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U.S. Army Corps of Engineers  
Washington, D.C. 20314-1000

DG-1110-1-3

CECW-E

Design Guide  
No. 1110-1-3

31 October 2001

**ENGINEERING AND DESIGN  
AIR STRIPPING**

- 1. Purpose.** This design guide (DG) provides design and construction information for implementation of air stripping systems.
- 2. Applicability.** This DG applies to all USACE Commands with planning, design, or construction responsibility for air stripping systems.
- 3. Distribution Statement.** Approved for public release; distribution is unlimited.
- 4. References.** Appendix A provides a listing of references used in this document.
- 5. Availability.** This DG is available at the following web site:  
<http://www.usace.army.mil/inet/usace-docs/dg/dg1110-1-3/toc.htm>. Hard copies produced by the user from the electronic media should be checked against the current electronic version prior to use to assure that the latest version is used.

FOR THE COMMANDER:



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4 Appendices  
(See Table of Contents)

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**TABLE OF CONTENTS**

<b>Subject</b>	<b>Paragraph</b>	<b>Page</b>
<b>CHAPTER 1 INTRODUCTION</b>		
Purpose	1-1	1-1
Definition	1-2	1-1
Scope	1-3	1-1
Theory	1-4	1-1
<b>CHAPTER 2 DESCRIPTION OF AIR STRIPPERS</b>		
Packed Column Air Strippers	2-1	2-1
Sieve Tray Air Stripper	2-2	2-2
Diffused aeration stripper	2-3	2-2
<b>CHAPTER 3 DESIGN METHODS</b>		
General	3-1	3-1
Packed Column	3-2	3-1
Sieve Tray	3-3	3-1
Diffused Aeration	3-4	3-1

**TABLE OF CONTENTS (continued)**

<b>Subject</b>	<b>Paragraph</b>	<b>Page</b>
<b>CHAPTER 4</b>		
<b>TREATABILITY</b>		
General	4-1	4-1
Fouling	4-2	4-1
Contaminant Effects	4-3	4-1
Loading Rate	4-4	4-1
Diameter	4-5	4-1
Treatability Study Scope	4-6	4-1
<b>CHAPTER 5</b>		
<b>COMPARISON OF AIR STRIPPERS</b>		
General	5-1	5-1
Efficiency	5-2	5-1
Fouling	5-3	5-1
Airflow Rate	5-4	5-2
Water Flow Rate	5-5	5-2
Pressure Drop and Power Consumption	5-6	5-3
<b>CHAPTER 6</b>		
<b>AIR POLLUTION CONTROL REQUIREMENTS</b>		
General	6-1	6-1
Off-Gas Treatment	6-2	6-3
Innovative Air Pollution Control Devices	6-3	6-3
<b>CHAPTER 7</b>		
<b>FLOODING</b>		
General	7-1	7-1
Occurrence of Flooding	7-2	7-1
Blower	7-3	7-1
<b>CHAPTER 8</b>		
<b>PROCESS CONTROL</b>		
General	8-1	8-1
Level Controls	8-2	8-1
Pressure Controls	8-3	8-1
<b>CHAPTER 9</b>		
<b>ECONOMIC EVALUATION</b>		9-1

## TABLE OF CONTENTS (continued)

<b>Subject</b>	<b>Page</b>
<b>APPENDIX A REFERENCES</b>	A-1
<b>APPENDIX B TREATABILITY STUDY SCOPE</b>	B-1
<b>APPENDIX C EXAMPLE AIR STRIPPING BY LOW PROFILE SIEVE TRAY DEVICE</b>	C-1
<b>APPENDIX D EXAMPLE AIR STRIPPING BY PACKED COLUMN</b>	D-1

## LIST OF TABLES

<b>Subject</b>	<b>Table</b>	<b>Page</b>
Molar Henry's Law Constants	1-1	1-2
Comparison of Air Strippers	5-1	5-2

## LIST OF FIGURES

<b>Subject</b>	<b>Figure</b>	<b>Page</b>
Packed Column Air Stripper	2-1	2-1
Low Profile Sieve Tray Air Stripper	2-2	2-2
Diffused Aeration Air Stripper	2-3	2-3
Material Balance	6-1	6-3
Cost Model	9-1	9-2

## CHAPTER 1 INTRODUCTION

**1-1. Purpose.** This document provides technical information for designing and constructing air stripping systems. Example designs are provided in the appendices. Basic information about air strippers can be found in the Tri-Service sponsored *Remediation Technologies Screening Matrix and Reference Guide*, <http://www.frtr.gov>.

**1-2. Definition.** Air strippers remove volatile organic chemicals (VOCs) from liquid (water) by providing contact between the liquid and gas (air). The gas (air) may then be released to the atmosphere or treated to remove the VOCs and subsequently released to the atmosphere.

**1-3. Scope.** This document describes packed column, low-profile sieve tray and diffused aeration air strippers. Steam stripping is not included. This document discusses the three types, compares them, and lists advantages and disadvantages of each type to provide information for selection. Design examples for the packed-column and the low-profile air stripper are included in the appendices.

**1-4. Theory.** Air stripping is the mass transfer of VOCs that are dissolved in water from the water phase to the air phase. The equilibrium relationship is linear and is defined by Henry's Law (Kavanaugh and Trussell, 1980; Shulka and Hicks, 1984). For low concentrations of volatile compound  $a$ :

$$p_a = H_a x_a$$

$a$ . At equilibrium, the partial pressure of a gas,  $p_a$ , above a liquid is directly proportional to the mole fraction of the gas,  $x_a$ , dissolved in the liquid. The proportionality constant,  $H_a$ , is known as the Henry's constant. The value of the constant generally increases or decreases with the liquid temperature (Plambeck, 1995). As a consequence, the solubility of gases generally decreases with increasing temperature (Plambeck, 1995). EPA (1998) has published a comprehensive document, *Henry's Law Constants, Fm Values, Fr Values and Fe Values for Organic Compounds*, at [http://www.epa.gov/ttn/oarpg/tl/fr\\_notices/appj.pdf](http://www.epa.gov/ttn/oarpg/tl/fr_notices/appj.pdf). Practical application of the technology for contaminant removal is generally limited to compounds with Henry's constant values greater than 100 atmospheres. The theory is developed in textbooks such as McCabe et al. (1993) and Treybal (1980).

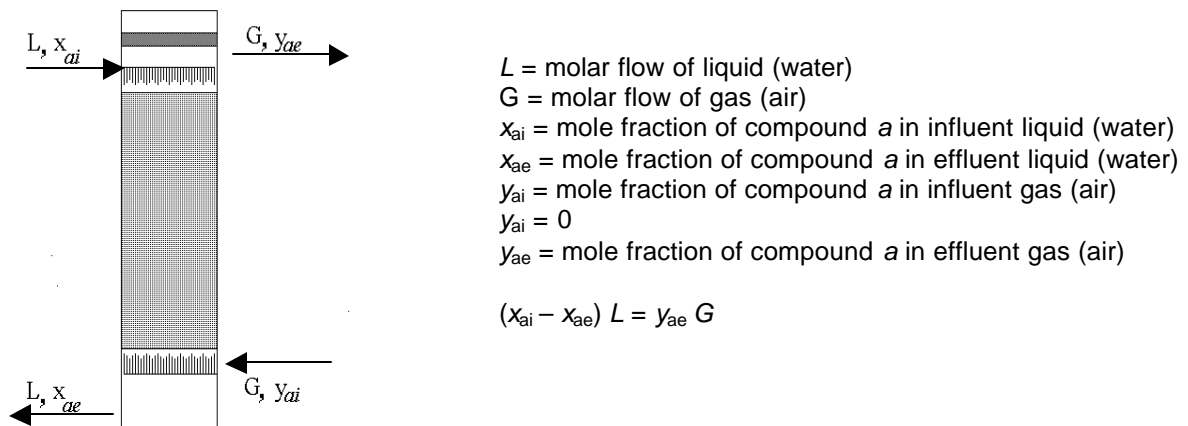
**Table 1-1**  
**Molar Henry's Law Constants at 293.16 K**

<i>Contaminant</i>	<i>[atm·m<sup>3</sup>/mole]</i>	<i>[Pa·m<sup>3</sup>/mole]</i>	<i>[Dimensionless]</i>
2,4 - D	1.02×10 <sup>-8</sup>	1.03×10 <sup>-3</sup>	7.65×10 <sup>-9</sup>
alachlor	3.20×10 <sup>-8</sup> to 1.20×10 <sup>-10</sup>	3.24×10 <sup>-3</sup> to 1.22×10 <sup>-5</sup>	2.40×10 <sup>-8</sup> to 9.00×10 <sup>-11</sup>
aldicarb, aldicarb sulfone and aldicarb sulfoxide	1.50×10 <sup>-10</sup>	1.52×10 <sup>-4</sup>	1.13×10 <sup>-9</sup>
atrazine	2.63×10 <sup>-9</sup>	2.66×10 <sup>-4</sup>	1.97×10 <sup>-9</sup>
carbofuran	1.02×10 <sup>-10</sup>	1.03×10 <sup>-5</sup>	7.65×10 <sup>-11</sup>
chlordane (gamma-chlordane)	1.30×10 <sup>-3</sup>	132	9.75×10 <sup>-4</sup>
dalapon	6.30×10 <sup>-8</sup>	6.38×10 <sup>-3</sup>	4.73×10 <sup>-8</sup>
dibromochloropropane (DBCP)	1.47×10 <sup>-4</sup>	14.9	1.10×10 <sup>-4</sup>
di (2-ethylhexyl) adipate	4.34×10 <sup>-7</sup>	4.40×10 <sup>-2</sup>	3.26×10 <sup>-7</sup>
di (2-ethylhexyl) phthalate (DEHP)	1.00×10 <sup>-4</sup>	10.1	7.50×10 <sup>-5</sup>
dinoseb	5.04×10 <sup>-4</sup>	51.1	3.78×10 <sup>-4</sup>
dioxin (2,3,7,8-TCDD)	1.62×10 <sup>-5</sup>	1.64	1.22×10 <sup>-5</sup>
endrin	4.00×10 <sup>-7</sup>	4.05×10 <sup>-2</sup>	3.00×10 <sup>-7</sup>
hexachlorobenzene (HCB)	3.00×10 <sup>-2</sup> to 7.00×10 <sup>-2</sup>	3.04×10 <sup>+3</sup> to 7.09×10 <sup>+3</sup>	2.25×10 <sup>-2</sup> to 5.25×10 <sup>-2</sup>
heptachlor and heptachlor epoxide	2.62×10 <sup>-3</sup>	265	1.97×10 <sup>-3</sup>
hexachlorocyclopentadiene (hex)	2.70×10 <sup>-2</sup>	2.74×10 <sup>+3</sup>	2.03×10 <sup>-2</sup>
methoxychlor	1.60×10 <sup>-5</sup>	162	1.20×10 <sup>-5</sup>
polychlorinated biphenyls (PCBs)	5.00×10 <sup>-5</sup> to 3.30×10 <sup>-4</sup>	5.1 to 33.44	3.75×10 <sup>-5</sup> to 2.48×10 <sup>-4</sup>
simazine	4.63×10 <sup>-10</sup>	4.69×10 <sup>-5</sup>	3.47×10 <sup>-10</sup>
toxaphene	5.00×10 <sup>-3</sup> to 6.30×10 <sup>-2</sup>	507 to 6.38×10 <sup>+3</sup>	3.75×10 <sup>-3</sup> to 4.73×10 <sup>-2</sup>
<a href="http://www.epa.gov/OGWDW/dwh/t-soc/chemical_name_(i.e._24-D,_alachlor...).html">http://www.epa.gov/OGWDW/dwh/t-soc/chemical_name_(i.e._24-D,_alachlor...).html</a>			
The molar density of water at 293.160 K, C <sub>0</sub> = 55.41 kg-mole/m <sup>3</sup>			
The universal gas constant, R = 8.3145 Pa·m <sup>3</sup> /kg mol· K			
1 Pa = 9.86923 × 10 <sup>-6</sup> atm			

b. Units, as defined by Henry's law, as stated, are standard atmospheres [atm] with the concentration of the solute given as the mole fraction of the solution. Practical application of Henry's law has resulted in corruption of the units to the point of confusion, as seen in Table 1-1.

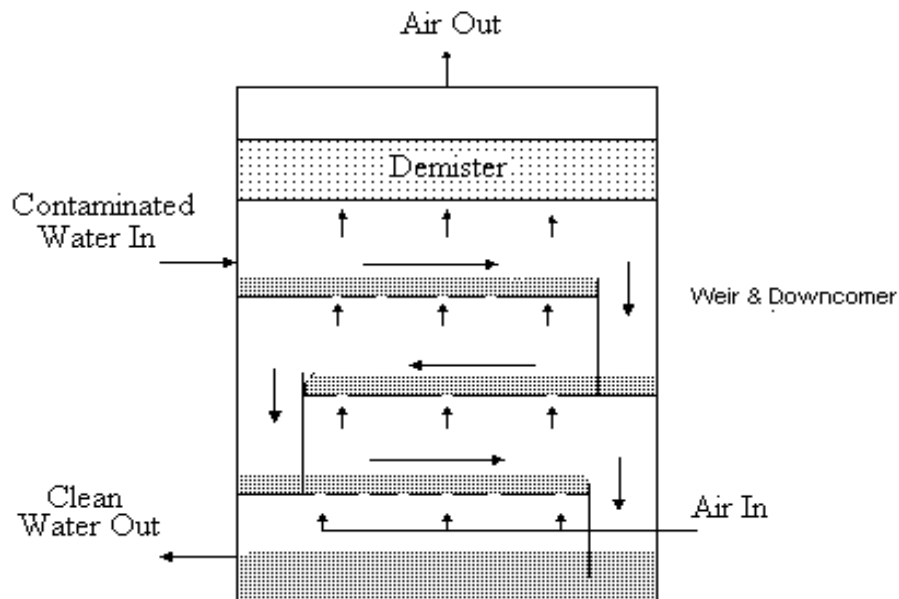
## CHAPTER 2 DESCRIPTION OF AIR STRIPPERS

**2-1. Packed Column Air Strippers.** Air strippers provide contact between air and water that encourages volatile materials to move from the water to the air. A packed column air stripper consists of a cylindrical column that contains a water distribution system above engineered (structured or dumped) packing with an air distributor below (see Figure 2-1). Water containing VOCs is distributed at the top of the column and flows generally downward through the packing material (Treybal, 1980). At the same time, air, introduced at the bottom of the column, flows upward through the packing (countercurrent flow). The packing provides an extended surface area and impedes the flow of both fluids, extending the contact between them. As water and air contact, VOCs move from the water to the air. The water leaves the bottom of the column depleted of VOCs. The VOCs transferred to the air exit the top of the column in the air stream. Off-gas (air) is released to the atmosphere or treated if necessary to meet emission limits. Detailed information on packed column air strippers is available in the literature (Kavanaugh and Trussell, 1980; Montgomery, 1985; Treybal, 1980).



**Figure 2-1. Packed column air stripper.**

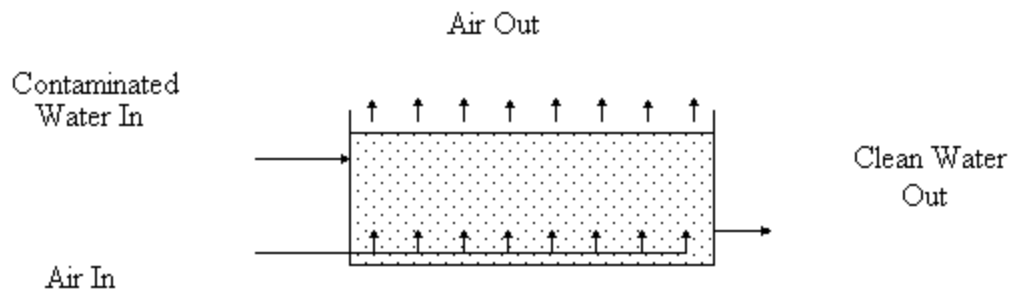
**2-2. Sieve Tray Air Stripper.** Sieve tray air strippers operate in a similar way to packed column air strippers (Figure 2-2). The difference is that the liquid (water) flows across trays that are perforated with small holes, over a weir, and through a downcomer, to the next lower tray, tray by tray, until the treated water flows from the bottom of the stripper. Gas (air) is bubbled through the holes in the trays, stopping the liquid from dripping through them. The VOCs are transferred from the liquid to the gas phase as the air is bubbled through the water on the trays. Detailed information on sieve tray units is available in the literature (Treybal, 1980).



**Figure 2-2. Low profile sieve tray air stripper.**

**2-3. Diffused Aeration Stripper.** A diffused aeration stripper is a vessel or liquid (water) reservoir with gas (air) diffusers near the bottom (Figure 2-3). Air enters through diffusers and rises through the liquid to exit at the top of the vessel. The VOCs move from the water to the air as the bubbles rise through the water. Transfer of the VOCs from the water to the air can be improved by increasing the vessel depth or by producing smaller bubbles. The air path through the liquid is straight and contact between the air and water is short. Therefore, diffused air is not efficient. Its main advantages are that it is simple and that it can handle water having high levels of suspended solids. Information on diffused aeration is available in the literature (Kavanaugh and Trussell, 1980; Patterson, 1985).





**Figure 2-3. Diffused aeration air stripper.**

## CHAPTER 3 DESIGN METHODS

**3-1. General.** The first step in designing an air stripper is to determine the extreme operating conditions: VOC concentrations allowed in the effluent, VOC concentrations in the influent, minimum liquid temperature, and influent flow rate (minimum and maximum). The next step is to calculate the total daily contaminant loading to the stripper and verify if the loading exceeds any regulation for discharge in the off-gas. A cost comparison (including water pre-treatment and off-gas treatment) is used to determine the optimum type of air stripper (packed column, low profile, or diffused aeration). Zoning regulations may limit stripper or stack height, or both. Manufacturers' software, commercial software, analytical equations, or graphical methods are used to size the air stripper, and are listed below.

**3-2. Packed Column.** Packed column air strippers are usually designed by the engineer and filled with commercially available plastic packing. The following methods are available for determining the size of a packed column air stripper:

- Analytical equations: Treybal (1980), Montgomery (1985), Shulka and Hicks (1984), Ball et al. (1984).
- Commercial software: "AirStrip," (Iowa State University, 1988).
- Manufacturer supplied software: Carbonair Environmental Systems, North East Environmental Products (see Paragraph A-5).
- McCabe-Thiele graphical method: McCabe et al. (1993), Treybal (1980).

**3-3. Sieve Tray.** Internal components of sieve tray air strippers, such as tray dimensions, hole diameter, and weir height, are different for each manufacturer. The manufacturer or fabricator designs sieve tray strippers. Each manufacturer has software designed specifically for their units. The following methods are available for determining the size of a low profile sieve tray air stripper:

- Analytical equations: Treybal (1980).
- Manufacturer supplied software: Carbonair Environmental Systems, North East Environmental Products (see Paragraph A-5).
- McCabe-Thiele graphical method: McCabe et al. (1993), Treybal (1980).

**3-4. Diffused Aeration.** Most "diffused aeration air strippers" are equalization basins with aeration added through diffusers to keep fine particulates in suspension. Unless the basins are extremely deep relative to their length and width, most of the "stripping" is attributable to surface diffusion. This phenomenon is caused by the short contact between the air and water and the lack of turbulence compared to engineered strippers. The effectiveness of diffused air

**DG 1110-1-3**  
**31 Oct 2001**

stripping has been extensively researched (Kyosai, 1991; Parker and Monteith, 1996; Sadek et al., 1996). Diffusers are designed by the diffuser manufacturer to transfer air into the water in combination with either separation of phases, as in dissolved air flotation (DAF), or mixing, as in activated sludge (AS). Water 8 (EPA, 1995) provides a model for evaluating the stripping potential of various aeration basin configurations.

## CHAPTER 4 TREATABILITY

**4-1. General.** Compounds with Henry's constant greater than 100 atm (moderate volatility) are generally amenable to air stripping.

**4-2. Fouling.** Retention or accumulation of solids within an air stripper is called fouling or scaling (these terms are used interchangeably). Bivalent metal ions frequently precipitate in air strippers. Influent that contains calcium (above 40 mg/L), magnesium (above 10 mg/L), iron (above 0.3 mg/L), or manganese (above 0.05 mg/L) may cause scaling (Hammer, 1975). When iron begins to precipitate, microbial growth increases the rate and amount of solids accumulation. Because the contact between air and water in any type of air stripper will result in oxidation, precautions are essential. Pre-treatment to remove interference, adding a chemical to prevent precipitation, or periodic cleaning of the air stripper to remove accumulation must be included in the design.

**4-3. Contaminant Effects.** Treatability studies are necessary when existing data are not adequate for predicting system performance and when interfering chemicals, such as alcohols, ketones, or surfactants, are present. A treatability study is needed in the rare instance when the concentration of the contaminant is in excess of one third of its solubility. Treatability studies are generally not required or recommended for standard air strippers operating within the range called for by the manufacturer of the trays or packing. However, if vapor pressure and solubility data for the contaminant are not available from references, such as Yaws (1994), or from the chemical manufacturer, a pilot study should be conducted.

**4-4. Loading Rate.** A pilot study is necessary if the anticipated loading rate of either air or water is outside the range for which design information is available. Manufacturers do not recommend operation outside the loading rate limits. Low hydraulic loading may cause low mass transfer efficiency. Increased air rates over the optimum are generally a waste of energy and may decrease the rate of water flow to the point of flooding.

**4-5. Diameter.** Even minor variations of the stripper diameter can have a significant effect on treatability. A change in diameter results in an inverse geometric effect on the loading and distribution of both air and water phases. "Safety factors" should be completely evaluated through the calculations to assure that the over-design does not adversely affect normal operation. Large-diameter towers are not generally available for treatability studies, so geometric similarity between the pilot scale and full scale is important.

**4-6. Treatability Study Scope.** A typical treatability study scope is included as Appendix B.

## CHAPTER 5 COMPARISON OF AIR STRIPPERS

**5-1. General.** The advantages and disadvantages of each type of stripper should be considered when making a selection. Either packed column or low profile air stripper will work in most situations, and are used extensively, but one may be more appropriate for the particular application. Diffused aeration strippers are less efficient for most applications, but their simplicity, ability to handle higher suspended solids, and better resistance to fouling are advantages. It may be necessary to do an economic analysis to help make the decision. Institutional factors, such as height restrictions or architectural restrictions, may require that a low profile air stripper be chosen even if a packed column stripper is more cost effective (see Table 5-1).

**5-2. Efficiency.** Packed column and low profile air strippers are capable of removing more than 99% of most VOC contaminants. Increasing the depth of the packing or the number of trays will increase the stripping. Increasing the airflow through a packed column may increase the efficiency. However, increasing the airflow beyond a certain point will induce a high pressure drop and will cause flooding.

**5-3. Fouling.** Air strippers frequently become fouled by mineral deposits when calcium exceeds 40 mg/L, iron exceeds 0.3 mg/L, magnesium exceeds 10 mg/L, or manganese exceeds 0.05 mg/L, or from biological growth. Air strippers may become plugged with solids that must be removed (Jaeger, Paragraph A-5). Packed column air strippers must either have the packing removed for cleaning or the packing must be washed with an acid solution (Jaeger, Paragraph A-5). Both operations are time consuming and costly. Low profile air strippers are often desirable when fouling is expected. Low profile units are often fastened together, tray by tray. Small units can easily be disassembled to physically remove the biological or mineral deposits. Larger units have access ports on the side of each tray for cleaning with a high-pressure water spray. Pre-treatment of the water prior to stripping is often required. Foaming control agents may be required for some liquids.

**Table 5-1  
Comparison of Air Strippers**

	<i>Packed Column</i>	<i>Low Profile</i>
Efficiency	Increases as packing height increases; 99%+	Increases as number of trays increases; 99%+
Cost	Lower at higher liquid flow rates	
Foam	Less foaming	
Air flow rates	Often use less air so air pollution devices, if needed, are smaller; wider range of air flow rates	
Fouling from calcium, iron, manganese suspended solids and biological growth		Easier to clean
Size	Tall	Compact; less conspicuous; better appearance

**5-4. Airflow Rate.** The ratio of air to water flow rates is generally lower for a packed column stripper than for a low profile air stripper for the same level of VOC removal. Packed column air strippers are typically operated at 5 to 250 cfm/ft<sup>2</sup> (1.5 to 76 (m<sup>3</sup>/min)/m<sup>2</sup>) of column cross-sectional area (Iowa State University, 1988). Low profile air strippers typically operate at 30 to 60 cfm/ft<sup>2</sup> (9 to 18 (m<sup>3</sup>/min)/m<sup>2</sup>) of tray area. Thus, the tray area of a low profile air stripper will usually be much larger than the tower cross-sectional area for the same treatment conditions. Low profile units are designed to operate over a fairly narrow range of airflow rates. If the airflow rate is too high for a low profile unit, the air blowing through the trays will form a jet and disperse most of the water. This results in low removal of the VOCs. If the airflow rate is too low, the water will flow down through the holes in the sieve trays. If the water flow rate decreases to a sieve tray as the result of changed operating conditions, the airflow rate through a low profile stripper cannot be reduced correspondingly, as it will be outside the operating range specified by the manufacturer. The cost of treating the off-gas will not be decreased in proportion with the liquid loading. Packed column air strippers can operate over a wide range of airflow rates. The advantage of this is that, if the water flow rate to the column decreases, the airflow rates can also be decreased. This will reduce the cost of treating the off-gas.

**5-5. Water Flow Rate.** In contrast to the airflow rate, the flow rate of water through a sieve tray unit will be between 1 and 15 gpm/ft<sup>2</sup> (0.04 to 0.6 (m<sup>3</sup>/min)/m<sup>2</sup>). Packed column strippers operate most efficiently over a narrow range of water flows, between 20 to 45 gpm/ft<sup>2</sup> (0.8 to 1.8 (m<sup>3</sup>/min)/m<sup>2</sup>) of tower cross-sectional area (Iowa State University, 1988). The manufacturer usually designs sieve tray air strippers. Items such as the length, location, and height of the

overflow weirs, weir geometry, clearance under the downcomer, fractional hold area, etc., are very important and must be designed by a manufacturer who is experienced with sieve tray columns. Additional trays can be added to many low profile air strippers if additional treatment is needed and the blower and motor are capable of handling the additional pressure drop from additional trays. Combining the airflow rate and the water flow rate results in an air-to water-ratio as low as 30 to as high as several hundred (volume to volume) (Carbonair, North East Environmental Products, Paragraph A-5) for sieve tray units.

**5-6. Pressure Drop and Power Consumption.** The pressure drop through the packing of a packed tower air stripper is often lower than the pressure drop through a comparable low profile unit. This allows a smaller blower and motor, with reduced electrical operating costs.

## CHAPTER 6 AIR POLLUTION CONTROL REQUIREMENTS

**6-1. General.** Off-gas from an air stripper may or may not need to be controlled, depending on the level of contaminants and on state and local regulations. If the loading of a contaminant or contaminants exceeds the amount allowed by regulation to be discharged to the air, treatment of the stripper off-gas will be required. This must be thoroughly evaluated, as air pollution controls will add major capital and O&M costs to the system. Packed columns use less air for a given loading of water and contaminant than do sieve tray air strippers. This is important when air pollution regulations require that the air leaving the unit be treated to remove the volatile organic chemicals before it is discharged to the atmosphere. In these cases, achieving the lowest airflow rate, and in turn the lowest air pollution control costs, may be the driving force in determining which type of air stripper to use.

$$x_{ai} L + y_{ai} G = x_{ae} L + y_{ae} G$$

which is the flow rate of contaminant  $a$ , where

- $L$  = molar flow of liquid (water)
- $G$  = molar flow of gas (air)
- $x_{ai}$  = mole fraction of contaminant  $a$  in influent liquid (water)
- $x_{ae}$  = mole fraction of contaminant  $a$  in effluent liquid (water)
- $y_{ai}$  = mole fraction of contaminant  $a$  in influent gas (air)
- $y_{ae}$  = mole fraction of contaminant  $a$  in effluent gas (air).

Assuming an uncontaminated air supply, we find:

$$y_{ai} = 0$$

$$x_{ai} L = x_{ae} L + y_{ae} G$$

Rearranging terms yields:

$$y_{ae} G = (x_{ai} - x_{ae}) L$$

$$\frac{G}{L} = \left( \frac{x_{ai} - x_{ae}}{y_{ae}} \right)$$

$$\% \text{ Removal} = \left( \frac{x_{ai} - x_{ae}}{x_{ai}} \right) 100\%$$

where



$p_{Te}$  = total pressure of gas(air) effluent  
 $p_{ae}$  = partial pressure of contaminant in a gas (air) effluent

From Dalton's Law of partial pressures,

$$y_{ae} = \frac{p_{ae}}{p_{Te}} \frac{\text{mole}}{\text{mole}}$$

At equilibrium, from Henry's law:

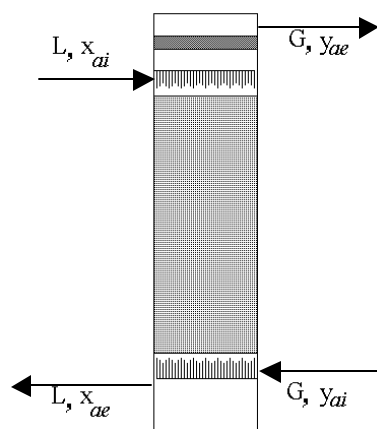
$$p_{ae} = H_a x_{ai} \text{ atm}$$

Substituting for  $p_{ae}$  yields:

$$y_{ae} p_{Te} = H_a x_{ai} \text{ atm}$$

$$y_{ae} = \frac{H_a x_{ai}}{p_{Te}} \text{ atm}$$

For the air pollution worst case, it must be assumed that all volatile contaminants introduced to the stripper are transferred to the air. The only positive control of pollutant transfer to the air is the rate of contaminated water pumped to the stripper.



**Figure 6-1. Material Balance.**

**6-2. Off-Gas Treatment.** Activated carbon and thermal oxidation are commonly used to treat the off-gas. The unit efficiency of either method is directly proportional to the concentration of the contaminant in the off-gas. Activated carbon is simple but does not destroy the contaminant and may result in potential disposal costs. Thermal oxidation destroys the contaminant but is more complex. Air pollution control devices should be evaluated before determining which device to use. “As can be expected, the lower the concentration [of VOCs] in the gas stream the higher the control cost” (Blaszczak, 1995).

**6-3. Innovative Air Pollution Control Devices.** Information on innovative air pollution control devices can be found in the *Remediation Technologies Screening Matrix and Reference Guide*.

## CHAPTER 7 FLOODING

**7-1. General.** Air strippers depend on a balance between air and water to provide the necessary intimate contact within the stripper. The induced turbulence within the system provides the energy required for separation of the volatile organics from the water. The air carries the volatiles away from the water.

**7-2. Occurrence of Flooding.** Excess airflow will cause flooding in air strippers, regardless of type. Extra blower head requirements (i.e., for “future” additional trays) should not be “thrown in” as a safety factor without providing an orifice plate to “burn up” the excess head. Obviously, if this is done, energy is wasted in oversizing.

**7-3. Blower.** A centrifugal blower can be modified to reduce the air output by changing or trimming the impellers. Impeller must be trimmed properly to maintain blower balance. Changing the blower sheaves and belts can change the speed and corresponding output of belt driven blowers.

## CHAPTER 8 PROCESS CONTROL

**8-1. General.** The pumps delivering the water and the blowers delivering the air are packaged with contacts, controllers, and appropriate alarms.

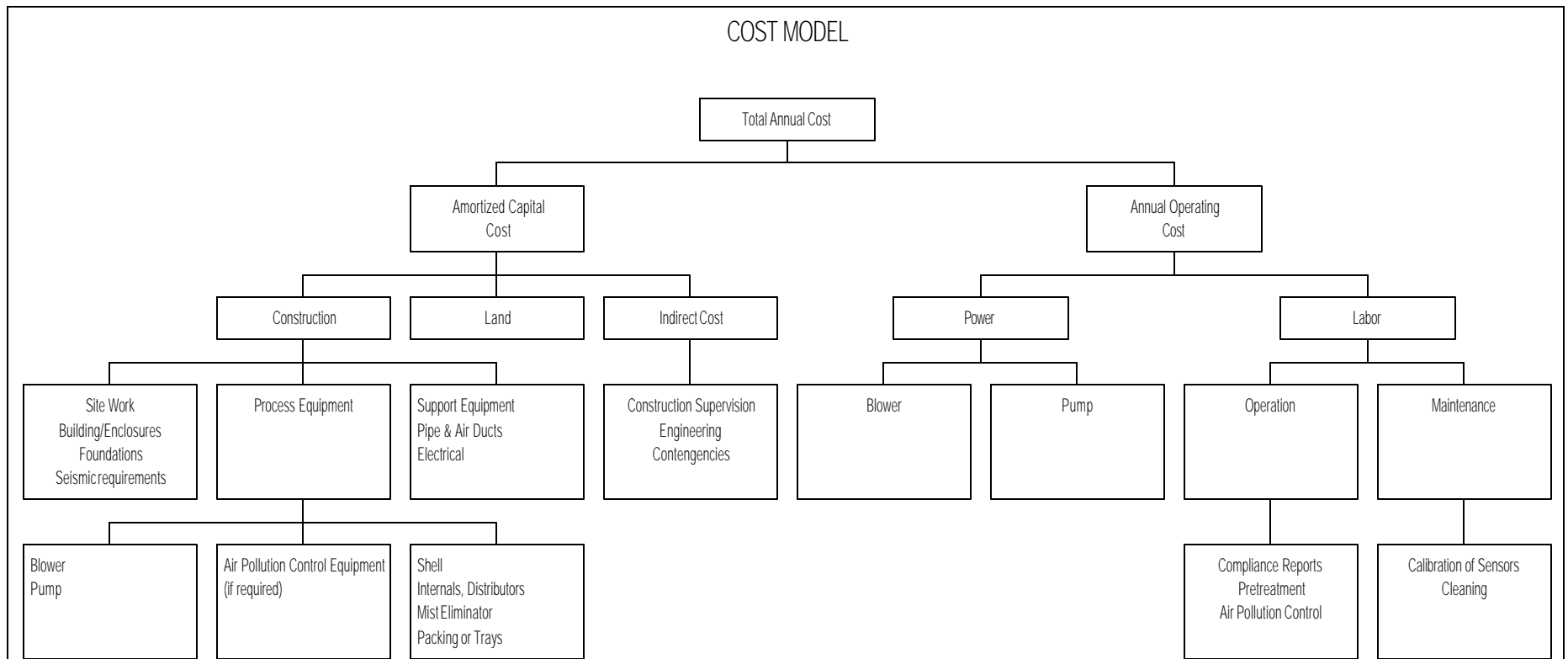
**8-2. Level Controls.** If the plant hydraulics or sampling requirements mandate that the effluent sump can not overflow, it must be equipped with level control and level alarms to prevent this. Feedback from the effluent sump level should turn the well or influent pumps down or off and activate an alarm when the sump level setting is exceeded. The controller for effluent pumps should allow alternating operation of lead, lag, and stand-by pumps, with low and high level alarms and pump control over-ride functions.

**8-3. Pressure Controls.** Feedback from the air stripper pressure sensors mounted in influent and effluent piping should turn down or shut off the blower and activate the alarm when the differential pressure across the stripper begins to rise. For energy economy, the blower control should also be interlocked with water flow to the stripper. The pressure differential disappears if the blower fails.

## **CHAPTER 9**

### **ECONOMIC EVALUATION**

Consider the advantages and disadvantages of each type of air stripper, along with capital costs, installation costs, and long term O&M, when the stripping system is designed (Ball et al., 1984). *Remedial Action Cost Engineering and Requirements System* (RACER, Paragraph A-5) software can be used to compare costs. RACER is an integrated, PC-based cost engineering software package developed and maintained by Talesman Partners. Costs for treating off-gas and fouling are major factors in the economic evaluation. Architectural restrictions may require a low profile air stripper or multiple strippers in series, even if a single packed tower stripper would, otherwise, be more cost effective. See Figure 9-1 for the cost model.



**Figure 9-1. Cost model.**

## **APPENDIX A REFERENCES**

### **A-1. Department of the Army.**

#### **AR 25-50**

Preparing and Managing Correspondence.

### **A-2. U.S. Army Corps of Engineers.**

#### **ER 385-1-92**

Safety and Occupational Health Requirements for Hazardous, Toxic, and Radioactive Waste (HTRW) and Ordnance and Explosive Waste (OEW) Activities.

#### **ER 1110-1-12**

Quality Management.

#### **ER 1110-1-263**

Chemical Data Quality Management for Hazardous, Toxic, and Radioactive Waste Remedial Activities.

#### **ER 1110-1-8155**

Design Analysis, Drawings and Specifications.

#### **ER 1110-3-1301**

Cost Engineering Policy Requirements for Hazardous, Toxic Radioactive Waste (HTRW) Remedial Action Cost Estimate.

#### **UFGS 01240**

Cost and Performance Report.

#### **UFGS 01351**

Safety, Health, and Emergency Response (HTRW/UST).

#### **UFGS 01450**

Chemical Data Quality Control.

#### **UFGS 02111**

Excavation and Handling of Contaminated Material.

DG 1110-1-3  
31 Oct 2001

**UFGS 02120**

Transportation and Disposal of Harardous Materials.

**UFGS 02150**

Piping: Off-Gas.

**UFGS 02521**

Water Wells.

**UFGS 11212**

Pumps: Water, Vertical Turbine.

**UFGS 11215**

Fans/Blowers/Pumps: Off- Gas.

**UFGS 11220**

Precipitation/Coagulation/Flocculation Water Treatment.

**UFGS 11226**

Vapor Phase Activated Carbon Units.

**UFGS 11242**

Chemical Feed Systems.

**UFGS 11243**

Chemical Treatment of Water for Mechanical Systems.

**UFGS 11301**

Air Stripper.

**UFGS 11360**

Plate and Frame Filter Press System.

**UFGS 11377**

Advanced Oxidation Process.

**UFGS 11378**

Thermal (Catalytic) Oxidation Systems.

**UFGS 11393**

Filtration System.



**UFGS 13405**

Process Control.

**UFGS15200**

Pipelines, Liquid Process Piping.

**A-3. Other Publications.**

**Avallone and Baumeister (1987)**

Avallone, E.A., and T. Baumeister III, *Marks Standard Handbook for Mechanical Engineers*, 9th Ed., McGraw-Hill, New York.

**Ball et al. (1984)**

Ball, W., M.D. Jones, and M.C. Kavanaugh, "Mass Transfer of Volatile Organic Compounds in Packed Tower Aeration," *Journal Water Pollution Control Federation*, **56**(2): 127–136.

**Blaszczak (1995)**

Blaszczak, B., "Technologies for Low Concentration Organic Vapor Gas Streams," *Control Technology Center News*, **7**(3): 1–2.

**Buonicore and Davis (1992)**

Buonicore, A.J., and W.T. Davis, *Air Pollution Engineering Manual*, Van Nostrand Reinhold, New York, pp. 31–52, 58–70.

**Hammer (1975)**

Hammer, M. J., *Water and Wastewater Technology*, John Wiley & Sons, New York, pp. 217–281.

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Kavanaugh, M., and R.R. Trussell, "Design of Aeration Towers to Strip Volatile Contaminants from Drinking Water," *Journal AWWA*, December, pp. 684–692.

**Kyosai (1991)**

Kyosai, S.R., "Effect of Water-Surface Desorption on Volatile Compound Removal under Bubble Aeration," *Research Journal WPCF*, **63**(6): 997–894.

**McCabe et al. (1993)**

McCabe, W.L., J.C. Smith, and P. Harriott, *Unit Operations of Chemical Engineering*, McGraw-Hill, New York, pp. 501–736.

**Montgomery (1985)**

James M. Montgomery, Consulting Engineers, Inc., *Water Treatment Principles & Design*, John Wiley & Sons, New York, pp. 237–261.

**NSF International (1999)**

NSF International, “Protocol for Equipment Verification Testing of Volatile Organic Chemical Removal,” NSF International, Ann Arbor, pp. 2-1–2-24.

**Parker and Monteith (1996)**

Parker, W.J., H.D. Monteith, “Stripping of VOCs from Dissolved Air Flotation,” *Environmental Progress*, **15**(2): 73–81.

**Patterson (1985)**

Patterson, J., *Industrial Wastewater Treatment Technology*, 2nd ed, Butterworths, Boston, Chap. 18.

**Perry (1984)**

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**Roberts et al. (1984)**

Roberts, P.V., C. Munz, and P. Dandliker, “Modeling Volatile Organic Solute Removal by Surface and Bubble Aeration,” *Journal Water Pollution Control Federation*, **56**(2): 157–163.

**Sadek et al. (1996)**

Sadek, S.E., J.D. Smith, A.T. Watkin, R. Gebel, “Mass Transfer of Volatile Organics from Large Open Basins,” *Environmental Progress*, **15**(2): 82–92

**Shulka and Hicks (1984)**

Shulka, H., and Hicks, R.E., “Process Design Manual for Stripping of Organics,” EPA-600/2-84-139

**Treybal (1980)**

Treybal, R., *Mass-Transfer Operations*, 3rd ed., McGraw-Hill, New York, pp. 275–313.

**Yaws (1994)**

Yaws, Carl L., *Handbook of Vapor Pressure*, Vol. 1–4, Gulf Publishing Company, Houston.

**A-5. Other Resources.**

Carbonair Environmental Systems, Inc., 2731 Nevada Avenue North, New Hope, MN 55427-2864, (612) 544-2154.

EPA (1995) "Water 8 Air Emissions Models Wastewater Treatment," Version 4.0.

<http://www.epa.gov/ttn/chief/software.html>.

EPA (1998) "How to Determine Henry's Law Constants."

[http://www.epa.gov/ttn/oarpg/tl/fr\\_notices/appj.pdf](http://www.epa.gov/ttn/oarpg/tl/fr_notices/appj.pdf)

EPA (1998) "Technical Fact Sheet Drinking Water and Health."

<http://www.epa.gov/OGWDW/dwh/t-soc/>

Federal Remediation Technologies Roundtable, "Remediation Technologies Screening Matrix and Reference Guide." U.S. Environmental Protection Agency, 401 M Street, S.W., Washington, D.C. 20460.

<http://www.frtr.gov>

Iowa State University (1988) "Air Strip, release 1.2," [dgschoel@iastate.edu](mailto:dgschoel@iastate.edu)

Jaeger Products, Inc. 1611 Peachleaf, Houston, TX 77039.

<http://www.jpadmin@jaeger.com/1006foul.htm>

National Center for Manufacturing Sciences (NCMS), 3025 Boardwalk, Ann Arbor, MI 48108-3266, "Solve DB."

<http://www.ncms.org>

North East Environmental Products, Inc., 17 Technology Drive, West Lebanon, NH 03784, (603) 298-7061.

Plambeck, James A. (1995) Updated November 3, 1996.

<http://www.Jim.Plambeck@ualberta.ca/>

"Remedial Action Cost Engineering and Requirements System (RACER)," Talisman Partners, Ltd., 5460 S. Quebec St. Suite 100, Englewood, CO 80111-1916.

## **APPENDIX B TREATABILITY STUDY SCOPE**

[Installation Name]

[Project]

[date]

## TABLE OF CONTENTS

<b>Subject</b>	<b>Paragraph</b>	<b>Page</b>
General	B-1	B-3
General Statement of Services	B-1 <i>a</i>	B-3
Qualifications	B-1 <i>b</i>	B-3
Reference Documents and Publications	B-2	B-3
Information	B-3	B-5
Quality	B-3 <i>a</i>	B-5
Confidentiality	B-3 <i>b</i>	B-5
Conflict of Interest	B-3 <i>c</i>	B-6
Services and Materials	B-3 <i>d</i>	B-6
Progress and Payments	B-4	B-6
Submittals, Meeting and Travel	B-5	B-6
Task 1: Treatability Study Work Plan	B-5 <i>a</i>	B-6
Task 2: Treatability Study Work Plan Review, Coordination, and Meeting Number 1	B-5 <i>b</i>	B-7
Task 3: Sample Collection, Preservation, Transportation Analyses Treatability Study Execution and Draft Report	B-5 <i>c</i>	B-7
Task 4: Draft Treatability Study Report Review, Coordination, and Meeting Number 2	B-5 <i>d</i>	B-7
Task 5: Final Treatability Study Report	B-5 <i>e</i>	B-7
Schedule	B-5 <i>f</i>	B-8
Format and Presentations	B-6	B-8
Technical Requirements	B-7	B-9
Technical Content	B-7 <i>a</i>	B-9
Technical Direction	B-7 <i>b</i>	B-9
Design Analysis	B-7 <i>c</i>	B-9
Drawings	B-7 <i>d</i>	B-9
Specifications	B-7 <i>e</i>	B-9
The Report	B-7 <i>f</i>	B-10
Project Records and File	B-8	B-10
Project File	B-8 <i>a</i>	B-10
Meeting Notes	B-8 <i>b</i>	B-10
Record Memos	B-8 <i>c</i>	B-11
Correspondence	B-8 <i>d</i>	B-11
Issues	B-8 <i>e</i>	B-11
Document Distribution	B-9	B-11

## **B-1. General.**

*a. General Statement of Services.* The U.S. Army Corps of Engineers (USACE), [ ] District, is contracting for Architect-Engineer (AE) services, including analytical support, to perform a treatability study and produce a treatability study report. The treatability study shall provide information to be included in the design analysis, on the drawings, and in the specifications. The technical feasibility of air stripping of the volatile HTRW contaminants from the [ground] water [extracted] from [ ] [site and project name] will be evaluated.

*b. Qualifications.* Qualifications shall be submitted with the treatability study work plan.

(1) *Process Engineer.* The AE shall submit the qualifications of the process (chemical, environmental, or mechanical) engineer designated to work on these documents. The engineer(s) shall have a minimum of [ ] [six (6)] years of process design experience, including [ ] [four (4)] projects that included treatability studies.

(2) *Laboratory.* The AE shall submit the qualifications of the laboratory designated to work on these documents. The chemist shall have a minimum of [ ] [six (6)] years of experience specific to treatability studies.

(a) *Chief Chemist.* Qualifications of the chief analytical chemist designated to oversee the analytical work shall be included in the work plan submittal. The chief chemist(s) shall have a minimum of six (6) years of experience, including four (4) years of organic chemical analyses.

(b) *Bench Chemists and Laboratory Technicians.* Qualifications of the chemists designated to work on these tasks shall be included in the work plan submittal.

(c) *Quality Assurance Laboratory Validation/Certification.* [ ] [certification for contaminants of concern] shall be included in the work plan submittal.

(3) *Project Manager.* This scope will be assigned an AE Project Manager (PM), to serve as the single point of contact (POC) for the [ ] District POC. Deviations, changes, and inadequacies related to the interim schedule or technical issues shall be immediately reported to the POC. Contractual questions related to this scope of services and compliance with delivery of the final manuscript shall be reported to the POC.

**B-2. Reference Documents and Publications.** Guidance and publications containing pertinent information include the following:

### **AR 25-50**

Preparing and Managing Correspondence, Appendix F.

**DG 1110-1-3**  
31 Oct 2001

**DG 1110-1-3**  
Air Stripping.

**ER 385-1-92**  
Safety and Occupational Health Document Requirements for Hazardous, Toxic and Radioactive Waste (HTRW) and Ordnance and Explosive Waste (OEW) Activities.

**ER 1110-1-12**  
Quality Management.

**ER 1110-1-263**  
Chemical Data Quality Management for HTRW Remedial Activities.

**ER 1110-345-700**  
Design Analysis, Drawings and Specifications.

**UFGS 01240**  
Cost and Performance Report.

**UFGS 01351**  
Safety, Health, And Emergency Response (HTRW/UST).

**UFGS 01450**  
Chemical Data Quality Control.

**UFGS 02150**  
Piping: Off-Gas.

**UFGS 02521**  
Water Wells.

**UFGS 11215**  
Fans/Blowers/Pumps; Off- Gas.

**UFGS 11220**  
Precipitation/Coagulation/Flocculation Water Treatment.

**UFGS 11226**  
Vapor Phase Activated Carbon Adsorption Units.

**UFGS 11242**  
Chemical Feed Systems.

**UFGS 11301**

Air Stripper.

**UFGS 11360**

Plate And Frame Filter Press System.

**UFGS 11377**

Advanced Oxidation Processes (AOP).

**UFGS 11378**

Thermal (Catalytic) Oxidation Systems.

**UFGS 11393**

Filtration System.

**UFGS 13405**

Process Control.

**UFGS 15200**

Pipelines, Liquid Process Piping.

In addition, industry and commercial standards—ASTM, ANSI, and ASME—included in the above references are useful and necessary.

**B-3. Information.**

*a. Quality.* Quality management shall be in accordance with ER 1110-1-12. The AE is responsible for completeness and accuracy of all work performed under this scope, and for compliance with all parts of the scope. Comprehensive quality control reviews shall be performed for accuracy, completeness of the work, compliance with the scope, and satisfaction of the scope requirements relating to quality of work performed. The Government relies upon the professional quality of the work that the AE will perform.

(1) *Completeness of Work.* The AE shall correct all deficiencies identified by the quality control review and by any other Government reviewers.

(2) *Accuracy of Work.* The AE shall verify all data and check all calculations in the quality control review. The AE shall correct all inaccuracies and errors identified by reviewers and by the AE quality control review.

*b. Confidentiality.* Documents and information developed or obtained in performance of the



work shall be considered privileged information of the United States Government. The AE shall not release information to anyone other than his/her own officers, employees, and agents who need to have access to the information to perform the work, and to U.S. Government officers designated by the POC. Requests for release of any of the information shall be referred to the POC for reply. The obligation to maintain the confidentiality of this information shall extend beyond the completion of this scope until released by the POC or determined by a Federal court of competent jurisdiction

c. *Conflict of Interest.* Prior to proposal submission, AE and subcontractor employees with access to the information and documents shall identify any potential conflicts of interest with the requirements of this scope. Any past or ongoing work conducted by, or involving, the AE, subcontractor(s), or respective personnel, for the Corps of Engineers, EPA, or other regulatory agencies regarding services required by this scope, may be considered as a conflict of interest. If the potential for a conflict exists, the USACE must be notified when it is discovered for a determination of eligibility for award of this scope. A statement on the potential for conflicts must be provided with the proposal for this scope.

d. *Services and Materials.* All labor, travel, and work described in the scope shall be supplied. All services, supplies, materials, equipment, plants, labors, and travel necessary to perform the work and render the data required under this scope are required to be furnished. Included are laboratory equipment, microcomputers, commercial software packages, modems, and facsimile (FAX) machines required to perform the work.

**B-4. Progress and Payments.** The AE shall submit progress reports with each payment request. Each listed task shall be completed and approved prior to commencing work on the next listed task. Scheduled and actual performance and task completion dates should be reported. Final payment on this delivery order will be made after all work is completed in compliance with the Delivery Order, after all required documentation has been submitted by the AE, and after all government audits and reviews have been completed.

**B-5. Submittals, Meetings, and Travel.** Personnel may be required to travel to attend meetings scheduled at the [ ] Offices, [ ], [ ], as part of this delivery order. Responsible representatives, approved by USACE for participation in the pilot study, shall attend the indicated meetings. The AE shall annotate comments and prepare meeting notes for each review meeting. Costs associated with travel shall be separately itemized in the delivery order cost. The AE shall assume, for purposes of negotiation, that [two] [three] people from the firm will attend each meeting.

a. *Task 1: Treatability Study Work Plan.* The AE shall review the criteria prior to preparing the initial submittal. The work plan will include:

- An execution plan for development of the treatability study in accordance with the criteria,

with explanatory text and notes and a detailed outline of the suggested technical requirements for each of the sections.

- The laboratory, the equipment, and personnel for accomplishing each effort.
- A schedule of the milestones to be accomplished.
- An organization chart with resumes, describing the qualifications of the personnel developing the document.
- The quality control plan describing internal reviews and technical editing responsibilities.
- A detailed outline for treatability study report.

The execution plan shall identify the resources the AE intends to use for accomplishing each effort.

*b. Task 2: Treatability Study Work Plan Review, Coordination, and Meeting Number 1.* Appropriate personnel shall attend a review meeting to address various subjects pertaining to the treatability study after receiving USACE comments on the work plan. Comments will be forwarded in advance to allow annotation prior to the meeting. A copy of the annotated comments shall be forwarded along with major points requiring discussion prior to the review meeting. Appropriate personnel shall make a presentation of the plan, the outline, total effort, content, and the work accomplished to date. Appropriate personnel shall participate in discussion designed to ensure understanding of the agency goals. The result of this meeting will be further USACE guidance and direction to proceed. Responsible team personnel shall be identified for approval in this preliminary meeting. Revisions to the execution plan may be required as a result of this meeting.

*c. Task 3: Sample Collection, Preservation, Transportation, Analyses, Treatability Study Execution and Draft Report.* The study shall be performed and a full draft of the treatability study report shall be prepared, in accordance with guidance and direction received at the initial submittal meeting, which shall be submitted for USACE review and approval.

*d. Task 4: Draft Treatability Study Report Review, Coordination, and Meeting Number 2.* Appropriate personnel shall attend a review meeting to address various subjects pertaining to the treatability study after receiving USACE comments on the draft report. Comments will be forwarded in advance to allow annotation prior to the meeting. A copy of the annotated comments shall be forwarded along with major points requiring discussion prior to the review meeting. Appropriate personnel shall make a presentation of the report and participate in discussion designed to ensure understanding of the agency goals. Revisions to the report may be required as a result of this meeting. Technical personnel shall participate in discussion with USACE personnel regarding comments and revisions to the draft report. The meeting will result in USACE direction for the AE to complete the final report.

*e. Task 5: Final Treatability Study Report.* The report shall be completed for implementation and record purposes in accordance with this scope of services. The final report will incorporate

all approved comments generated by review of previous submittals, any revisions in the format, technical content, grammar, or as otherwise required to ensure that the documents are in the proper form.

*f. Schedule.* The publication document is required 423 calendar days from the notice to proceed. A schedule proposed to achieve that result follows:

<i>Scheduled Task</i>	<i>Day of Required Completion</i>
Notice to Proceed	CD [ ]
Task 1: Work Plan	CD [ ]
Task 2: Work Plan Review, Coordination, and Meeting Number 1	CD [ ]
Task 3: Sample Collection, Preservation, Transportation, Treatability Study Execution and Draft Report	CD [ ]
Task 4: Draft Treatability Study Report Review, Coordination, and Meeting Number 2	CD [ ]
Task 5: Final Report	CD [ ]
Total calendar days	CD [ ]

**B-6. Format and Presentations.**

*a.* The report shall be marked as to the stage of development, i.e., preliminary draft, second draft, and final, by header or footer at the right margin of each page. The stage markings shall be removed from the final document. The signed and approved publication document shall be converted to PDF format by AE.

*b.* Text shall conform as completely as is feasible to Chapter IV of AR 25-50.

*c.* Documents will be prepared on IBM compatible magnetic media using Microsoft Word, Times New Roman 10 point, twelve (12) characters per inch, with left and right margins on 8-1/2 × 11 inch pages equal to one (1) inch. Drafts shall be double-spaced. Page numbers shall be centered at the bottom of each page. Header and footers shall be mirror images on facing pages. Final and publication copies shall be double sided print.

*d.* Submittals may be electronic or high quality print hard copy suitable for reproduction. Hard copy submittals shall be stapled, except one copy to the POC shall not be stapled or fastened in any way. Documents shall not be bound with plastic.

e. A cover page on draft documents shall identify the Corps of Engineers, HTRW-CX, Omaha, NE, Control Number, the AE, and the date. This page will not be included on the publication and PDF copies.

f. Submittals shall incorporate all previous review comments and shall be complete and not just copies of affected pages. Disposition of each review comments shall be documented and shall be marked as follows:

- “A” approved and will be incorporated.
- “D” disapproved.
- “W” withdrawn by the government with the approval of the originator.
- “E” exception as noted

## **B-7. Technical Requirements.**

a. *Technical Content.*

b. *Technical Direction.* ER 1110-345-700, *Design Analysis, Drawings and Specifications*, outlines the standard documents for construction contracts.

c. *Design Analysis.* Reasoning is presented in the design analysis text, with supporting calculations included in appendices. The treatability study report shall support the sizing of the air stripper and preparation of the design calculations, design analysis, plans, and specifications for the air stripping system without need to refer to other documents for analytical or treatability data.

d. *Drawings.* The drawings must clearly depict the existing layout, show the materials to be treated, indicate any site restraints, and show the desired restoration.

e. *Specifications.* UFGS 01351, *Safety, Health, and Emergency Response (HTRW/UST)*, and UFGS 01450, *Chemical Data Quality Control*, cover the health and safety and chemistry, respectively. Duplicate or overlapping coverage of either topic is expressly prohibited. UFGS 02111, *Excavation and Handling of Contaminated Material*, covers excavation of the contaminated material. UFGS 02120, *Transportation and Disposal of Hazardous Materials*, covers disposal of any contaminated residuals that will not remain on site.

### **UFGS 02150**

Piping: Off-Gas.

### **UFGS 11211**

Pumps: Water, Centrifugal.

**UFGS 11212**

Pumps: Water, Vertical Turbine.

**UFGS 11215**

Fans/Blowers/Pumps; Off-Gas.

**UFGS 11220**

Precipitation/Coagulation/Flocculation Water Treatment.

**UFGS 11226**

Vapor Phase Activated Carbon Adsorption Units.

**UFGS 11242**

Chemical Feed Systems.

**UFGS 11243**

Chemical Treatment of Water for Mechanical Systems.

**UFGS 11250**

Water Softeners, Cation-Exchange (Sodium Cycle).

**UFGS 11301**

Air Stripper.

**UFGS 11378**

Thermal (Catalytic) Oxidation Systems.

*f. The Report.* The AE shall edit the material to clearly support the designer in translation of the treatability study data into clear contract requirements.

**B-8. Project Records and File.**

*a. Project File.* The AE shall assemble all memos and records obtained or developed by the AE in the performance of this scope. The AE shall make an index of all project records, which shall be complete at the completion of this scope. The AE shall organize these records using a chronological method with a supplementary topic index. At the completion of the work under this scope, the AE shall place the originals of all project records, including the index, in secure boxes, mark the boxes with the control number, and send them to the POC. The AE shall not retain copies of any of the correspondence and records without written permission from the POC.

*b. Meeting Notes.* The AE shall be responsible for taking notes and preparing the reports for all meetings. Meeting notes shall be prepared in typed form and the original furnished to the

POC (within 10 working days after the date of the meeting) for concurrence and distribution. Each meeting report shall include, as a minimum:

- Project name and control number.
- Date and location of the meeting.
- Attendance list, including each the name of each attendee with the organization and telephone number.
- Written comments with the action noted shall be attached to each copy of the report.
- Discussion items.

*c. Record Memos.* The AE shall provide a record or file memo of each contact, meeting, conference, discussion, telephone conversation, or verbal directive that the AE or any employees of the AE participate in regarding the subject documents, irrespective of who the other participants may have been. Records and memos shall be dated and shall identify the participants, subjects discussed, and conclusions reached. The memos shall be numbered sequentially and shall be incorporated in the project file. A copy of all memos shall be submitted monthly to the POC (do not duplicate these submittals).

*d. Correspondence.* The AE shall keep a record of each piece of written correspondence related to the performance of this Delivery Order. The pieces of correspondence shall be numbered sequentially and shall be incorporated in the project file as described in paragraph B-8a. Any distribution of said correspondence will be made by the District.

*e. Issues.* Issues requiring Corps action or response and issues concerning the schedule shall be highlighted by a letter to the POC or [ ] per paragraph B-1b(3).

**B-9. Document Distribution.** Unless otherwise directed, all submittals and review material shall be submitted to the addresses at Table B-1:

**Table B-1  
 Distribution**

Number of Copies	Item	Addressee
1 1 4 4 2 2	Memos Meeting Notes Work Plan Draft Report Final Report Diskette	Commander U.S. Army Corps of Engineers U.S. Army Engineer District, [ ] [ ] [City], [State] [Zip]
2 2 1	Work Plan Draft Report Final Report	Commander U.S. Army Corps of Engineers ATTN: CENWO-HX (Technical Manager) 12565 West Center Road Omaha, NE 68144-3869

## APPENDIX C

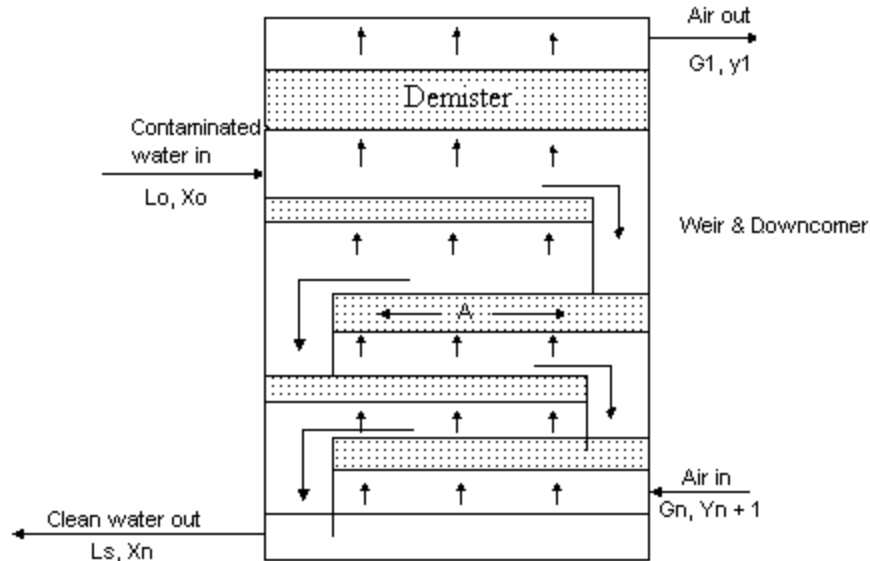
### EXAMPLES OF AIR STRIPPING BY LOW PROFILE SIEVE TRAY DEVICE

**C-1. Example in SI Units.** This example will illustrate a method of making preliminary design calculations to size a low profile sieve tray air stripper. Final designs depend heavily on the design of the trays. Unfortunately, this information is often not available to the designer. As a result, the final design and size of the unit must be determined from information supplied by the manufacturer. Low profile sieve tray air strippers are usually secured as complete units assembled on skids at the factory and shipped as a unit rather than being designed and constructed from job drawings and specifications. The steps in the preliminary design calculations follow (refer to Figure C-1).

- Determine the minimum and maximum volume of water to be air stripped, the minimum temperature of the water, and the maximum concentration of volatile organic chemicals (VOC) in the untreated water to be air stripped.
- Determine the desired concentration (percent removed) of the VOC in the treated water.
- Calculate the theoretical number of sieve trays needed to remove the VOC to the desired concentration.
- Estimate the tray efficiency and the number of actual trays needed.
- Estimate the size (cross-sectional area) of the perforated plate section of each tray.
- Estimate the pressure drop through the air stripper.
- Estimate the size of the air blower motor (kW).

*a. Determine the volume of water to be air stripped, the minimum temperature of the water, and concentration of all the volatile organic chemicals (VOC) in the untreated water. The inlet water contains 10 mg/L of the volatile organic chemical (VOC) trichloroethylene (TCE). (Note: If the inlet water contains more than one VOC, repeat the process for each to estimate the number of trays needed for each VOC. Use the largest number of trays for the estimated design.) The flow rate of water to be treated is 0.2 m<sup>3</sup> per minute. The minimum temperature of the water is 20°C.*





**Figure C-1. Cross-sectional area of perforated plate section.**

*b. Determine the desired concentration of the TCE in the treated water. The desired concentration of TCE in the discharge water is 0.1 mg/L (99% removal).*

*c. Calculate the theoretical number of sieve trays needed to remove the VOC to the desired concentration. The theoretical number of trays required is estimated by using the following relationship (Treybal, 1980):*

$$N_{\text{theoretical}} = \frac{\log \left[ \frac{X_0 - \frac{Y_{n+1}}{m} \left( 1 - \frac{1}{S} \right) + \frac{1}{S}}{X_n - \frac{Y_{n+1}}{m}} \right]}{\log S}$$

where

- $X_0$  = concentration of contaminant (TCE) in the inlet water phase: 10 mg/L  
 $X_n$  = concentration of contaminant (TCE) in the treated water phase: 0.1 mg/L

- $N$  = number of theoretical plates. Assumes that the liquid on each plate is completely mixed and that the vapor leaving the plates is in equilibrium with the liquid.
- $H$  = Henry's constant (kPa)
- $m$  = slope of equilibrium curve ( $H/Pt$ )
- $G$  = kg-moles air/min
- $L$  = kg-moles of water/min
- $Pt$  = ambient pressure (kPa)
- $S$  = stripping factor ( $mG/L$ )
- $Y_{n+1}$  = concentration of volatiles in the air entering the air stripper.

(1) For air stripping  $Y_{n+1} = 0$  (the concentration of TCE in the air entering the air stripper is zero) and the equation becomes:

$$N_{\text{theoretical}} = \frac{\log \left[ \frac{(X_0)}{(X_n)} \left( 1 - \frac{1}{S} \right) + \frac{1}{S} \right]}{\log S}$$

(2) In this example, the inlet concentration of TCE ( $X_0$ ), the desired outlet concentration of TCE ( $X_n$ ), the liquid temperature, and flow rate are known. The airflow rate ( $G$ ) must be determined and is related to the perforated plate area of each tray. Several combinations of airflow rates and number of trays should be calculated to determine the best economic balance between having more trays and a lower airflow rate (higher capital costs vs. lower operating costs) and fewer trays and a higher air flow rate (lower capital costs vs. higher operating costs). An economic comparison is beyond the scope of this example. For this example use an air-to-water ratio of  $37 \text{ m}^3$  of air to  $1 \text{ m}^3$  of water (see paragraph 5-5).

(3) Substituting into the above equation yields:

$$H = 5.57 \times 10^4 \text{ kPa (for TCE at } 20^\circ\text{C)}$$

$$Pt = 101 \text{ kPa (101 kPa at sea level, 86 kPa at 1500 m elevation)}$$

$$m = \frac{H}{Pt} = \left( \frac{5.57 \times 10^4 \text{ kPa}}{101 \text{ kPa}} \right) = 551 \frac{\text{mole H}_2\text{O}}{\text{mole}} = \frac{551 \text{ kgmole H}_2\text{O}}{\text{kgmole air}}$$

$$G = \frac{37 \text{ m}^3 \text{ air}}{\text{min}} \times \frac{\text{kg - mole air}}{24.0 \text{ m}^3 \text{ air @ } 20^\circ\text{C}} = 1.54 \frac{\text{kg - mole air}}{\text{min}}$$

$$L = \frac{1 \text{ m}^3 \text{ H}_2\text{O}}{\text{min}} \times \frac{1000 \text{ kg H}_2\text{O}}{\text{m}^3 \text{ H}_2\text{O}} \times \frac{\text{kg mole H}_2\text{O}}{18 \text{ kg H}_2\text{O}} = \frac{55.6 \text{ kg - mole H}_2\text{O}}{\text{min}}$$

$$S = \left( \frac{551 \text{ kg mole H}_2\text{O}}{\text{kg mole air}} \right) \left( \frac{1.54 \text{ kg mole air}}{\text{min}} \right) \left( \frac{55.6 \text{ kg mole water}}{\text{min}} \right)$$

$$= 15.3$$

$$N_{\text{theor}} = \frac{\log \left[ \frac{10 \frac{\text{mg}}{\text{L}}}{0.1 \frac{\text{mg}}{\text{L}}} \times \left( 1 - \frac{1}{15.3} \right) + \frac{1}{15.3} \right]}{\log 15.3} = 1.66$$

d. Estimate the tray efficiency and the number of actual trays needed. In actual practice a condition of complete equilibrium does not exist. The overall plate efficiency is:

$$E = \frac{N_{\text{theoretical}}}{N_{\text{actual}}}$$

Rearranging gives the number of actual trays as:

$$N_{\text{actual}} = \frac{N_{\text{theoretical}}}{E}$$

The efficiency is highly dependent on the design of the trays and the vapor flow rate. From manufacturer's data, the appropriate range appears to be  $E = 0.4$  to  $0.6$  (i.e., 40 to 60% efficient). Using the above relationship and assuming 50% tray efficiency, and substituting into the above equation, gives the number of actual trays needed as:

$$N_{\text{actual}} = \frac{1.66}{0.50} = 3.32 = 4$$

e. Estimate the size (cross-sectional area) of the perforated plate section of each tray. The cross-sectional area of the perforated plate section of each tray is related to the airflow rate; 9 to 18 m<sup>3</sup> per minute per m<sup>2</sup> of tray area is common (see Paragraph 5-4). For this example, use 18 m<sup>3</sup> per minute per m<sup>2</sup> of tray area. The area is:

$$\frac{0.2 \text{ m}^3 \text{ H}_2\text{O}}{\text{min}} \times \frac{37 \text{ m}^3 \text{ air}}{\text{m}^3 \text{ H}_2\text{O}} \times \frac{\text{m}^2 \text{ plate area}}{18 \text{ m}^3 \frac{\text{air}}{\text{min}}} = 0.41 \text{ m}^2$$

Estimate that the downcomer and weir area is 20% of each plate. The total cross-sectional area of each plate is:

$$0.41 \text{ m}^2 + 0.41 \times 0.2 \text{ m}^2 = 0.49 \text{ m}^2$$

*f. Estimate the pressure drop through the air stripper.* Most of the pressure drop through the air stripper is from the head of liquid on each tray times the number of trays. The depth of liquid on the trays typically varies from 8 to 12 cm of water. Assume 10 cm water for this example. The other pressure drop is from the piping from the blower to the air stripper and inlet and exit losses in the column. This will vary from system to system. An estimate for these losses is 25 cm water. From this information, the total pressure drop through the system is as follows:

$$N \text{ trays} = 3.32; \text{ round up to } 4$$

$$4 \text{ trays} \times 10 \text{ cm} \frac{\text{H}_2\text{O}}{\text{tray}} + 25 \text{ cm H}_2\text{O} = 65 \text{ cm H}_2\text{O}$$

*g. Estimate the size of the blower motor (kW).* The size of the blower motor is a function of the flow rate of air and the pressure drop. Methods of estimating the size of the blower motor can be found in reference books (McCabe et al., 1993; Avallone and Baumeister, 1987; Perry, 1984) and will not be calculated in this example.

**C-2. Example in English Units.** This example will illustrate a method of making preliminary design calculations to size a low profile sieve tray air stripper. Final designs depend heavily on the design of the trays. Unfortunately, this information is often not available to the designer. As a result, the final design and size of the unit must be determined from information supplied by the manufacturer. Low profile sieve tray air strippers are usually secured as complete units assembled on skids at the factory and shipped as a unit rather than being designed and constructed from job drawings and specifications. The steps in the preliminary design calculations follow (refer to Figure C-1).

- Determine the minimum and maximum volume of water to be air stripped, the minimum temperature of the water, and the maximum concentration of volatile organic chemicals (VOC) in the untreated water to be air stripped.
- Determine the desired concentration (percent removed) of the VOC in the treated water.

- Calculate the theoretical number of sieve trays needed to remove the VOC to the desired concentration.
- Estimate the tray efficiency and the number of actual trays needed.
- Estimate the size (cross-sectional area) of the perforated plate section of each tray.
- Estimate the pressure drop through the air stripper.
- Estimate the size of the blower motor (hp).

a. Determine the volume of water to be air stripped, the minimum temperature of the water and concentration of all the volatile organic chemicals (VOC) in the untreated water. The inlet water contains 10 mg/L of the volatile organic chemical (VOC) trichloroethylene (TCE). (Note: If the inlet water contains more than one VOC, repeat the process for each to estimate the number of trays needed for each VOC. Use the largest number of trays for the estimated design.) The flow rate of water to be treated is 50 gpm. The minimum temperature of the water is 60°F.

b. Determine the desired concentration of the TCE in the treated water. The desired concentration of TCE in the discharge water is 0.1 mg/L (99% removal).

c. Calculate the theoretical number of sieve trays needed to remove the VOC to the desired concentration. The theoretical number of trays required is estimated by using the following relationship (Treybal, 1980):

$$N_{\text{theoretical}} = \frac{\log \left[ \frac{\left( X_0 - \frac{Y_{n+1}}{m} \right) \left( 1 - \frac{1}{S} \right) + \frac{1}{S}}{\left( X_n - \frac{Y_{n+1}}{m} \right)} \right]}{\log S}$$

where

- $X_0$  = concentration of contaminant (TCE) in the inlet water phase: 10 mg/L  
 $X_n$  = concentration of contaminant (TCE) in the treated water phase: 0.1 mg/L  
 $N$  = number of theoretical plates. Assumes that the liquid on each plate is completely mixed and that the vapor leaving the plates is in equilibrium with the liquid.  
 $H$  = Henry's Constant (atm)  
 $m$  = slope of equilibrium curve ( $H/P_t$ )

- $G$  = lb- moles air/min  
 $L$  = lb- moles of water/min  
 $S$  = stripping factor ( $mG/L$ )  
 $Pt$  = ambient pressure (atm)  
 $Y_{n+1}$  = concentration of volatiles in the air entering the air stripper.

(1) For air stripping  $Y_{n+1} = 0$  (the concentration of TCE in the air entering the air stripper is zero) and the equation becomes:

$$N_{\text{theoretical}} = \frac{\log \left[ \left( \frac{X_0}{X_n} \right) \left( 1 - \frac{1}{S} \right) + \frac{1}{S} \right]}{\log S}$$

(2) In this example, the inlet concentration of TCE ( $X_0$ ), the desired outlet concentration of TCE ( $X_n$ ), and the liquid temperature and flow rate are known. The airflow rate ( $G$ ) must be determined and is related to the perforated plate area of each tray. Several combinations of air flow rates and number of trays should be calculated to determine the best economic balance between having more trays and a lower air flow rate (higher capital costs vs. lower operating costs) and fewer trays and a higher air flow rate (lower capital costs vs. higher operating costs). An economic comparison is beyond the scope of this example. For this example use an air-to-water ratio of 5 cfm of air to 1 gpm of water.

(3) Substituting into the above equation yields (for TCE at 20°C):

$$H = 550 \text{ atm}$$

$$Pt = 1.0 \text{ atm (Note: } 1.0 \text{ atm at sea level, } 0.86 \text{ atm at } 5000 \text{ ft)}$$

$$m = \frac{H}{Pt} = \frac{550 \text{ atm}}{1 \text{ atm}} = \frac{550 \text{ lb-mole H}_2\text{O}}{\text{lb-mole air}}$$

$$G = \frac{5 \text{ ft}^3}{\text{min}} \times \frac{\text{lb-mole air}}{380 \text{ ft}^3 \text{ air (@ } 60^\circ \text{ F)}} = 0.0132 \frac{\text{lb-mole air}}{\text{min}}$$

$$L = \frac{1 \text{ gal}}{\text{min}} \times \frac{8.34 \text{ lb H}_2\text{O}}{\text{gal H}_2\text{O}} \times \frac{\text{lb-mole H}_2\text{O}}{18 \text{ lb}} = \frac{0.463 \text{ lb-mole H}_2\text{O}}{\text{min}}$$

$$S = \frac{550 \text{ lb-mole H}_2\text{O}}{1 \text{ lb-mole air}} \times \frac{0.0132 \text{ lb-mole/min}}{0.463 \text{ lb-mole/min}} = 15.7$$

$$N_{\text{theor}} = \frac{\log \left[ \frac{10 \frac{\text{mg}}{\text{L}}}{0.1 \frac{\text{mg}}{\text{L}}} \times \left( 1 - \frac{1}{15.7} \right) + \frac{1}{15.7} \right]}{\log 15.7} = 1.65$$

d. Estimate the tray efficiency and the number of actual trays needed. In actual practice, a condition of complete equilibrium does not exist. The overall plate efficiency is:

$$E = \frac{N_{\text{theoretical}}}{N_{\text{actual}}}$$

Rearranging gives the number of actual trays as:

$$N_{\text{actual}} = \frac{N_{\text{theoretical}}}{E}$$

The efficiency is highly dependent on the design of the trays and the vapor flow rate. From manufacturer's data, the appropriate range appears to be  $E = 0.4$  to  $0.6$  (i.e. 40 to 60% efficient). Using the above relationship and assuming 50% tray efficiency, and substituting into the above equation, gives the number of actual trays needed as:

$$N_{\text{actual}} = \frac{1.65}{0.50} = 3.3 = 4$$

e. Estimate the size (cross-sectional area) of the perforated plate section of each tray. The cross-sectional area of the perforated plate section of each tray is related to the airflow rate; 30 to 60  $\text{cfm/ft}^2$  is common (see Paragraph 5-4) For this example, use 60  $\text{cfm/ft}^2$ . Using this and the air-to-water ratio of 5  $\text{cfm}$  of air to 1  $\text{gpm}$  of water and the water flowrate of 50  $\text{gpm}$  gives the cross-sectional area as

$$50\text{gpm} \times \frac{5\text{cfm}}{1\text{gpm}} = 250\text{cfm}$$

$$250\text{cfm} \times \frac{1\text{ft}^2}{60\text{cfm}} = 4.17\text{ft}^2$$

Estimate that the downcomer and weir area is 20% of each plate. The total cross-sectional area of each plate is:

$$4.17 + 4.17 \times 0.2 = 5.0\text{ft}^2$$

*f. Estimate the pressure drop through the air stripper.* Most of the pressure drop through the air stripper is from the head of liquid on each tray times the number of trays. The depth of liquid on the trays typically varies from 3 to 5 in. of water. Assume 4 in. for this example. The pressure drop from the air flowing through the holes in the sieve tray is usually insignificant to the other pressure drops in the system and will be ignored for this example. The other pressure drop is from the piping from the blower to the air stripper and inlet and exit losses in the column. This will vary from system to system. An estimate for these losses is 10 in. From this information the total pressure drop through the system is as follows:

$$N \text{ trays} = 3.3; \text{ round up to } 4$$

$$4 \text{ trays} \times 4\text{in. wg} \frac{\text{H}_2\text{O}}{\text{tray}} + 10\text{in. wgH}_2\text{O} = 26\text{in. wgH}_2\text{O}$$

*g. Estimate the size of the blower motor (hp).* The size of the blower motor is a function of the flow rate of air and the pressure drop. Methods of estimating the size of the blower motor (hp) can be found in reference books (McCabe et al., 1993; Avallone and Baumeister, 1987; Perry, 1984) and will not be calculated in this example.



## APPENDIX D EXAMPLE AIR STRIPPING BY PACKED COLUMN

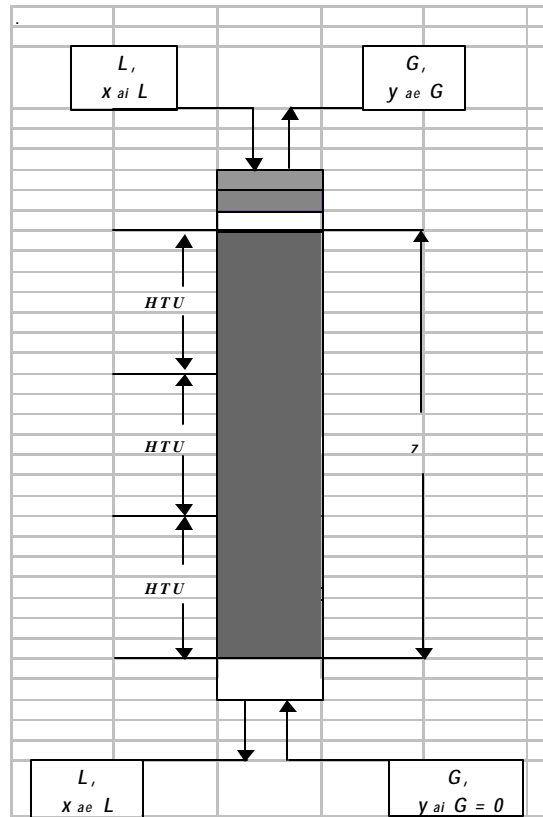


Figure D-1. Random "dumped" packed tower.

### D-1. Parameters.

$NTU$  = number of transferunits

$HTU$  = heightof transfer unit[m]

$Z = NTU \times HTU$  packingdepth[m]

$L$  = molarliquid(water)flowperunitofstripper $\alpha$ cross-sectionalarea  $\left[ \frac{\text{kg-mole}}{\text{m}^2 \text{ sec}} \right]$

$G$  = molargas(air)flow perunitofstripper $\alpha$ cross-sectionalarea  $\left[ \frac{\text{kg-mole}}{\text{m}^2 \text{ sec}} \right]$

$x_{ai}$  = molefraction of contaminant  $a$  in liquid (water) influent  $\left[ \frac{\text{kg-mole}}{\text{kg-molewater}} \right]$

$$x_{ae} = \text{molefraction of contaminant } a \text{ in liquid(water) effluent} \left[ \frac{\text{kg-mole}}{\text{kg-molewater}} \right]$$

$$y_{ai} = \text{molefraction of contaminant } a \text{ in gas(air) influent} \left[ \frac{\text{kg-mole}}{\text{kg-moleair}} \right]$$

$$y_{ae} = \text{molefraction of contaminant } a \text{ in gas(air) effluent} \left[ \frac{\text{kg-mole}}{\text{kg-moleair}} \right]$$

$$(x_{ai} - x_{ae}) L = (y_{ae} - y_{ai}) G$$

which is moles of contaminant  $a$  transferred from liquid to gas per unit of stripper cross-sectional area per unit time (kg-mole/s)

$$\left( \frac{x_{ai} - x_{ae}}{y_{ae} - y_{ai}} \right) = \frac{G}{L} \left[ \frac{\text{kg-mole air}}{\text{kg-mole water}} \right]$$

which is the molar ration of gas (air) to liquid (water), and assumning uncontaminated influent air:

$$y_{ai} = 0$$

$$\frac{G}{L} = \left( \frac{x_{ai} - x_{ae}}{y_{ae}} \right)$$

where  $x_{ai}$  and  $L$  are field measurements and  $x_{ae}$  is imposed by ARAR, and

$$p_{Te} = \text{total pressure of gas (air) effluent (atm)}$$

$$P_{ae} = \text{partial pressure of contaminant } a \text{ in gas (air) effluent (atm).}$$

From Dalton's Law of partial pressures:

$$y_{ae} = \frac{P_{ae}}{p_{Te}} \left[ \frac{\text{mole}}{\text{mole}} \right] \text{ or } \left[ \frac{\text{atm}}{\text{atm}} \right]$$

$$P_{ae} = y_{ae} p_{Te} \text{ [atm]}$$

at equilibrium from Henry's Law:

$$P_{ae} = H_a x_{ai} \text{ [atm]}$$

substituting yields:

$$y_{ae} p_{Te} = H_a x_{ai} \text{ [atm]}$$

$$y_{ae} = \frac{H_a x_{ai}}{p_{Te}} \text{ [atm]}$$

and from the material balance:

$$(x_{ai} - x_{ae}) \left( \frac{L}{G} \right) = y_{ae} \left[ \frac{\text{mole}}{\text{mole}} \right]$$

Again substituting gives

$$(x_{ai} - x_{ae}) \left( \frac{L}{G} \right) = \frac{H_a x_{ai}}{p_{Te}}$$

$$\frac{x_{ai} - x_{ae}}{x_{ai}} = \frac{H_a \left( \frac{G}{L} \right)}{p_{Te}}$$

The fraction of contaminant transferred from liquid (water) to gas (air) phase is:

$$\frac{C_{ai} - C_{ae}}{C_{ai}} = \frac{x_{ai} - x_{ae}}{x_{ai}}$$

where

$C_{ai}$  = concentration of contaminant  $a$  in liquid (water) influent [ $\mu\text{g/L}$ ]

$C_{ae}$  = concentration of contaminant  $a$  in liquid (water) effluent [ $\mu\text{g/L}$ ].

For convenience, the flows of water and air are measured volumetrically

$$C_{ai} (L) Q_L = C_{ae} (L) Q_L + C_{ae} (G) Q_G$$

and

$$\frac{C_{ai} - C_{ae}}{C_{ai}} = \left( \frac{H_a}{p_{Te}} \right) \left( \frac{Q_G}{Q_L} \right)$$

where  $p_{Te}$  is measured as a fraction of the standard atmosphere (atm),  $H'_a$  is the dimensionless Henry's constant  $H_a/C_0RT$ , actually (volume/volume),  $Q_g/Q_L$  is reduced to common flow units [ $m^3/m^3$ ], and  $C_0$  is the molar density of water at 20°C, 55.41 kg mole/ $m^3$ . The theoretical minimum, equilibrium, moles of gas required  $G_{min}/L$  is calculated from the influent and effluent concentrations and the "dimensionless" Henry's constant ( $H'_a$ ).

$$R_u = 0.08205746 \left[ \frac{m^3 \text{ atm}}{\text{kg-mole K}} \right] \text{ the universal gas constant}$$

At 1 atm and 20°C the molar density of water is  $C_0$ , 55.41 kg-mole/ $m^3$ .  $Q_G/Q_L$  [ $m^3/m^3$ ] is the air-to-water ratio,  $ATW$ .

$$y_{ae} = H_a x_{ai}/p_{Te} \text{ (mole/mole)}$$

Substituting gives

$$\frac{L(x_{ai} - x_{ae})}{G} = \frac{H_a x_{ai}}{p_{Te}}$$

and rearranging yields

$$\frac{G_{min}}{L} = \frac{(x_{ai} - x_{ae}) p_{Te}}{H_a x_{ai}}$$

which is the equilibrium molar ratio of gas (air) to liquid (water).

## D-2. Develop the Design Basis.

a. Characterize the influent conditions and effluent requirements, including RI/FS data + total organics + background inorganics and minimum water temperature.

**Table D-1  
Contaminants**

<i>Contaminant</i>	<i>Formula</i>	<i>GMW*</i> <i>[g/g-mole]</i>	<i>CAS Number</i>	<i>H<sub>a</sub>**</i> <i>[atm/mole/mole]</i>
Benzene	C <sub>6</sub> H <sub>6</sub>	78.11	71-43-2	309.2
Toluene	C <sub>6</sub> H <sub>5</sub> CH <sub>3</sub>	92.14	108-88-3	353.1
Trichloroethylene (TCE)	C <sub>2</sub> HCl <sub>3</sub>	131.50	79-01-6	506.1

\*The [gram] molecular weight of the contaminant.  
\*\* *H<sub>a</sub>* at 20°C (296.13 K).

b. Design the pumping system to maintain the flow. Use the real flow rate, not rounding up. Discharge head adjustments for the stripper are added to the TDH. The aggregate flow from the hydraulic barrier is 440 gpm (0.0278 m<sup>3</sup>/s) in this example.

c. Design the pre-treatment system to prevent scale/slime from clogging the stripper (if water is high in hardness, iron or manganese).

**Table D-2  
Background Inorganic Concentrations**

<i>Ion</i>	<i>mg/L</i>	<i>GMW</i>	<i>Valence</i>	<i>GEqW*</i>	<i>meq/L</i>	<i>mg/L asCaCO<sub>3</sub></i>
CO <sub>2</sub>	O	44	-2	22	0.00	0.00
<b>Anions</b>						
SO <sub>4</sub>	60	96	-2	48	1.25	62.46
Cl	54	35	-1	35	1.52	76.15
HCO <sub>3</sub>	30	61	-1	61	0.49	<u>24.58</u>
					TOTAL	163.19
CaCO <sub>3</sub>		100	0	50	0.00	0.00
<b>Cations</b>						
Na	10	23	1	23	0.43	21.75
Ca	40	40	2	20	2.00	99.80
Fe	0.3	56	2	28	0.01	0.54
Mg	10	24	2	12	0.82	41.12
Mn	0.05	55	2	27	0.00	<u>0.09</u>
					TOTAL	163.29

\* GEqW is the [gram] equivalent weight of the inorganic ion.

d. Construct a contaminant material balance for the stripping system.

**Table D-3  
Removal Requirements**

<i>Contaminant</i>	<i>Concentration</i> <i>[ng/L]</i>			<i>Mole Fraction</i> <i>[mole/mole]</i>	
	<i>Influent,</i> <i>C<sub>ai</sub></i>	<i>Effluent</i> <i>Standard,</i> <i>C<sub>ae</sub></i>	<i>Removal</i> <i>Requirement</i>	<i>x<sub>ai</sub></i>	<i>x<sub>ae</sub></i>
	Total VOCs	2500	NA	NA	NA
Benzene	750	10	98.7%	0.17330	0.00231
Toluene	1000	100	90.0%	0.19588	0.01959
Trichloroethylene (TCE)	750	100	86.7%	0.10294	0.01373

e. Assess the air pollution control requirements from the material balance and the regulations.

**D-3. Determine the Column Diameter.**

a. Determine a preliminary stripper cross-sectional area for the sustained pumping rate, 440 gpm (0.02776 m<sup>3</sup>/s) using 45 gpm/ft<sup>2</sup> (0.03056 m/s) for the stripper surface loading.

$$\begin{aligned}
 A &= \frac{Q \text{ ft}^2}{45 \text{ gpm}} \left( \frac{Q \text{ m}^2 \text{ s}}{0.03056 \text{ m}^3} \right) \\
 &= 0.0222 \frac{Q \text{ ft}^2}{\text{gpm}} \left( 32.72 Q \frac{\text{s}}{\text{m}} \right) \\
 &= 0.0222(440 \text{ gpm}) \frac{\text{ft}^2}{\text{gpm}} \left( 32.72 \left( 0.02776 \frac{\text{m}^3}{\text{s}} \right) \frac{\text{s}}{\text{m}} \right) \\
 &= 9.7778 \text{ ft}^2 \left( 0.9084 \text{ m}^2 \right)
 \end{aligned}$$

b. Divide the are by the number of strippers.

$$\begin{aligned}
 a &= \frac{A}{\#} \\
 &= \frac{9.7778}{2} \text{ ft}^2 \left( \frac{0.9084 \text{ m}^2}{2} \right) \\
 &= 4.889 \frac{\text{ft}^2}{\text{stripper}} \left( \frac{0.4542 \text{ m}^2}{\text{stripper}} \right)
 \end{aligned}$$

c. Divide  $a = \pi (d^2/4)$  the unit area by  $\pi$ , multiply by 4 and take the square root.

$$\begin{aligned}
 d &\approx \sqrt{\frac{4a}{\delta}} \\
 d &\approx \sqrt{\frac{4(4.889)}{\delta}} \left( \sqrt{\frac{4(0.4542)}{\delta}} \right) \\
 d &\approx \sqrt{6.22473} (\sqrt{0.5783}) \\
 d &\approx 2.5 \text{ ft} (0.762 \text{ m})
 \end{aligned}$$

d. Bracket the calculated diameter with the nearest standard diameters. In this example, a 2.5-ft (0.762-m) diameter column is standard for most manufacturers. The availability of standard metric sizes should be verified.

#### D-4. Find a Suitable Packing.

a. Find packings in the diameter range of roughly 5 to 10% of the stripper diameter. The rule of thumb is 1 in. of packing diameter per 1 ft of tower diameter; 2.5 in. (0.0635 m) packing is not standard for most manufacturers.

b. Reconsider the number of strippers if the packings and diameters don't correspond. Three 2-ft diameter strippers with 2-in. packing could be used in lieu of two 2.5-ft-diameter strippers.

b. Find the area of the standard diameter strippers.

$$\begin{aligned}
 a &= \delta \frac{d^2}{4} \\
 &= \frac{(2.5 \text{ ft})^2}{4} \left( \frac{(0.762 \text{ m})^2}{4} \right) \\
 &= 4.908 \text{ ft}^2 (0.456 \text{ m}^2)
 \end{aligned}$$

d. Calculate the surface hydraulic loading  $Q/A$  and compare the loading with various packing manufacturers' recommendations.

$$\frac{Q_L}{A} = \frac{220 \text{ gpm}}{4.908 \text{ ft}^2} \left( \frac{0.01388 \frac{\text{m}^3}{\text{s}}}{0.456 \text{ m}^2} \right) \text{ per stripper}$$

$$V_L = 44.82 \frac{\text{gpm}}{\text{ft}^2} \left( 0.03044 \frac{\text{m}}{\text{s}} \right)$$

e. Adjust the system configuration to get the hydraulics within the recommended range.

**D-5. Calculate the Minimum Gas Flow.** Determine  $G_{\min}$  and the critical contaminant from the following relationship:

$$\frac{Q_{G \min}}{Q_L} = \frac{(C_{ai} - C_{ac})}{H_a C_{ai}}$$

**Table D-4**  
**Critical Contaminant**

For $P_{te} = 1 \text{ atm}$ and $20^\circ\text{C}$ (296.13 K) $H_a = H_a/C_o R T$			
Contaminant	$\frac{(C_{ai} - C_{ac})}{C_{ai}}$	$H_a$	$\frac{Q_{G \min}}{Q_L}$
Benzene	0.9867	0.2320	4.253 $\frac{\text{m}^3}{\text{m}^3}$
Toluene	0.9000	0.2649	3.397 $\frac{\text{m}^3}{\text{m}^3}$
Trichloroethylene (TCE)	0.8667	0.3797	2.283 $\frac{\text{m}^3}{\text{m}^3}$
<b>Critical Contaminant (Benzene)</b>			
$\frac{Q_{G \min}}{Q_L}$	=	4.253 $\frac{\text{m}^3}{\text{m}^3}$	(maximum)



**D-6. Calculate the Mass Transfer Rate.** Use a model, if available, to confirm the results.

$$\frac{a_w}{a_t} = 1 - e^{-1.45 \left(\frac{S_c}{S}\right)^{0.75} N_{Re}^{0.01} N_{Fr}^{-0.05} N_{we}^{0.2}}$$

$$\frac{1}{K_{LA}} = \frac{1}{H_a K_G a_w} + \frac{1}{K_L a_w}$$

where

$$a_w = \text{wetted surface area of the packing (m}^2\text{/m}^3\text{)}$$

$$a_t = \text{total surface area of the packing (m}^3\text{/m}^2\text{)}$$

$$K_{LA} = \text{overall mass transfer rate (m/s)}$$

$$K_L = \text{liquid phase mass transfer rate (m/s)}$$

$$K_G = \text{gas phase mass transfer rate (m/s).}$$

a. Calculate the dimensionless numbers (<http://www.processassociates.com/process/dimen> gives a comprehensive listing and definitions of dimensionless numbers).

$$N_{Re} = \left(\frac{1}{a_t}\right) \frac{V_L \mathbf{r}_L}{\mathbf{m}_L} \quad \text{Reynolds Number}$$

$$N_{Fr} = a_t \frac{V_L^2}{g_c} \quad \text{Froude Number}$$

$$N_{we} = \left(\frac{1}{a_t}\right) \frac{V_L \mathbf{r}_L}{g_c S} \quad \text{Weber Number}$$

$$N_{Sc} = \frac{\mathbf{m}_L}{\mathbf{r}_L D_L} \quad \text{Schmidt Number}$$

$$g_c = 9.807 \frac{\text{m}}{\text{s}^2} \quad \text{gravitation constant}$$

b. Look up the properties of the liquid (water) at the minimum water temperature,  $T$  (Table D-5).

**Table D-5**  
**Water at 20°C (293.16 K)**

$s = 0.072764 \frac{\text{N}}{\text{m}} = \frac{\text{kg}}{\text{s}^2}$	liquid surfacetension
$\mathbf{m}_L = 0.0010042 \frac{\text{kg}}{\text{m s}}$	liquidviscosity
$\mathbf{r}_L = 998.20 \frac{\text{kg}}{\text{m}^3}$	liquid density

c. Look up the properties of the critical contaminant, benzene, at the minimum water temperature,  $T$ ,

$$D_L = 8.91 \times 10^{-10} \frac{\text{m}^2}{\text{s}} \quad \text{liquiddiffusivityof benzene at } 20^\circ\text{C (296.13 K)}$$

d. Obtain data from product literature (Table D-6).\*

**Table D-6**  
**Packing Characteristics**

$d_p = 0.0508 \text{ m}$	nominal diameter
$a_t = 157 \frac{\text{m}^2}{\text{m}^3}$	totalsurfacearea
$s_c = 0.033 \frac{\text{kg}}{\text{s}^2}$	criticalsurfacetension for polyethylenepacking
$c_f = 15$	packing factor

e. Liquid mass velocity is as follows.

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\* Jaeger Tripacks 2-in. (50.8 mm) plastic media.

$$\begin{aligned}
 L &= \mathbf{r}_L \frac{Q_L}{A} \left[ \frac{\text{kg}}{\text{m}^2 \text{ s}} \right] \text{ liquid mass velocity at } 0.01388 \frac{\text{m}^3}{\text{s}} \text{ with an nominal column diameter of } 0.76 \text{ m} \\
 &= 998.19 \times \left( \frac{0.01388}{0.45599} \right) \\
 &= 30.38 \frac{\text{kg}}{\text{m}^2 \text{ s}}
 \end{aligned}$$

f. Calculate the Reynolds Number,  $N_{\text{Re}}$ .

$$\begin{aligned}
 N_{\text{Re}} &= \frac{V_L \mathbf{r}_L}{a_t \mathbf{m}_L} \text{ (Reynolds Number)} \\
 V_L &= 0.3043 \frac{\text{m}}{\text{s}} \text{ from Paragraph D-4d} \\
 \mathbf{r}_L &= 998.19 \frac{\text{kg}}{\text{m}^3} \\
 a_t &= 157 \frac{\text{m}^2}{\text{m}^3} \\
 \mathbf{m}_L &= 0.0010042 \frac{\text{kg}}{\text{m s}} \\
 N_{\text{Re}} &= \frac{0.3043 \times 998.19}{157 \times 0.0010042} \\
 &= 192.7 \\
 N_{\text{Re}}^{0.1} &= 1.692
 \end{aligned}$$

g. Calculate the Froude Number,  $N_{\text{Fr}}$ .

$$\begin{aligned}
 N_{\text{Fr}} &= \frac{a_t V_L^2}{g_c} \text{ (Froude Number)} \\
 &= \frac{157 \times (0.3043)^2}{9.807} \\
 &= 0.01483 \\
 N_{\text{FR}}^{-0.05} &= 1.234
 \end{aligned}$$

h. Calculate the Weber Number,  $N_{\text{We}}$ .

$$\begin{aligned}
 N_{We} &= \left( \frac{1}{a_t} \right) \frac{V_L^2 r_L}{g_c s} \quad (\text{Weber Number}) \\
 &= \left( \frac{1}{157} \right) \frac{(30.39)^2 \times 998.19}{9.807 \times 0.072764} \\
 &= 0.08094 \\
 N_{We}^{0.2} &= 0.6048
 \end{aligned}$$

i. Calculate the wetted area of the packing,  $a_w$  from the dimensionless relation:

$$\frac{a_w}{a_t} = 1 - \exp \left[ -1.45 \left( \frac{s_c}{s} \right)^{0.75} \left( N_{Re}^{0.1} N_{Fr}^{-0.05} N_{We}^{0.2} \right) \right]$$

$$\begin{aligned}
 N_{Re}^{0.1} N_{Fr}^{-0.05} N_{We}^{0.2} &= 1.692 \times 1.234 \times 0.6048 \\
 &= 1.263
 \end{aligned}$$

$$\begin{aligned}
 \left( \frac{s_c}{s} \right)^{0.75} &= \left( \frac{0.033}{0.0728} \right)^{0.75} \\
 &= (0.45352)^{0.75} \\
 &= 0.553
 \end{aligned}$$

j. Calculate the wetted surface area.

$$\begin{aligned}
 \frac{a_w}{a_t} &= 1 - \exp[-1.45(0.553 \times 1.263)] \\
 &= 1 - \exp(-1.0125) \\
 &= 1 - 0.3633 \\
 &= 63.67\% \\
 a_t &= 157 \frac{\text{m}^2}{\text{m}^3} \\
 a_w &= 63.67\% (157) \\
 a_w &= 99.96 \frac{\text{m}^2}{\text{m}^3}
 \end{aligned}$$

k. Calculate the liquid phase mass transfer coefficient, Onda  $K_L$  from the following relationship:

$$K_L \left( \frac{r_L}{m_L g_c} \right)^{\frac{1}{3}} = 0.0051 \left( \frac{V_L r_L}{a_w m_L} \right)^{\frac{2}{3}} \left( \frac{m_L}{r_L D_L} \right)^{-0.5} (a_t d_p)^{0.4}$$

$$\begin{aligned} \left( \frac{r_L}{m_L g_c} \right)^{\frac{1}{3}} &= \left[ \frac{998.19}{(0.0010042)(9.8066)} \right]^{\frac{1}{3}} \\ &= (101,361)^{1/3} \\ &= 46.63 \end{aligned}$$

$$\begin{aligned} \left( \frac{V_L r_L}{a_w m_L} \right)^{\frac{2}{3}} &= \left( \frac{0.3043 \times 998.19}{99.96 \times 0.0010042} \right)^{\frac{2}{3}} \\ &= (302.7)^{\frac{2}{3}} \\ &= 45.08 \end{aligned}$$

$$\begin{aligned} \left( \frac{m_L}{r_L D_L} \right)^{-0.5} &= \left[ \frac{0.0010042}{(998.19)(8.91 \times 10^{-10})} \right]^{-0.5} \\ &= (1129)^{-0.5} \\ &= 0.02976 \end{aligned}$$

$$\begin{aligned} (a_t d_p)^{0.4} &= (157 \times 0.0508)^{0.4} \\ &= (7.9756)^{0.4} \\ &= 2.2946 \end{aligned}$$

$$\begin{aligned} K_L \left( \frac{r_L}{m_L g_c} \right) &= 0.0051 \left( \frac{V_L r_L}{a_w m_L} \right)^{\frac{2}{3}} \left( \frac{m_L}{r_L D_L} \right)^{-0.5} (a_t d_p) \\ K_L &= \frac{0.0051 \times 45.08 \times 0.02976 \times 2.2946}{46.63} \end{aligned}$$

$$K_L = 0.0003367 \frac{\text{m}}{\text{s}}$$

l. Calculate the gas phase mass transfer coefficient, Onda  $K_G$ , using a stripping factor ( $R$ ) between 2 and 5. Try  $R = 2.5$  if air pollution control is required,  $R = 4.5$  if it isn't.

$$\frac{K_G}{(a_t D_G)} = 5.23 \left( \frac{G}{a_t \mathbf{m}_G} \right)^{0.7} \left( \frac{\mathbf{m}_G}{\mathbf{r}_G D_G} \right)^{\frac{1}{3}} (a_t d_p)^{-2.0}$$

m. Look up the properties of the gas (air) at the minimum water temperature,  $T$  (Table D-7).

**Table D-7**  
**Air at 20°C (293.16 K) and 1 atm**

$\mathbf{m}_G$	=	$1.773 \times 10^{-5} \frac{\text{kg}}{\text{m s}}$	gasviscosity
$\mathbf{r}_G$	=	$1.2046 \frac{\text{kg}}{\text{m}^3}$	gasdensity

n. Look up the properties of the critical contaminant, benzene, at the minimum water temperature,  $T$ .

$$D_G = 9.37 \times 10^{-6} \frac{\text{m}^2}{\text{s}} \quad \text{gasdiffusivity(benzeneinairat20°C,1atm)}$$

o. Calculate the gas flow rate from the relationship:

$$\begin{aligned} \frac{Q_{G \min}}{Q_L} &= \frac{(C_{ai} - C_{ae})}{H'_a C_{ai}} \\ &= 4.253 \text{ from Table D-4} \\ V_L &= 0.03044 \frac{\text{m}}{\text{s}} \\ V_{G \min} &= 4.2635 \times 0.03044 \\ &= 0.1297 \frac{\text{m}}{\text{s}} \end{aligned}$$

$$\begin{aligned}
 R &= 3.5 \\
 V_G &= R \times V_{G_{\min}} \\
 V_G &= 3.5 \times 0.1297 \\
 &= 0.4531 \frac{\text{m}}{\text{s}} \\
 G &= V_G r_G \\
 &= 0.4531 \frac{\text{m}}{\text{s}} \times 1.2046 \frac{\text{kg}}{\text{m}^3} \\
 &= 0.5458 \frac{\text{kg}}{\text{s m}^2}
 \end{aligned}$$

*p.* See Table D-6 for packing characteristics,  $a_t$  and  $d_p$ .

$$\begin{aligned}
 \left( \frac{G}{a_t m_G} \right)^{0.7} &= \left( \frac{0.5458}{157 \times 1.773 \times 10^{-5}} \right)^{0.7} \\
 &= (196.06)^{0.7} && \text{Gas phase Reynolds number} \\
 &= 40.24
 \end{aligned}$$

$$\begin{aligned}
 \left( \frac{m_G}{r_G D_G} \right)^{\frac{1}{3}} &= \left( \frac{1.773 \times 10^{-5}}{1.2046 \times 9.37 \times 10^{-6}} \right)^{\frac{1}{3}} \\
 &= (1.571)^{\frac{1}{3}} && \text{Gas phase Schmidt number} \\
 &= 1.162
 \end{aligned}$$

$$\begin{aligned}
 (a_t d_p)^{-2.0} &= (157 \times 0.0508)^{-2.0} \\
 &= (7.976)^{-2.0} \\
 &= 0.01572
 \end{aligned}$$

$$\begin{aligned}
 a_t D_G &= 157 \times 9.37 \times 10^{-6} \\
 &= 0.001471 \frac{\text{m}}{\text{s}}
 \end{aligned}$$

$$\begin{aligned}\frac{K_G}{(a_t D_G)} &= 5.23 \times 40.24 \times 1.162 \times 0.157 \\ &= 3.846 \\ K_G &= 3.853 \times 0.00147 \\ &= 0.005658 \frac{\text{m}}{\text{s}}\end{aligned}$$

q. Calculate the overall mass transfer coefficient, Onda  $K_{LA}$ .

$$\begin{aligned}\frac{1}{K_{LA}} &= \frac{1}{H'_a K_G a_w} + \frac{1}{K_L a_w} \\ &= \frac{1}{0.2320 \times 0.005658 \times 99.96} + \frac{1}{0.003367 \times 99.96} \\ &= 7.622 + 29.71 \\ &= 37.33 \\ K_{LA} &= 0.02679 \text{ s}^{-1}\end{aligned}$$

$$\begin{aligned}HTU &= \frac{V_L}{K_{LA}} \\ &= \frac{0.03044}{0.02679} \\ &= 1.136\text{m}\end{aligned}$$

r. Determine  $NTU$  for the selected  $R$ .

$$\begin{aligned}R &= \frac{G}{G_{\min}} \\ &= \frac{H'_a}{P_{Te}} \times \frac{G}{L} \\ &= 3.5\end{aligned}$$

$$NTU = \left( \frac{R}{R-1} \right) \ln \left( \frac{\left[ \left( \frac{x_{ai}}{x_{ae}} \right) (R-1) \right] + 1}{R} \right)$$



$$\begin{aligned}
 NTU &= \left( \frac{3.5}{3.5-1} \right) \ln \left[ \frac{\left[ \left( \frac{750}{10} \right) (3.5-1) \right] + 1}{3.5} \right] \\
 &= \left( \frac{3.5}{2.5} \right) \ln \left( \frac{(75 \times 2.5) + 1}{R} \right) \\
 &= 1.4 \times \ln \left( \frac{187.5 + 1}{3.5} \right) \\
 &= 1.4 \times \ln \left( \frac{188.5}{3.5} \right) \\
 &= 1.4 \times \ln 53.86 \\
 &= 1.4 \times 3.99 \\
 &= 5.88
 \end{aligned}$$

$$\begin{aligned}
 Z &= NTU \times HTU \\
 &= 5.88 \times 3.07 \\
 &= 17.13 \text{ m}
 \end{aligned}$$

$$\frac{A}{W} = \frac{0.4132 \frac{\text{m}^3}{\text{s}} \text{ air}}{0.02776 \frac{\text{m}^3}{\text{s}} \text{ water}}$$

$$\frac{A}{W} = 14.89$$

s. Calculate the system headlosses, including the packing, the stripper inlet, and the exit losses. Size equipment, including blowers and pumps. Verify that blower discharge pressure is less than the value that would cause flooding.

#### D-7. Complete the Design.

a. The following drawings are required.

- (1) Site plans.
- (2) Profiles.
- (3) Layout drawings.

(4) Details.

b. Design Analysis should be done in accordance with ER 1110-345-700, *Design Analysis, Drawings, and Specifications*, containing the following:

(1) Narrative.

(2) Documentation.

(3) Description.

(4) Calculations.

(5) Computer print out with documentation.

c. Specifications should be done in accordance with ER 1110-1-8155, and the following United Facilities Guide Specifications

02150 Piping; Off-Gas.

02521 Water Wells.

11212 Pumps Water Vertical Turbine.

11215 Fans/Blowers/Pumps Off-Gas.

11220 Precipitation/Coagulation/Flocculation Water Treatment.

11242 Chemical Feed Systems.

11378 Thermal (Catalytic) Oxidation Systems.

13405 Process Control.

15200 Pipelines, Liquid Process Piping.

d. Cost Estimate should be done in accordance with ER 1110-3-1301, *Cost Engineering Policy Requirements for Hazardous, Toxic Radioactive Waste (HTRW) Remedial Action Cost Estimate*.

e. Draft O&M manual should include cleaning procedures, as well as the O&M of the mechanical equipment.