 LET GLOAD=G/((3.1416/4.)*(D¢2))
755 LET GFLUX=(GLOAD*GDENSITY)/60.
760 LET GRe=GFLUX/(SURFAREA*GVISCOS)
765 LET GSc=GVISCOS/(GDENSITY*GDIFF)
770 REM Appropriate gas equation constant depends upon packing size:
775 REM      Lower value of 2.0 used if pack-size < 15 mm (5/8 inch)
780 IF SIZE<0.625 THEN 795
785 LET C=5.23
790 GO TO 800
795 LET C=2.0
800 LET kG=C*SURFAREA*GDIFF*(GRe¢0.7)*(GSc¢0.33333)/(Shape¢2)
```

```
803 REM Calculate predicted overall mass transfer coefficient:
805 LET INVKL=(1./kL)+(1./(Hc*kG))
810 LET KLiq=1./INVKL
812 REM Calculate predicted mass transfer rate:
815 LET KLa=KLiq*WETAREA
817 REM Print predicted column performance parameters for
819 REM       each set of experimental conditions:
820 LPRINT " RUN # ";COUNT
822 LPRINT " --------"
825 LET COUNT=COUNT+1
830 LPRINT "   COLUMN OPERATING CONDITIONS:"
835 LPRINT "          WATER FLOW RATE= ";
840 LPRINT USING "##.#";L;
845 LPRINT                  " Ft¢3/Min";"     or  ";Lgpm;"gal/min"
850 LPRINT "          AIR FLOW RATE= ";
855 LPRINT USING "###.#";G;
860 LPRINT                 " Ft¢3/Min  at ";GTEMP;"F"
865 IF StanCond=0 THEN 875
870 LPRINT "          AIR FLOW RATE=";Gstd;"SCFM (at 32 F)"
875 LPRINT
880 LPRINT "          WATER VOLUME FLUX= ";
885 LPRINT USING "##.##";LLOAD;
890 LPRINT                      " (Ft¢3/Min)/Ft¢2    or   ";
895 LPRINT USING "##.#";LgpmLOAD;
900 LPRINT                       " (gal/min)/Ft¢2"
905 LPRINT "          AIR VOLUME FLUX= ";
910 LPRINT USING "###.#";GLOAD;
915 LPRINT                         " (Ft¢3/Min)/Ft¢2"
920 LPRINT "          AIR TO WATER VOLUME RATIO= ";
925 LPRINT USING "###.#";G/L;
930 LPRINT                    " Ft¢3/Ft¢3"
935 LPRINT
940 LPRINT "          WATER MASS FLUX= ";
945 LPRINT USING "#.###";LFLUX;
950 LPRINT                      " Slugs/(Ft¢2*Sec)"
955 LPRINT "          AIR MASS FLUX= ";
960 LPRINT USING "#.###¢¢¢¢";GFLUX;
965 LPRINT                         " Slugs/(Ft¢2*Sec)"
970 LPRINT "          AIR TO WATER MASS RATIO= ";
975 LPRINT USING "#.###¢¢¢¢";GFLUX/LFLUX;
980 LPRINT                   " Lb/Lb"
985 LPRINT
990 LPRINT "   PREDICTED MASS TRANSFER VALUES BY THE ONDA CORRELATIONS:"
995 LPRINT "          kL= ";
1000 LPRINT USING "#.###¢¢¢¢";kL;
1005 LPRINT                      " Ft/Sec"
1010 LPRINT "         kG= ";
1015 LPRINT USING "#.###¢¢¢¢";kG;
1020 LPRINT                      " Ft/Sec"
1025 LPRINT "         KL= ";
1030 LPRINT USING "#.###¢¢¢¢";KLiq;
1035 LPRINT                         " Ft/Sec"
1040 LPRINT
1045 LPRINT "         SPECIFIC WETTED SURFACE AREA= ";
1050 LPRINT USING "###.#";WETAREA;
1055 LPRINT                         " Ft¢2/Ft¢3"
1060 LPRINT "         WETTED TO TOTAL SURFACE AREA RATIO= ";
1065 LPRINT USING "#.##";WETAREA/SURFAREA;
1070 LPRINT
```

```
1075 LPRINT "          KLa= ";
1080 LPRINT USING "#.###¢¢¢¢";KLa;
1085 LPRINT                       " 1/Sec      or   ";
1090 LPRINT USING "##.#";KLa*3600.;
1095 LPRINT                       " 1/Hrs"
1100 FOR QQ=1 TO 10
1105 LPRINT
1110 NEXT QQ
1115 IF StanCond=1 THEN 1125
1120 LPRINT
1150 REM Check if all experimental data from input file has been evaluated:
1195 IF EOF(1) THEN 1500
1200 GOTO 650
1500 CLOSE#1
2000 END
```

## APPENDIX C-4

Sample Output - Onda Model Predictions
Computer Program

```
ONDA MODEL PREDICTIONS
----------------------



   BASIC PARAMETER VALUES:
   -----------------------


   VOC PROPERTIES:
          TCE
          Hc= 0.30 Atm*(Ft^3 water/Ft^3 air)
          H=  387 Atm*(mole water/mole air)


   COLUMN PACKING PROPERTIES:
          PACKING TYPE  -- 1-inch Ballast Saddles
          MATERIAL  -- Polyethylene
          CRITICAL SURFACE TENSION= .00226 Lb/Ft
          PACKING SIZE= 1 Inches
          SPECIFIC TOTAL SURFACE AREA= 62 Ft^2/Ft^3


   COLUMN DIMENSIONS:
          COLUMN DIAMETER= 1 Ft


   WATER PROPERTIES:
          TEMPERATURE= 55 F
          DENSITY= 1.94 Slugs/Ft^3
          VISCOSITY= 0.254E-04 Lb*Sec/Ft^2
          SURFACE TENSION= 0.00507 Lb/Ft
          DIFFUSION COEFFICIENT FOR TCE = 0.73E-08 Ft^2/Sec


   AIR PROPERTIES:
          TEMPERATURE= 55 F
          DENSITY= 0.241E-02 Slugs/Ft^3
          VISCOSITY= 0.370E-06 Lb*Sec/Ft^2
          DIFFUSION COEFFICIENT FOR TCE = 0.83E-04 Ft^2/Sec
```

## Sample Output (cont.) - Onda Model Predictions

```
RUN #  4
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  COLUMN OPERATING CONDITIONS:
         WATER FLOW RATE=  3.3 Ft^3/Min      or   25 gal/min
         AIR FLOW RATE=  44.0 Ft^3/Min  at  55 F

         WATER VOLUME FLUX=  4.26 (Ft^3/Min)/Ft^2     or   31.8 (gal/min)/Ft^2
         AIR VOLUME FLUX=  56.0 (Ft^3/Min)/Ft^2
         AIR TO WATER VOLUME RATIO=  13.2 Ft^3/Ft^3

         WATER MASS FLUX= 0.138 Slugs/(Ft^2*Sec)
         AIR MASS FLUX= 0.225E-02 Slugs/(Ft^2*Sec)
         AIR TO WATER MASS RATIO= 0.163E-01 Lb/Lb

  PREDICTED MASS TRANSFER VALUES BY THE ONDA CORRELATIONS:
         kL= 0.516E-03 Ft/Sec
         kG= 0.307E-01 Ft/Sec
         KL= 0.489E-03 Ft/Sec

         SPECIFIC WETTED SURFACE AREA=  33.5 Ft^2/Ft^3
         WETTED TO TOTAL SURFACE AREA RATIO= 0.54
         KLa= 0.164E-01 1/Sec        or   59.0 1/Hrs
```