A SELECTION GUIDE FOR VOLATILIZATION TECHNOLOGIES FOR WATER TREATMENT

IT Corporation
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A SELECTION GUIDE FOR VOLATILIZATION TECHNOLOGIES FOR WATER TREATMENT

By

Jeffrey L. Fleming
IT Corporation
Knoxville, Tennessee 37923

Project Officer

HAZARDOUS WASTE ENGINEERING RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
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FOREWORD

Today's rapidly developing and changing technologies and industrial practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both the public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances also have important health and environmental implications. The Hazardous Waste Engineering Research Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs, and regulations of the Agency; the permitting and other responsibilities of the state and local government; and the needs of both large and small businesses in handling their wastes responsibly and economically.

This document describes methods for evaluating the applicability of various volatilization technologies for removing organic chemicals from contaminated water. The information generated from this program will be useful to both government officials and industry members concerned with this aspect of water pollution control.

For further information, please contact the Land Pollution Control Division of the Hazardous Waste Engineering Research Laboratory.

Thomas R. Hauser, Director
Hazardous Waste Engineering Research Laboratory

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LIST OF SYMBOLS*

C	--	concentration (mole fraction/mole fraction, wt % or gmol/m$_3$)
f	--	fraction remaining (mole fraction/mole fraction)
G	--	gas flow rate (cfm or moles/hour)
h	--	humidity
H	--	Henry's Law constant (mole fraction/mole fraction)
ΔHv	--	heat of vaporization
i	--	component in solution
K_L		overall mass transfer coefficient (m/hr)
k_l	--	liquid phase mass transfer coefficient (m/hr)
k_g	--	gas phase mass transfer coefficient (m/hr)
L	--	liquid flow rate (gpm or moles/hr)
N	--	number of stages in a column
P	--	pressure (atm, mm Hg, in water)
P_i	--	partial pressure of component in vapor (atm, mm Hg, in water)
P_T	--	total pressure (atm, mm Hg, in water)
R	--	universal gas constant (1.987 cal/gmol ^{O}K, 0.7302 (atm-ft^3)/(lbmol ^{O}R), 8.2 X 10^{-5}m^{3}atm/gmol ^{O}K)
S	--	stripping factor (HG/L)
t	--	time (hours, minutes, days)
T	--	temperature (^{O}F, ^{O}C, ^{O}K, ^{O}R)
t_h	--	half-life (hours)
V	--	volume (gallons, liters, m^3, ft^3)
X_i	--	mole fraction of component i in liquid phase
Y_i	--	mole fraction of component i in vapor phase
MW	--	molecular weight
s	--	specific surface area of liquid phase (m^2/m^3)
$\alpha_{1,2}$	--	relative volatilities of components 1 and 2

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* These symbols are the author's and not necessarily standard symbols.

CONVERSION FACTORS
Metric to U.S. Customary

Metric Name	Symbol	Multiplier	U.S. customary unit Abbreviation	Name
centimeter(s)	cm	0.3937	in.	inches
centimeter(s) per hour	cm/h	0.3937	in./h	inches per hour
cubic meter	m^3	8.1071×10^{-4}	acre-ft	acre-foot
		35.3147	ft^3	cubic foot
		264.25	Mgal	million gallons
cubic meters per day	m^3/d	2.6417×10^{-4}	Mgal/d	million gallons per day
cubic meters per hectare	m^3/ha	1.069×10^{-4}	Mgal/acre	million gallons per acre
cubic meters per second	m^3/s	22.82	Mgal/d	million gallons per day
degrees Celsius	°C	1.8(°C) + 32	°F	degrees Fahrenheit
gram(s)	g	0.0022	lb	pound(s)
hectare	ha	2.4711	acre	acre
		0.004	mi^2	square miles
Joule	J	9.48×10^{-4}	Btu	British thermal unit
kilogram(s)	kg	2.205	lb	pound(s)
kilograms per hectare	kg/ha	0.0004	tons/acre	tons per acre
kilograms per hectare per day	kg/ha·d	0.893	lb/acre·d	pounds per acre per day
kilograms per square centimeter	kg/cm^2	14.49	$lb/in.^2$	pounds per square inch
kilometer	km	0.6214	mi	mile
kilowatt	kW	1.34	hp	horsepower
liter	L	0.0353	ft^3	cubic foot
		0.264	gal	gallon(s)
liters per hectare per day	L/ha·d	0.11	gal/acre·d	gallons per acre per day
liters per second	L/s	0.035	ft^3/s	cubic feet per second
		22.826	gal/d	gallons per day
		15.85	gal/min	gallons per minute
		0.023	Mgal/d	million gallons per day
megagram (metric tonne)	Mg(or t)	1.10	ton(short)	ton(short)
megagrams per hectare	mg/ha	0.446	tons/acre	tons per acre
megajoule	MJ	0.278	kWh	kilowatt hour
megaliters (liters x 10^6)	ML	0.264	Mgal	million gallons
meters(s)	m	3.2808	ft	foot (feet)
meters per second	m/s	2.237	mi/h	miles per hour
micrograms per liter	ug/L	1.0	ppb	parts per billion
milligrams per liter	mg/L	1.0	ppm	parts per million
nanograms per liter	ng/L	1.0	ppt	parts per trillion
Newtons per square centimeter	N/cm^2	1.45	$lb/in.^2$	pounds per square inch
square centimeter	cm^2	0.155	$in.^2$	square inch
square kilometer	km^2	0.386	mi^2	square mile
square meter	m^2	10.76	ft^2	square foot

SECTION 1

INTRODUCTION

The purpose of this guide is to aid in determining whether a particular volatilization technology can successfully remove organic contaminants from water. It describes the performance evaluation of common volatilization technologies and provides an approach for selecting the appropriate technology for a given situation. Data necessary for the evaluation are described and, whenever possible, background data are given for selected hazardous organics. In addition to being useful for equipment selection, it can be used as an educational tool for background data on volatilization technologies or as a decision-making tool for purchasing a mobile technology.

The impetus for developing a guide stems from involvement of the Hazardous Waste Engineering Research Laboratory's Releases Control Branch in technical assistance activities that require assessment of the feasibility and cost of various treatment options. It was recognized that EPA On-Scene Coordinators (OSC) and their technical support personnel are often faced with changing or uncertain conditions that could affect the cost and feasibility of removing volatile substances from water. As conditions change or as some of the uncertainties are resolved, the OSC's technical support personnel are called upon to revise their estimates accordingly. It was recognized that the OSC and their technical support staffs did not have a concise guide on the subject of volatilization technologies and their application to spill cleanup operations.

People with some technical training in chemistry and thermodynamics, but limited experience in participating or coordinating cleanup activities at uncontrolled hazardous waste sites will find the guide useful. (A review of volatilization is provided for those with little experience in this area or who may need a refresher.) OSC can use this guide to reduce duplication of effort, accelerate the production of cost and performance estimates for decision-makers, and promote consistency in estimation procedures. Technical personnel who support the OSC by developing cost and performance estimates for water treatment options are the principal target audience for this guide.

HOW TO USE THIS GUIDE

This guide assists the reader to apply a five-phase process for evaluating the applicability of a volatilization technology:

Phase 1. Preliminary assessment of the feasibility of volatilization
Phase 2. Site characterization
Phase 3. Calculation of basic material properties
Phase 4. Technology evaluation
Phase 5. Equipment selection

The flow chart in Figure 1 shows the technology selection process in greater detail and indicates the pertinent sections of the guide for each step of the selection process.

Phase 1 is a preliminary assessment to determine the feasibility of utilizing volatilization technologies for water pollution control. Normally, volatilization is only considered for removing low concentrations of volatile materials. Water with a high percentage of organics should be disposed of in some other manner. Further, compounds that will volatilize at a rate close to or below the evaporation rate of water are not likely candidates for volatilization.

Phase 2, site characterization (Section 2), requires a complete evaluation of the site as a necessary part of the selection process. A checklist of important site data for the evaluation is provided.

Phase 3, calculation of basic material properties (Section 3), involves determining the properties of the spilled material. Several properties of selected compounds are provided; however, for a variety of different organics, other sources must be used to determine the properties of the spilled material. Some of these sources are provided in the references; readers are advised to contact the chemical manufacturer if data are not available.

The technology evaluation phase (Phase 4, found in Section 4) is designed to eliminate technologies from consideration at each evaluation step, thus avoiding additional work on technologies that are not suitable for the application. The technology evaluation process eliminates systems based on a sequential evaluation of:

1. Removal ranges

2. Flowrate and time requirements for treatment

3. Emissions generated by treatment

Technologies still under consideration after the evaluation of these parameters should then be examined on the basis of their costs. Costs for pretreatment, disposal of treated water, emission controls, and water polishing units (not addressed in this guide) should be added to costs for treatment by volatilization as given in Section 4. Based on the problems inherent in providing accurate cost estimates, it is recommended that cost differences exceed a factor of two before eliminating a technology.

Phase 5, equipment selection (Sections 5 and 6), is the final step in selecting a treatment unit for use at a site. This is a complex decision for which no summary method is possible. Data in these sections are designed to provide background information on the available technologies in order to help the on-site field worker make an intelligent selection.
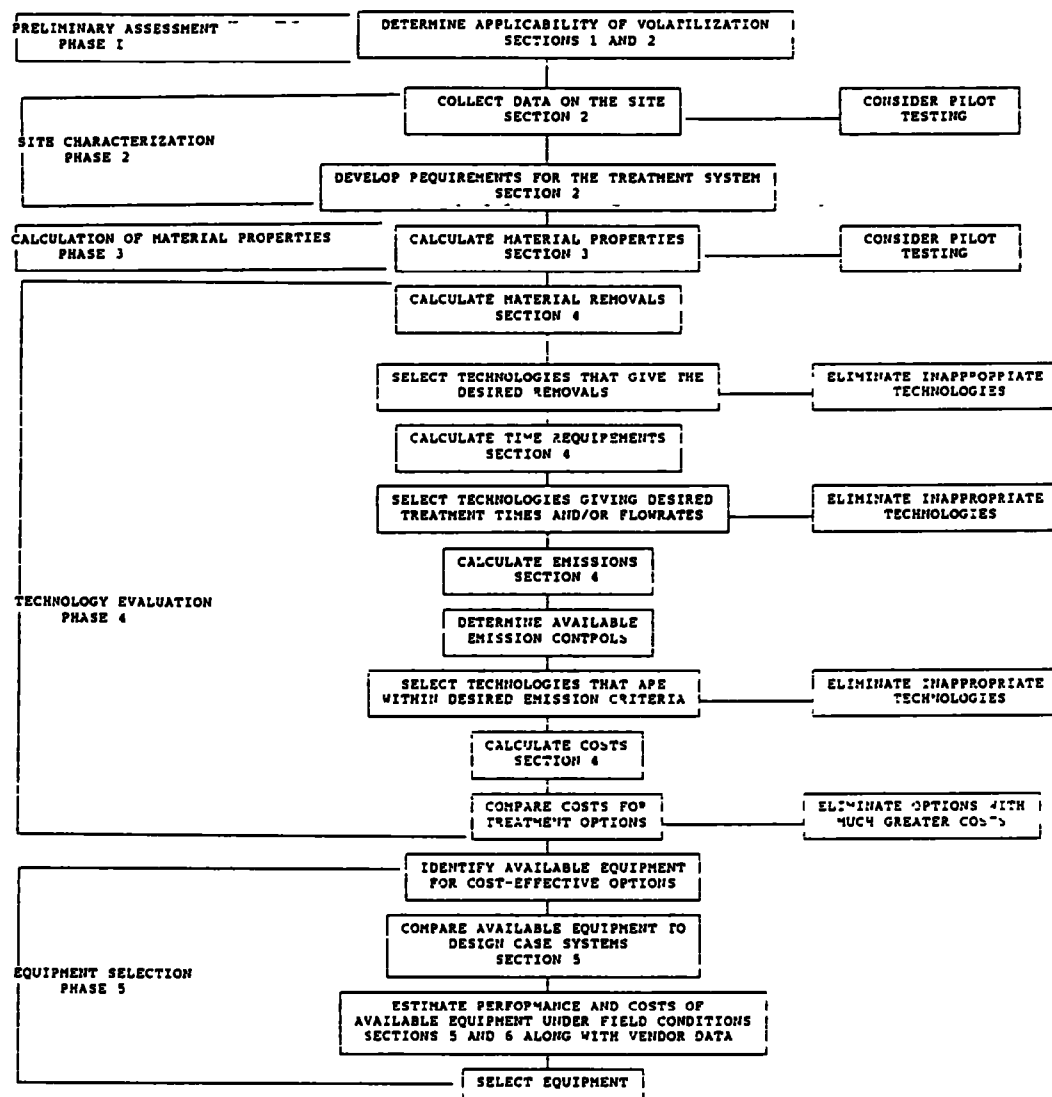
Figure 1. Decision tree for volatilization process selection

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Of particular note, Section 5 presents more details for the various technologies in preceding sections. Section 5 may be too lengthy for many readers who can obtain a rapid evaluation using Sections 2, 3, and 4 without additional details on how the data were obtained. An example application of this guide is given in Appendix A.

LIMITATIONS OF THE GUIDE

The guide is, of necessity, written about "representative" types of equipment and about selected situations. Although the final selection of equipment should take into account the factors cited in the guide, it will be necessary to consider the individual characteristics of the equipment and the situation in which it will be applied.

A variety of other technologies, such as cross-flow air stripping and a proprietary activated carbon/stripping hybrid technology, are not included because of their similarity to other technologies or because systems are not available for widespread use. The guide does not address mobile or readily transportable technologies for treating the offgases from the described volatilization technologies.

In addition, the guide is not designed to be the sole reference for making the final selection of a treatment system. There are situation-specific considerations that are beyond its scope. As examples the problems caused by poor water quality (e.g., salts, solids, biological material); evaluating the significance of differences between equipment of the same type; or performing pilot tests, cannot be adequately addressed in this guide.

Pilot Testing

Estimates made in accordance with this guide's method, along with variations between units of the same type, will normally be within a factor of 2 to 3 of actual system performance. However, much of the available data on Henry's Law are only accurate within an order of magnitude, which reduces the accuracy of performance evaluations, particularly for low Henry's Law constant. Also, when the equipment is significantly different from design case assumptions, or when treatment conditions are far from normal, estimates made using this manual may not be valid. In cases where it is important to obtain a better estimate for equivalent performance, pilot testing is recommended if time is available.

Pilot testing proves cost effective when the test cost is outweighed by the resultant savings during operation. This is true when long-term treatment is expected, the scale of treatment units is much larger than available pilot units, and the pilot test is designed to give information that can alter equipment selection for treatment. Normally, preliminary performance estimates on the candidate full-scale units should be completed before pilot testing; the test should then be designed to demonstrate specific points. The manner in which the pilot test could reduce costs should be known before testing begins.

Much equipment available for mobile treatment is considered pilot scale for use in demonstrations leading to large permanent installations. Often, this equipment scale is all that is necessary for a temporary application requiring a mobile unit. In this case, it is advisable to try the equipment rather than devise a bench-scale test, particularly if the test is not to be run on-site with the actual water to be treated.

VOLATILIZATION OF ORGANIC COMPOUNDS FROM WATER: A REVIEW

This section is provided as a brief review of the principles of volatilization. It also introduces the terminology used throughout the guide.

Treatment technologies addressed herein involve volatilization of organic solutes, which requires transfer of the organic from the liquid to the gas phase. The extent to which these solutes are distributed between the phases is dictated by the approach to thermodynamic equilibrium that is achieved.

Equilibrium is attained when the net transfer of a solute between phases ceases at the prevailing conditions of temperature and pressure. A complete discussion may be found in many texts on the subject of equilibrium (1-4).

The rate of mass transfer is dependent on a number of factors including the departure of the system from equilibrium: The further the two phases are from equilibrium, the faster the rate of mass transfer. Also, the rate of mass transfer is directly dependent on the surface area of the interface between the phases, the resistance to mass transfer at the interface, and the degree of mixing in each phase. The nature and degree of dispersion of the phases is of prime importance.

Equipment used for gas-liquid operations should provide intimate contact between the two phases in order to reduce mass transfer resistance and to permit increased interphase transfer of the constituents. The degree of contact can be increased using a variety of devices, but greater phase contacting generally requires more sophisticated equipment.

Heat and mechanical energies are required to increase the rate of volatilization. Heat is necessary to increase the system temperature so that a more favorable equilibrium is reached and to provide the energy required for vaporization of a liquid. Mechanical energy is required for dispersing liquids and gases. In air stripping, the energy comes from cooling water and air; in steam stripping, energy comes from condensation of steam.

The thermodynamic equilibrium between phases can be represented by the relative volatility, described mathematically as

$$\alpha_{1,2} = \frac{Y_1/X_1}{Y_2/X_2} \qquad (1)$$

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where:

α 1,2 = relative volatilities of components 1 and 2,

Y_1 = mole fraction of component 1 in vapor phase,

Y_2 = mole fraction of component 2 in vapor phase,

X_1 = mole fraction of component 1 in liquid phase.

X_2 = mole fraction of component 2 in liquid phase.

Relative volatility is concentration-dependent, which is a greater factor at high concentrations.

For dilute solutions of organics in water, the equilibrium between vapor and liquid phases can also be described by the Henry's Law constant (H). This constant relates vapor-phase concentration to liquid-phase concentration mathematically as

$$H = Y_i/X_i \tag{2}$$

where:

H = Henry's Law constant,

Y_i = mole fraction of solute in the vapor phase at equilibrium,

X_i = mole fraction of solute in the liquid phase at equilibrium,

and Henry's Law constant is assumed to be constant at low organic concentrations in water.

The use of Henry's Law in air stripping ignores the volatilization of water. This assumption holds for compounds with a Henry's Law constant much greater than that of water (H water 0.03 at 25°C).

Henry's Law constants are an area of confusion and misunderstanding in some literature discussions. When using these constants, certain assumptions are implied about the vapor-liquid equilibrium relationship. The two most important assumptions are:

1. that the vapor behaves like an ideal gas (valid when total pressure <100 psig), and

2. that the solution is very dilute.

For systems in which the organic has limited solubility* in water, the

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* "Limited Solubility" is an area of considerable debate and cannot be adequately defined. This limit will vary by compounds, temperature, etc. However, the author suggest that a rough estimate for this limit could be between 100 ppm (0.001%) and 10,000 ppm (1%).

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linear relationship represented by Henry's Law will hold within certain limits. This limit is system-specific and requires experimental data to be predicted. In most cases for organics with low solubilities, Henry's Law constant will approximate the vapor-liquid equilibrium of a system up to the solubility of the organic in water. The use of Henry's Law constants can, therefore, be a powerful tool for designing volatilization equipment.

Another source of confusion about Henry's Law constants arises over units. A Henry's Law constant may be defined in many combinations of units. In this guide, Henry's Law constants are defined as:

$$\frac{\text{Mole fraction of component i in vapor}}{\text{Mole fraction of component i in liquid}} = \frac{Y_i}{X_i}$$

This constant is independent of the solute or solvent, and is a unitless number. All other Henry's Law constants are condition- or compound-specific. Some other forms of the constant are also unitless, but are not consistent with the previous definition. For example, one can define a Henry's Law constant as:

$$\frac{\text{Concentration in vapor } (g/cm^3)}{\text{Concentration in liquid } (g/cm^3)}$$

This definition gives a unitless number. However, it is not equivalent to a Henry's Law constant defined in mole fractions (Y_i/X_i), and is dependent on the molecular weight of the compound. This constant is not equal to Y_i/X_i because, although both numbers are unitless, they are not dimensionless. The units used to describe a unitless constant must be known to use the constant correctly. Another example of this problem is the unitless constant of parts per million (ppm): It must be known whether the concentration is expressed in volume percent or weight percent in order to utilize the data. Similarly, before a unitless Henry's Law constant can be used correctly for the purposes of this manual, the units employed in its calculation must be known. Table 1 shows some conversion factors of common Henry's Law constant found in the literature.

All Henry's Law constants must be determined experimentally However, very little experimental data exist for dilute, low-solubility organic contaminants in water. Instead, methods for estimating Henry's Law constants from pure component physical properties or compound structures are routinely used. Some of these procedures are described in Section 3.

For distillation systems, relative volatility (mathematically described in Eq. 1) is normally used to describe the vapor-liquid equilibrium.

TABLE 1. HENRY'S LAW CONSTANT CONVERSION FACTORS*

Multiply	By (Units)	To obtain
H_i	$1/P_T$ (1/atm)	H
H_A	$55,556/P_T$ $\dfrac{gmol/(m^3\text{-}atm)}{m^3\text{-}atm}$	H
H_B	$4.559(T/P_T)$ (unitless)	H
H_C	1343 (unitless)	H

*All conversion factors assume dilute solutions in water and air taken at standard conditions of 1 atm pressure and 25°C temperature.

Legend:

H   = Henry's Law constant (Y_i/X_i, unitless)

H_i = Henry's Law constant (P_i/X_i, atm)

H_A = Henry's Law constant P_i/C, [(atm^{-m3})/gmol]

H_B = Henry's Law constant (P_i/CRT, unitless)

H_C = Henry's Law constant C/C, $g(cm^{-3})/g(cm^{-3})$ or $gmol(cm^{-3})/gmol(cm^{-3})$ unitless

PT   = total pressure (atm)

P_i = partial pressure of organic in vapor

T   = temperature (°K)

MW = molecular weight of the organic

C   = concentration

Y_i = mole fraction of component i in vapor

X_i = mole fraction of component i in liquid

R   = universal gas constant

Conventionally, the more volatile component is numbered 1 so the relative volatility is always greater than or equal to 1. At 1 atmosphere pressure and $100^{\circ}C$ the relative volatility of a dilute, low-solubility organic in water is equal to the Henry's Law constant at $100^{\circ}C$. Because these are the conditions at which a distillation column or steam stripper normally operates, Henry's Law constant can be used to describe vapor-liquid equilibrium behavior in both distillation and steam-stripping systems.

SECTION 2

SITE CHARACTERIZATION

Site characterization defines the treatment requirement and as such, is the first phase in selecting a treatment method. Many factors must be evaluated, ranging from the nature and concentration of the contaminant to local ordinances (Table 2). It is important that each item in Table 2 be considered so that the most suitable system can be selected.

INSTRUCTIONS AND EXPLANATIONS

This checklist is provided to ensure that all information necessary to assess the site and its treatment is obtained. Some of the items are self-explanatory; others are discussed below.

Extent of Treatment Needed

If phases are evident, that is, if a film or layer of organic is present above or below the water layer, then a phase separation should be performed by skimming in a pond, pumping from multiple levels in a well, or using a separation tank. The organic phase should be disposed of separately, normally by proper packaging and shipment to an approved disposal facility. Then, if desired, the aqueous phase can be treated on site.

Effluent Requirements

Discharge options could include discharge into public sewer systems, in-plant water treatment system, a permitted NPDES discharge point, transferred off-site for disposal in an approved manner, or recharged into an aquifer. Restrictions and limitations on these options should be determined before a decision is reached.

Properties of Spilled Material

Henry's Law constant must be determined as outlined in Section 3. To calculate Henry's Law constant, the operating temperature of each system is required. Methods to obtain this temperature are provided in Section 5.

Data on the basic properties of the contaminants must be gathered before selecting a technology. Solubility may be used to estimate the maximum concentration in the water to be treated, and to determine reflux concentrations for steam stripping. Toxicity and flammability are necessary to determine any emission limits. The reactivity and other fate properties of the material are important to calculate material disappearance and for safety considerations. Safe handling requirements are necessary for selecting the proper equipment.

TABLE 2. CHECKLIST FOR SITE EVALUATION

o Influent characterization
    ____ Contaminant identity
    ____ Contaminant concentration (mole fraction) in water
    ____ Total quantity of water to be treated
    ____ Number, type, and thickness of nonaqueous layers
    ____ Influent flowrate

o Effluent requirements
    ____ Available discharge options
    ____ Available discharge capacity
    ____ Discharge concentration limits
    ____ Discharge flow requirements

o Properties of spilled material (see Section 3)
    ____ Henry's Law constant (mole fraction)
    ____ Solubility
    ____ Toxicity
    ____ Sorptive properties
    ____ Reactivity (hydrolysis, photolysis, biodegradation)
    ____ Flammability of vapor
    ____ Handling requirements (safety)
    ____ Disposal requirements for concentrated material
    ____ Other contaminants in water

o Climate
    ____ Season during which water treatment is anticipated
    ____ Average ambient air temperature
    ____ Average precipitation
    ____ Solar radiation
    ____ Wind
    ____ Relative humidity

o Site-specific considerations
    ____ Water temperature
    ____ Site accessibility
    ____ Water location (surface/groundwater)
    ____ Response time requirements
    ____ . Volatile emissions limits
    ____ Altitude

o Integration with other treatment options
    ____ Relationship with other water treatment technologies at the
         site
    ____ Emission control devices

o Environmental considerations
    ____ Residential characteristics
    ____ Ambient air quality
    ____ OSHA requirements
    ____ Municipal requirements

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If concentrated organic compounds are to be generated by phase separation or steam stripping, disposal requirements for this material must also be considered before selecting a treatment option. Finally, other contaminants in the water should be determined to assess any pretreatment that might be necessary to prevent fouling, corrosion, etc.

Climate

The most important climatic consideration is the ambient temperature. An average daily temperature must be used in calculation of Henry's Law constants. If treatment is expected to continue over a long period of time, calculations should be made for average temperature during each month of the treatment. Average precipitation, solar radiation, relative humidity, and wind speed (available from a variety of sources, including local airports) also affect the evaluation, particularly in sites consisting of open bodies of water. To account for these effects at least partially, use measured water temperatures for the operational temperature of supplied water.

Site-Specific Considerations

Selecting the proper technology and support equipment depends upon the accessibility of the site, location of water (groundwater vs. surface water), and the necessary response time.

Emission limits at the site are affected by land usage in the area around it. The altitude of the site does not generally alter the outcome of the evaluation, but the effects of lower boiling temperatures and air densities can affect material removal rates. If the site is at a high altitude, data in this manual can be recalculated for these effects (see Section 3).

Integration with Other Treatment Systems

Careful evaluation of the site characteristics, as outlined previously, define the treatment requirements; the need for an integrated water treatment system often becomes apparent from this exercise. The requirements for each unit operation in the integrated system must then be defined and each unit selected based on available selection criteria.

Often, a single type of treatment unit is inadequate to meet operational and removal requirements. Several units may then be used in series. A common example is using sand filtration for solids removal, then air or steam stripping to remove a large portion of a volatile organic, followed by carbon adsorption to polish the effluent to meet a low discharge standard.

Air emission standards are a critical consideration at many treatment sites. Options for emission control technologies must be considered, along with water treatment technologies, to yield total treatment costs. This cost can then be compared to the cost of other technologies, such as carbon adsorption, that generate lower emissions.

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SECTION 3

MATERIAL PROPERTIES AND ESTIMATION METHODS

To aid in estimating material properties, Appendix B lists common physical properties and Henry's Law constants for volatile organic compounds that are designated as hazardous substances under the Comprehensive Environmental Response Compensation and Liability Act (CERCLA). Synonyms and chemical formulas are listed for some compounds, followed by solubility, vapor pressure and Henry's Law constant information. If the compound either reacts with water (hydrolyzes) or decomposes in water by some other mechanism, then this information is listed with the solubility data.

Care should be exercised while using the data presented in Appendix B. Although these data are the best available at the time of writing, some experimental data were not available for certain compounds. For this reason, the appendix gives both theoretical and experimental data available for the listed compounds. These data are satisfactory for making preliminary engineering evaluations of the technologies. However, for design and construction purposes, experimental data collected at the actual operating temperature should be used.

ESTIMATION METHODS

Henry's Law constants are very sensitive to temperature variation, so experimental data taken at one temperature requires correction for use at another. In this section, methods are given for predicting the variation of Henry's Law constants with temperature and pressure, as well as for predicting Henry's Law constants from other physical properties.

Estimation of Henry's Law Constants from Vapor Pressure and Solubility Data

Case I: Vapor Pressure and Solubility at the Same Temperature--

The most common method for estimating Henry's Law constants is to divide the pure compound vapor pressure by its solubility limit in water. For compounds with low solubilities, this method is theoretically sound. Attempts at making this type of prediction are a source of confusion in the area of vapor-liquid equilibrium because of neglecting certain terms, such as molecular weight. However, if careful attention is given to the units and calculation procedures, this method can yield useful results from readily available data.

Vapor pressure and solubility data used to calculate Henry's Law constants must be taken at the same temperature and expressed in consistent units. Qualitative solubility data, such as slightly soluble, insoluble, very soluble, etc., are not useful for estimating Henry's Law constant. Data must be expressed quantitatively, such as grams per liter, at a given temperature. Pure compound vapor pressure can be taken from vapor pressure or boiling point data, the boiling point being the temperature at which the vapor pressure is 1 atm (or other pressure as specified).

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Case II: Vapor Pressure and Solubility Data at Different Temperatures --

If vapor pressure and solubility data are available, but were taken at different temperatures, the vapor pressure must be adjusted to conform to the solubility data, since prediction of the temperature effect on compound solubility is not as accurate and should be avoided. Vapor pressure is adjusted for the temperature of interest using the Clausius-Clapeyron equation:

$$\frac{dP}{dT} = \frac{P \Delta Hv}{RT^2} \tag{3}$$

where:

P   = vapor pressure (atm),

T   = temperature (^{O}K),

ΔH_v = heat of vaporization of the organic (cal/gmol),

R   = universal gas constant,

    = 1.987 (cal)/(gmol) (^{O}K), and

    = 0.7302 (atm)(ft^3)/(lb-mol)(^{O}R)

This equation is useful at atmospheric pressure, when the ideal gas law may be assumed. The integrated form of Equation 3, assuming ΔH_v is independent of temperature, is as follows:

$$\ln \frac{P}{P_o} = \frac{\Delta H_v}{RT_o} - \frac{\Delta H_v}{RT} \tag{4}$$

where:

P_o = vapor pressure of known data at temperature To, and

P   = calculated vapor pressure at temperature of interest, T.

If two or more data points for compound vapor pressure are known, interpolation techniques may be used to obtain vapor pressures at various temperatures. In addition, equations are available in published literature (5) to calculate vapor pressures for certain temperature ranges.

Once vapor pressure and solubility data are known, Henry's Law constant can be calculated by the following equation:

$$H = \frac{P/P_T}{0.18 \ C/MW} \tag{5}$$

where:

C   = weight percent (wt %) organic at maximum solubility (%),
MW   = molecular weight of organic (g/gmol)
H   = unitless Henry's Law constant (mole fraction/mole fraction)
P   = vapor pressure of pure organic (atm), and
P_T = total pressure (atm).
0.18 = MW of water/100

This equation assumes a low concentration of the organic.

Estimation of Henry's Law Constants for Various Temperatures

Often the desired operating temperature differs from published data on Henry's Law constants. In this case, the Henry's Law constant must be adjusted to the system's operating temperature. When Henry's Law constants are known for several temperatures, a linear interpolation must be used to find the Henry's Law constant of interest. This method should prove accurate enough for preliminary performance estimates if the desired temperature is bounded by data on both higher and lower temperatures.

Methods are available to express Henry's Law as a function of temperature, thereby permitting calculation at any temperature. These methods require experimental determination at several temperatures to determine values of various constants given in the equation. Goldstein (6) gives a good treatment of this topic and provides calculated values for Henry's Law constants for a variety of organic compounds at several temperatures.

Estimation of Henry's Law Constants for Various Pressures

Vapor pressure is a function of total pressure, although this dependency can be ignored under the range of conditions normally found in the field. The definition of Henry's Law in this manual assumes a total pressure of one atmosphere.

To adjust Henry's Law constants for pressure, multiply the value given in mole fraction/mole fraction by atmospheric pressure at sea level and then divide by the operating pressure in the same units. For Henry's Law constants presented in units of pressure, division by the ambient pressure will normally give the unitless Henry's Law constant as used in this manual. (See Table 1 for a summary of such conversions.)

Estimation for Compounds with High Solubilities in Water

If an organic is miscible with water, Equation 5 for Henry's Law constant reduces to:

$$H = \frac{P}{P_T} \tag{6}$$

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where:

P = vapor pressure of pure organic, and

P_T = total pressure.

Equation 6 uses

$$H = \frac{P}{P_T} + 1 + \frac{MW(100 - C)}{18C}$$ (7)

where:

MW = molecular weight of organic, and

C = weight percent (wt %) of organic at its solubility limit.

SECTION 4
TECHNOLOGY EVALUATION

Performance and cost data for the representative equipment designs discussed in Section 5 are covered in this section. These data are estimated to be within an error factor of 2 to 3 of the actual performance and cost that were found for similar systems in actual use. However, available field systems may differ widely from the design assumptions used in developing these data.

This section should only be used to obtain a rough estimate of the relative merits of the technologies presented. Data in Section 5 should then be used to compare the performance of available equipment to the estimated performance and cost.

The process of system evaluation is divided into four major steps: (1) the organic removal obtained using each continuous flow unit; (2) the time required for treatment; (3) the emissions resulting from operation; and (4) the cost of the units, their mobilization, and operation. The evaluation process is intended to eliminate technologies based on performance and then permit the selection of the best remaining technology based on cost.

ORGANIC REMOVALS

Figures 2 through 9 give organic removals for technologies that allow continuous operation. These are the bubble column (Figures 2 and 3); spray column (Figures 4 and 5); packed-column air stripper (Figure 6); cooling tower (Figures 7 and 8); and packed-column steam stripper (Figure 9). The figures have material removals plotted for each of four operating modes. For all technologies, the selected cases represent approximate operating ranges for gas and liquid flow for a clean water and organic feed. Detailed operating modes are described in Section 5.

During actual treatment, the operating range can be limited by a variety of factors (Section 6) that will reduce maximum gas and liquid throughput. The removal is dependent on the ratio of gas and liquid flow rates: If site factors limit one flowrate, the other may be reduced by the same percentage to obtain the organic removals shown in the figures.

Figures 2 through 9 are calculated based on Henry's Law constants, number of stages, and gas-to-liquid ratios. As such, they are theoretical calculations that assume ideal column operation. Departures from the ideal will occur in all real systems, although the magnitude of these

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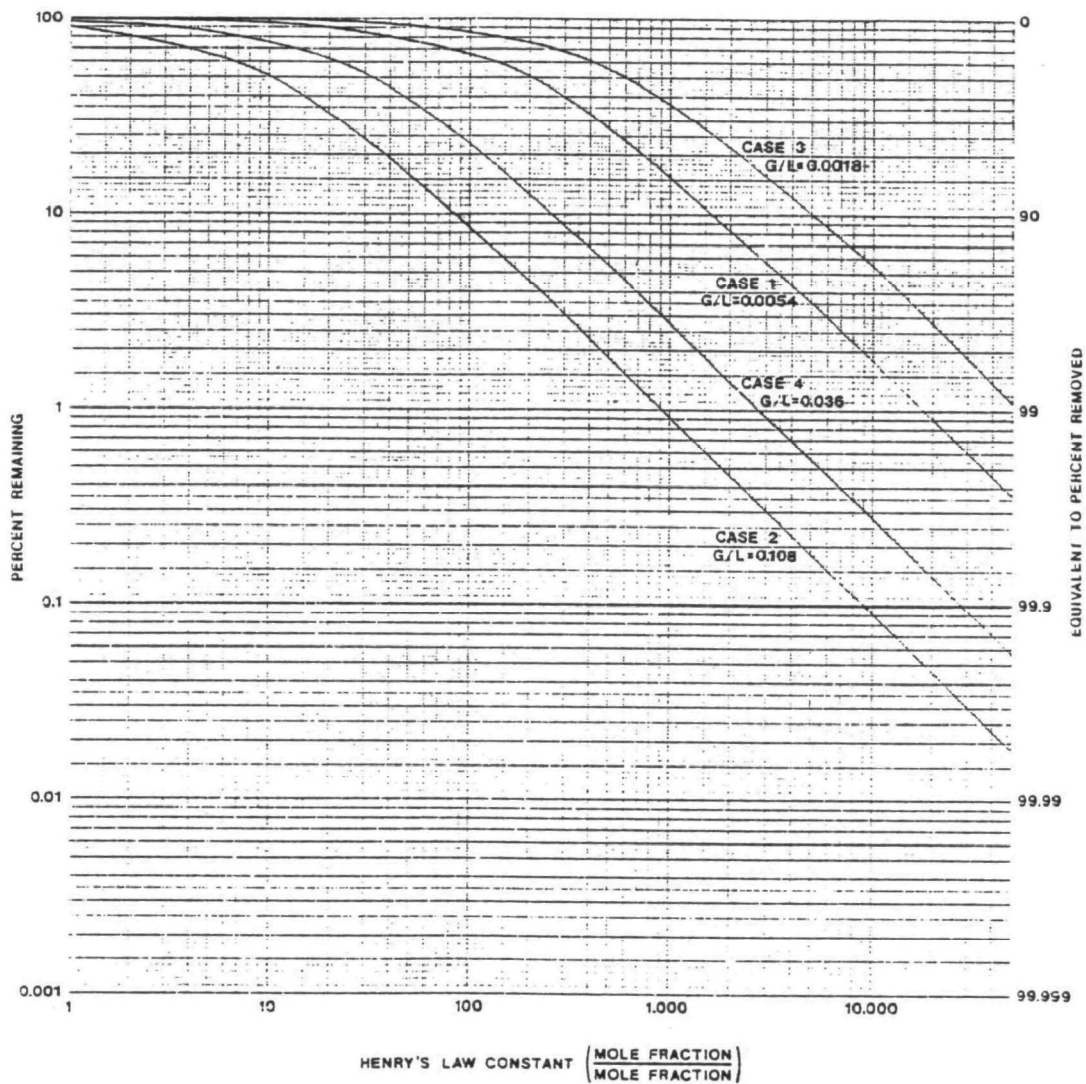
Figure 2. Bubble column design basis, organic removal, parallel operation

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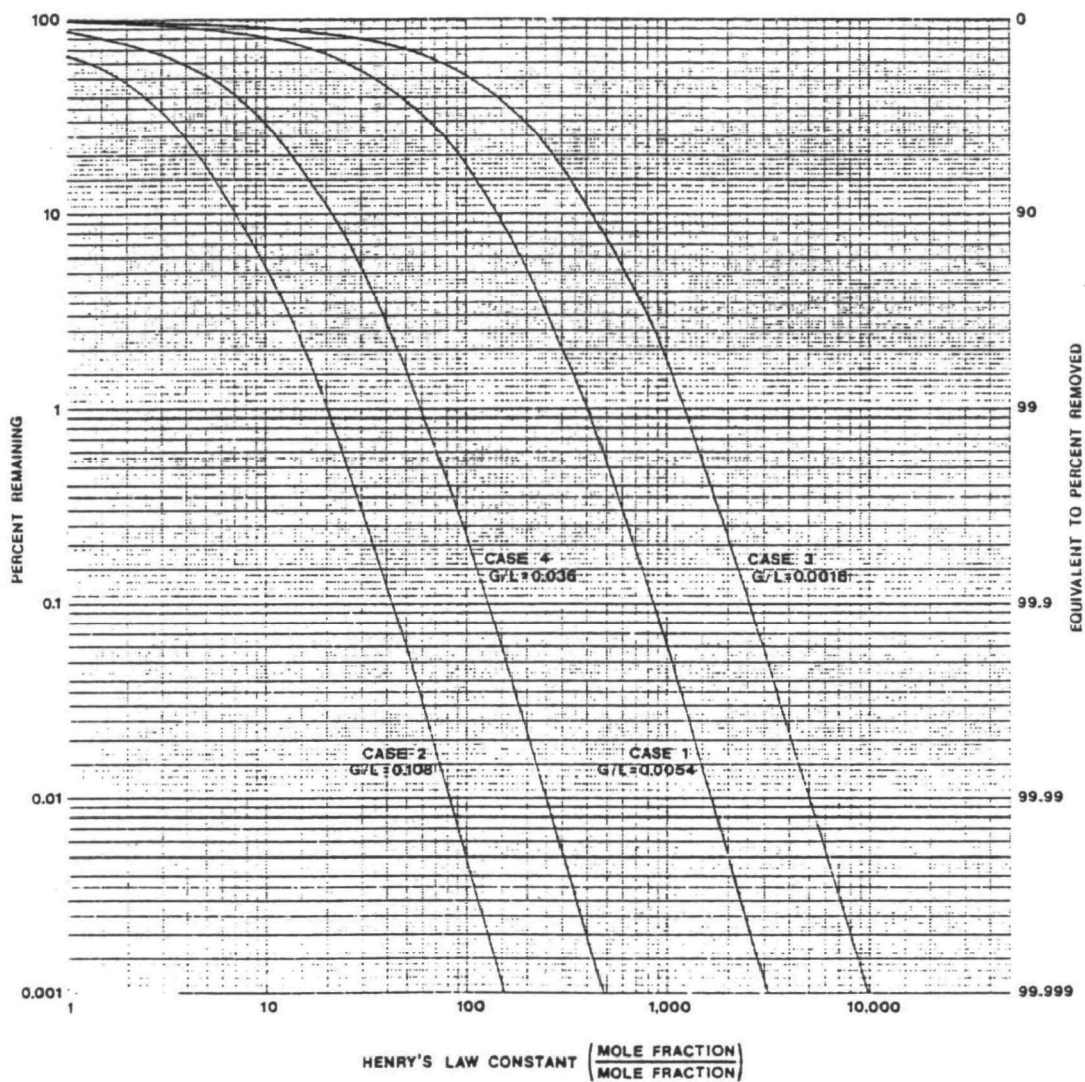
Figure 3. Bubble column design basis, organic removal, series operation (4 columns)

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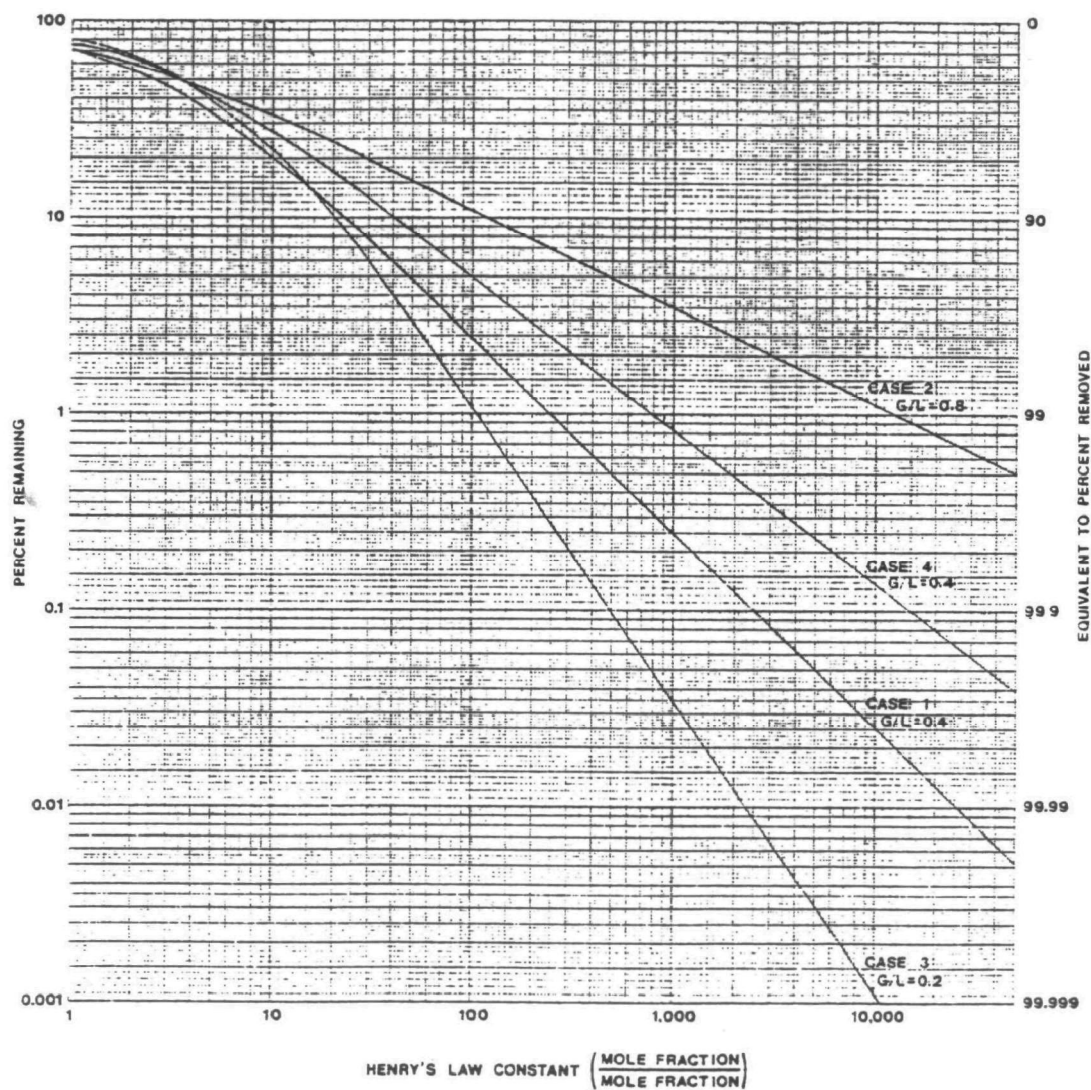
Figure 4. Spray column design basis, organic removal, parallel operation

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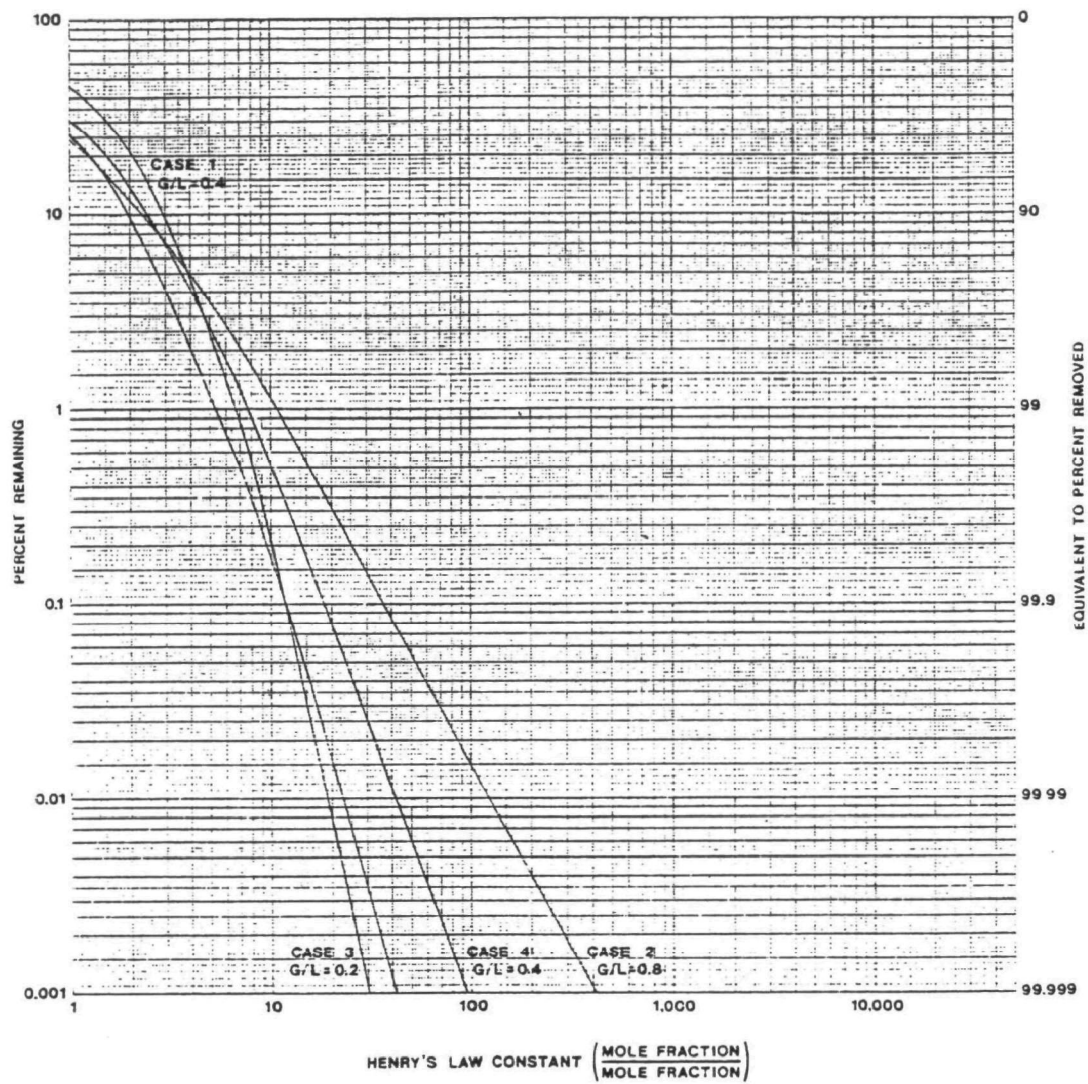
Figure 5. Spray column design basis, organic removal, series operation (4 columns)
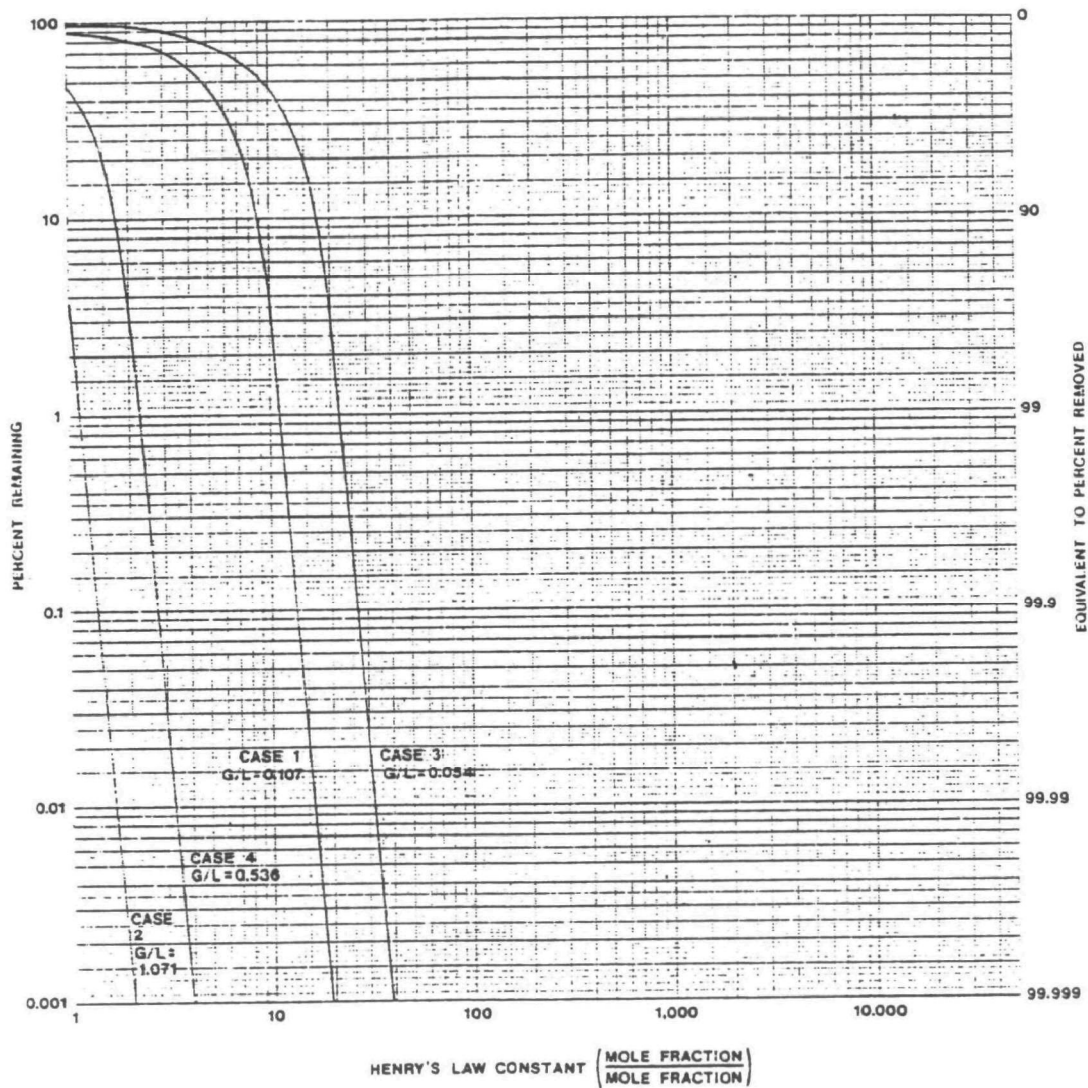
Figure 6. Packed air-stripping column design basis, organic removal, single column operation
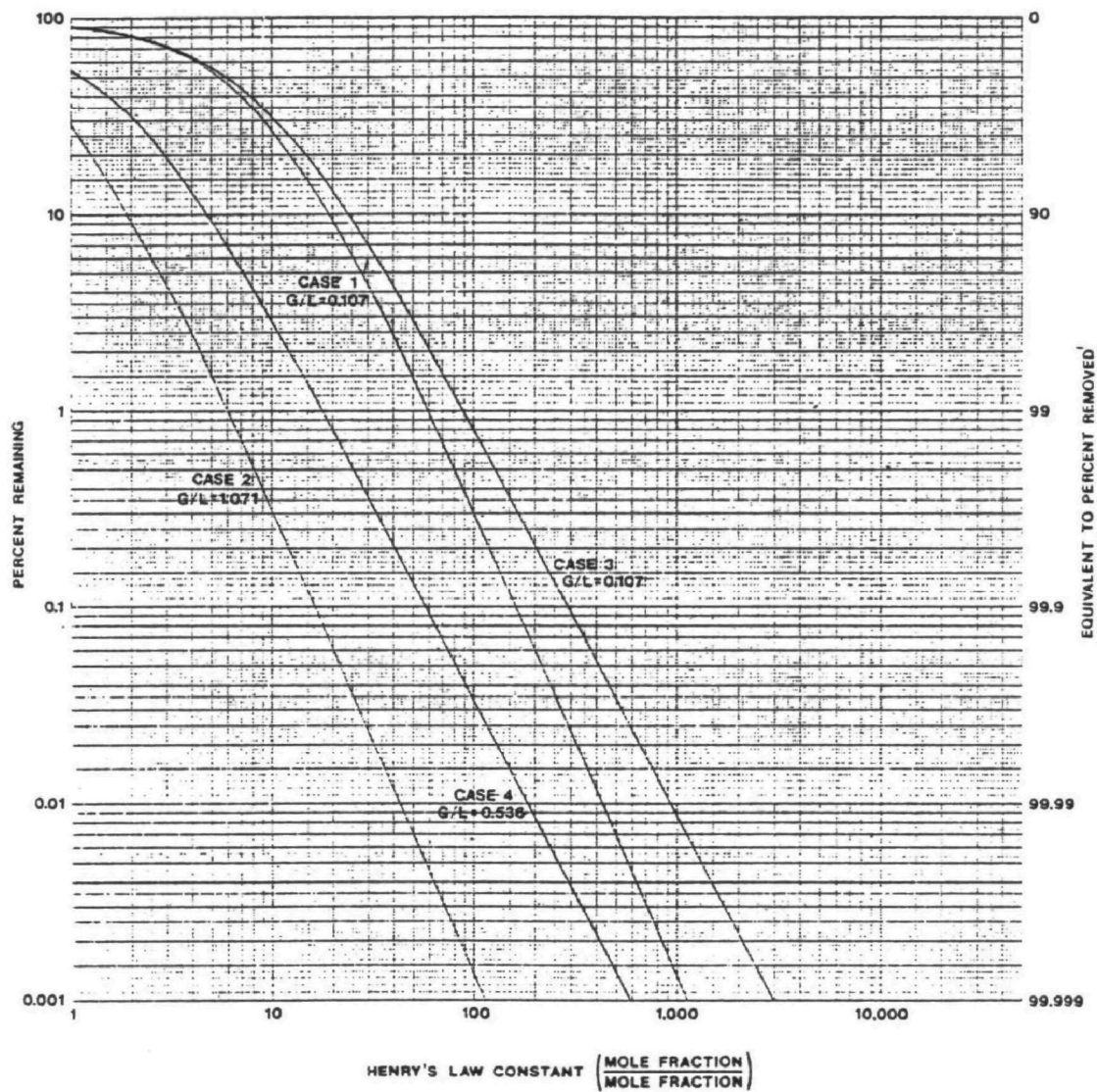
Figure 7. Cooling tower design basis, organic removal, parallel operation
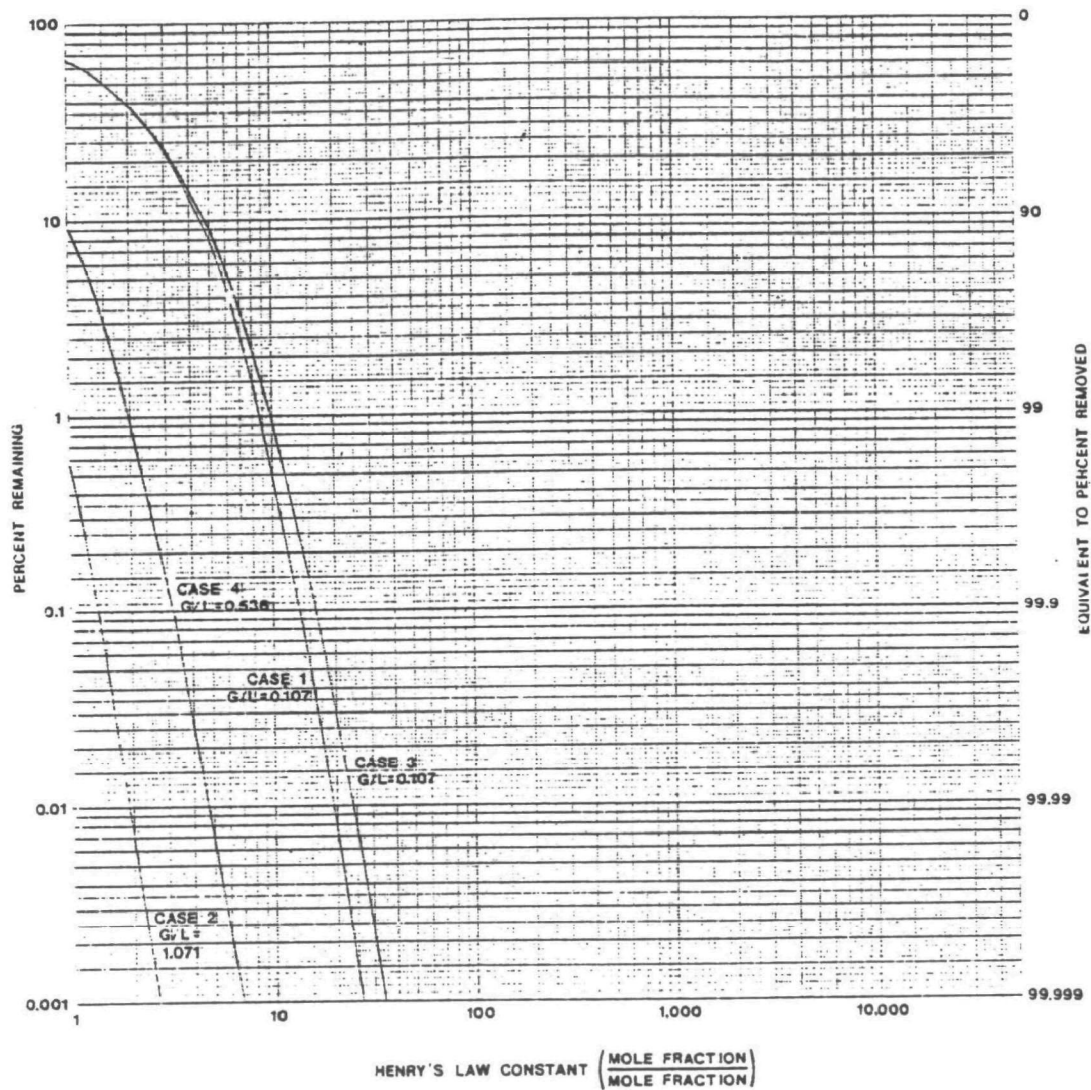
Figure 8. Cooling tower design basis, organic removal, series operation
(4 columns)
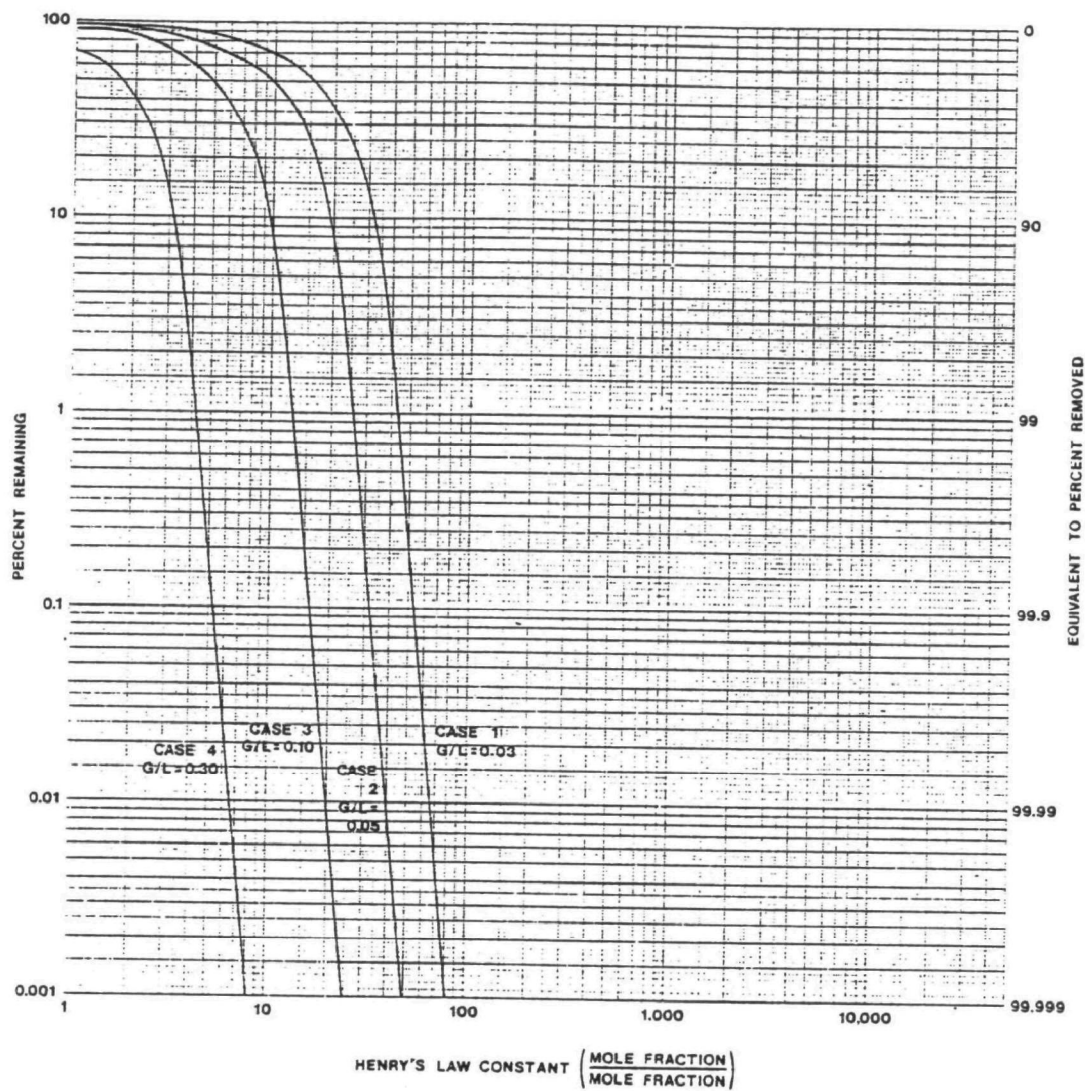
Figure 9. Packed column steam stripper design basis, organic removal

departures can vary greatly from system to system. The departures are caused by: (1) gas and liquid short-circuiting, (2) adsorption and absorption of the organic onto impurities in the water, and (3) improper placement of packings, distributors, and other column internals.

In any real operating system, the removal curves begin to level off at high removal percentages. It is impossible to predict exactly where the limit is; the specific column must be operated as it will be used. A reasonable estimate of a single-column maximum removal would be between 99% and 99.9%, although no data exist that allow this generalization. It should be noted that this limitation is partially due to the limits of single-column operation. We suggest that when high removals are necessary, multiple columns should be used in series.

Removal calculations for designs with multiple units presented in Section 5 on trailers (i.e., bubble column, spray column, cooling tower) were developed for both series and parallel operation of the units.

TIME REQUIREMENTS FOR REMOVAL

The batch systems of unaided evaporation, surface sprayers, and surface aerators are best evaluated by comparing the half-lives of organics in model impoundments employing the three systems. (A half-life is the time required to volatilize one-half of the organic from the impoundment.)

For this comparison, the model impoundment is a square, steep-sided basin 100 ft long x 100 ft wide x 10 ft deep. Figure 10 is a plot of the half-lives of the volatile organic using the three batch systems against the contaminant's Henry's Law constant. For both surface spraying and aeration, results are plotted for two sizes of commercially available units, representing the design cases in Section 5. These units are transportable and proportional to the model impoundment size.

No attempt is made to quantify effects of other incidental variables such as climatic conditions (wind and temperature), differences in a particular equipment design, and quality of the contaminated water. Instead, reasonable average values for the key variables are estimated based on probable field conditions, as explained in Section 5. As a rule of thumb, results obtained in the field should generally agree with the plotted values by a factor of 2 to 3, but there are exceptions.

To evaluate the time necessary to obtain a desired organic removal efficiency, refer to Figure 11 for the required number of half-lives. Then multiply by the hours per half-life from Figure 10 to obtain the required treatment time.
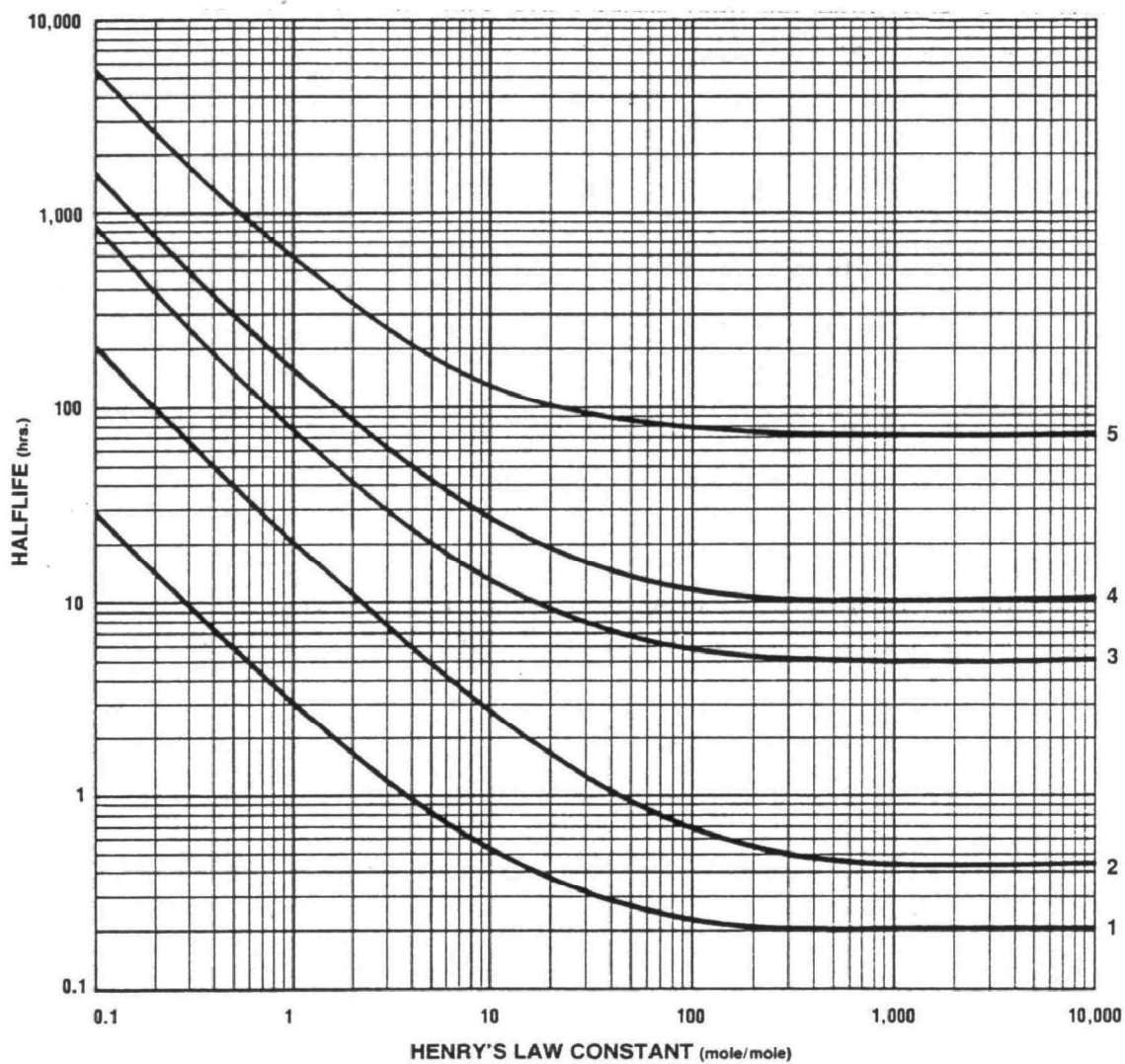
Figure 10. Half-life in model impoundment, batch systems

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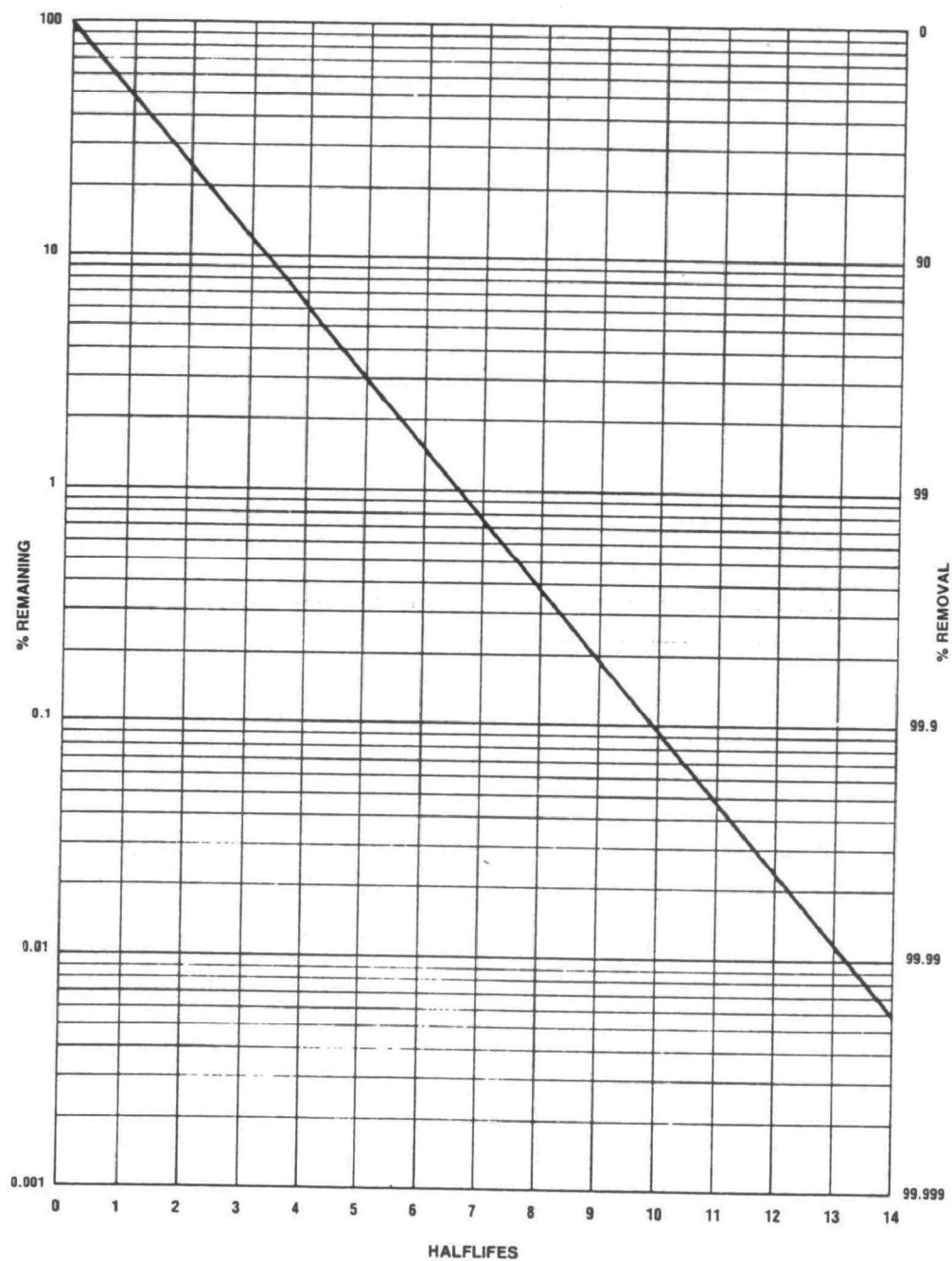
Figure 11.   Number of half-lives required to obtain removals

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The continuous systems of air or steam stripping can be used to augment volatilization from an impoundment. The discharge from the treatment system could either be placed back into the impoundment or sent to off-site disposal. Where the discharge is placed back into the impoundment, the half-life in the pond will be governed by the equation:

$$t_h = 0.693 \ \frac{V}{L(1-f)} \tag{8}$$

where:

t_h = half-life of organic in the impoundment,

V = volume of the impoundment,

L = liquid flowrate of the treatment unit, and

f = organic fraction remaining after treatment, based on the Kremser equation (4).

Results of this equation are plotted in Figures 12-19 for the design case systems and operating modes in treating the model impoundment. The same data are also presented in Table 3, along with batch system data. These figures and table neglect the volatilization occurring naturally from the impoundment. The actual half-life, including this or any other competing removal mechanism, can be obtained using the following equation:

$$\frac{1}{t_h} = \frac{1}{t_{h1}} + \frac{1}{t_{h2}} + \dots \tag{9}$$

where:

t_h = half-life of the organic in the impoundment, and t_{hx} =

half-life of the organic, considering mechanism x.

The half-life thus obtained can then be used with Figure 11 to calculate the time requirement for any removal percentage.

Examination of the half-life figures shows that surface aerators will normally be the best option to augment volatilization from an impoundment. However, operational constraints of surface aeration, the desire to control organic emissions, or the unavailability of a surface aerator may require the use of one of the other units for this service.

Table 4 compares the design case continuous treatment units, assuming off-site discharge is available. In this case, the treatment time is purely a function of liquid flowrate. For convenience, the percent removals for each of four Henry's Law constants also appear.
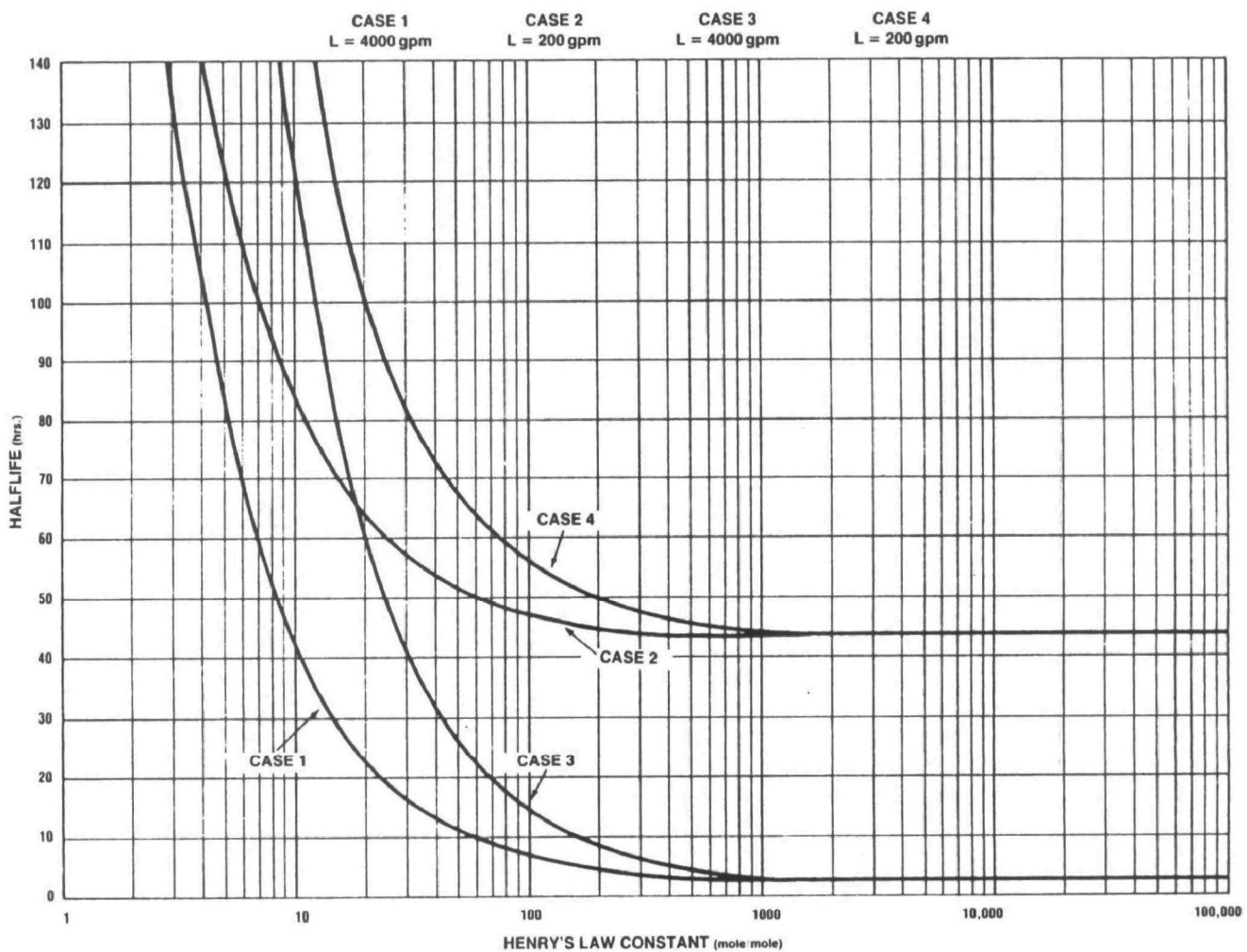
Figure 12. Half-life in model impoundment, bubble column design basis, parallel operation

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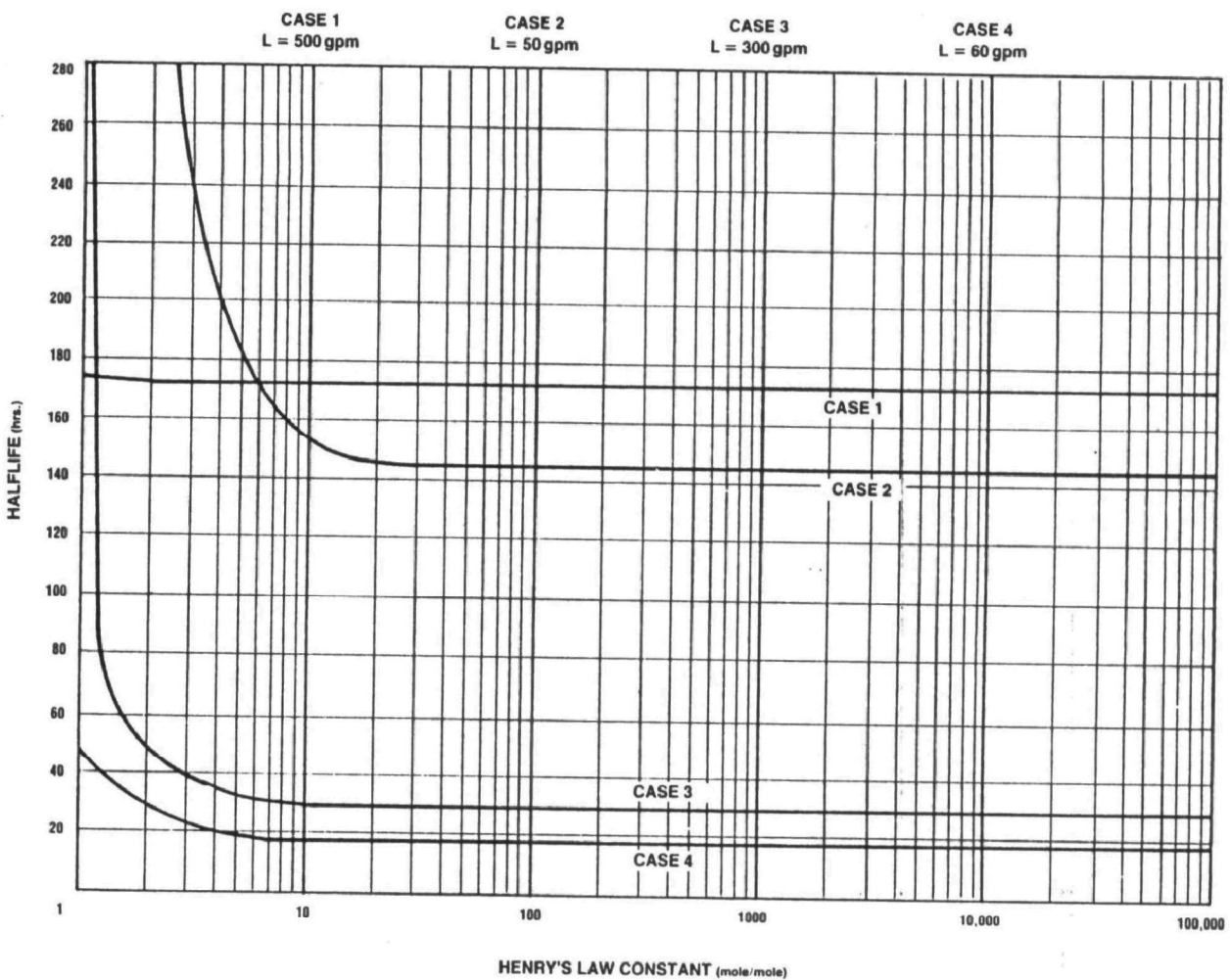
Figure 13. Half-life in model impoundment, bubble column design basis, series operation

31
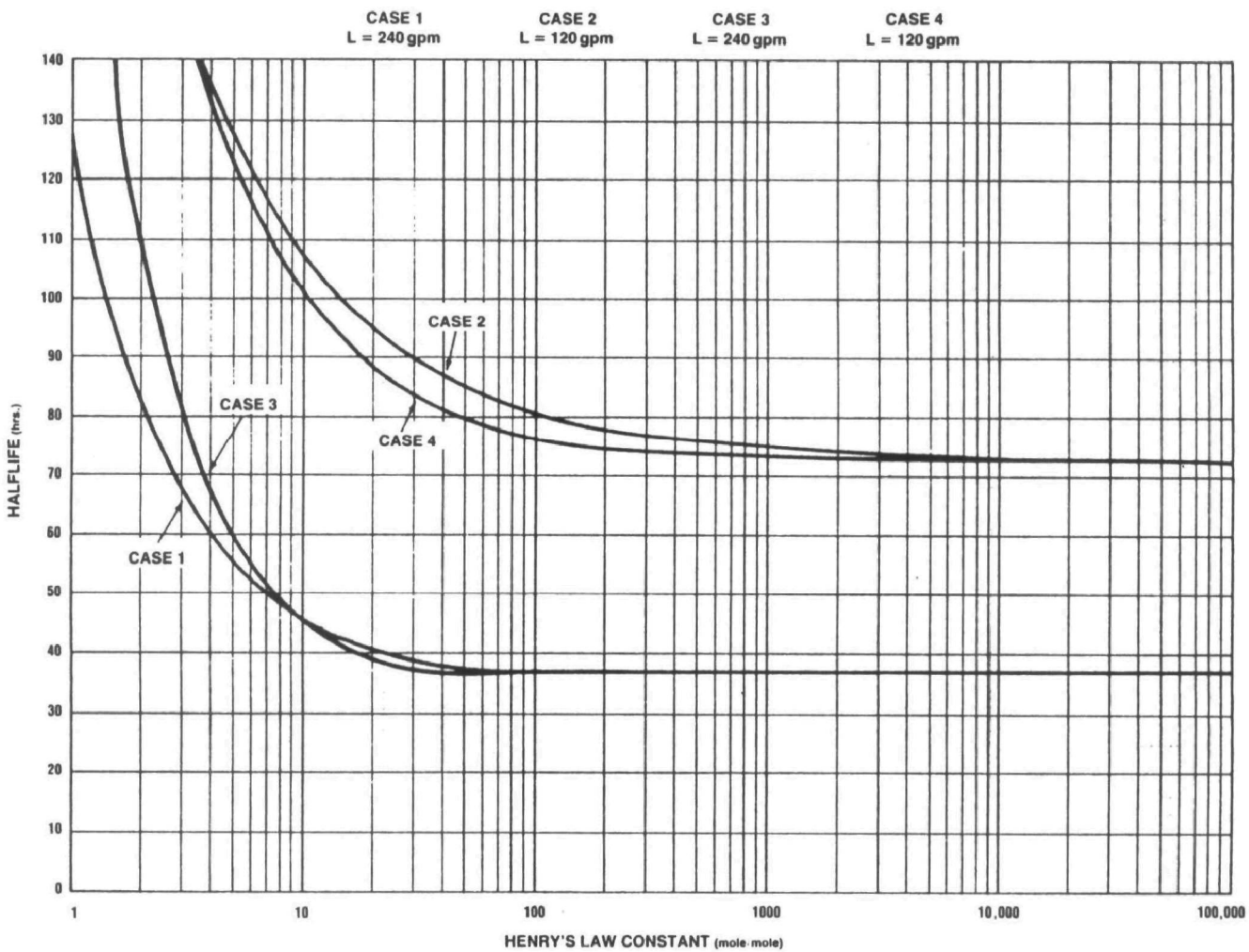
Figure 14. Half-life in model impoundment, spray column design basis, parallel operation

32
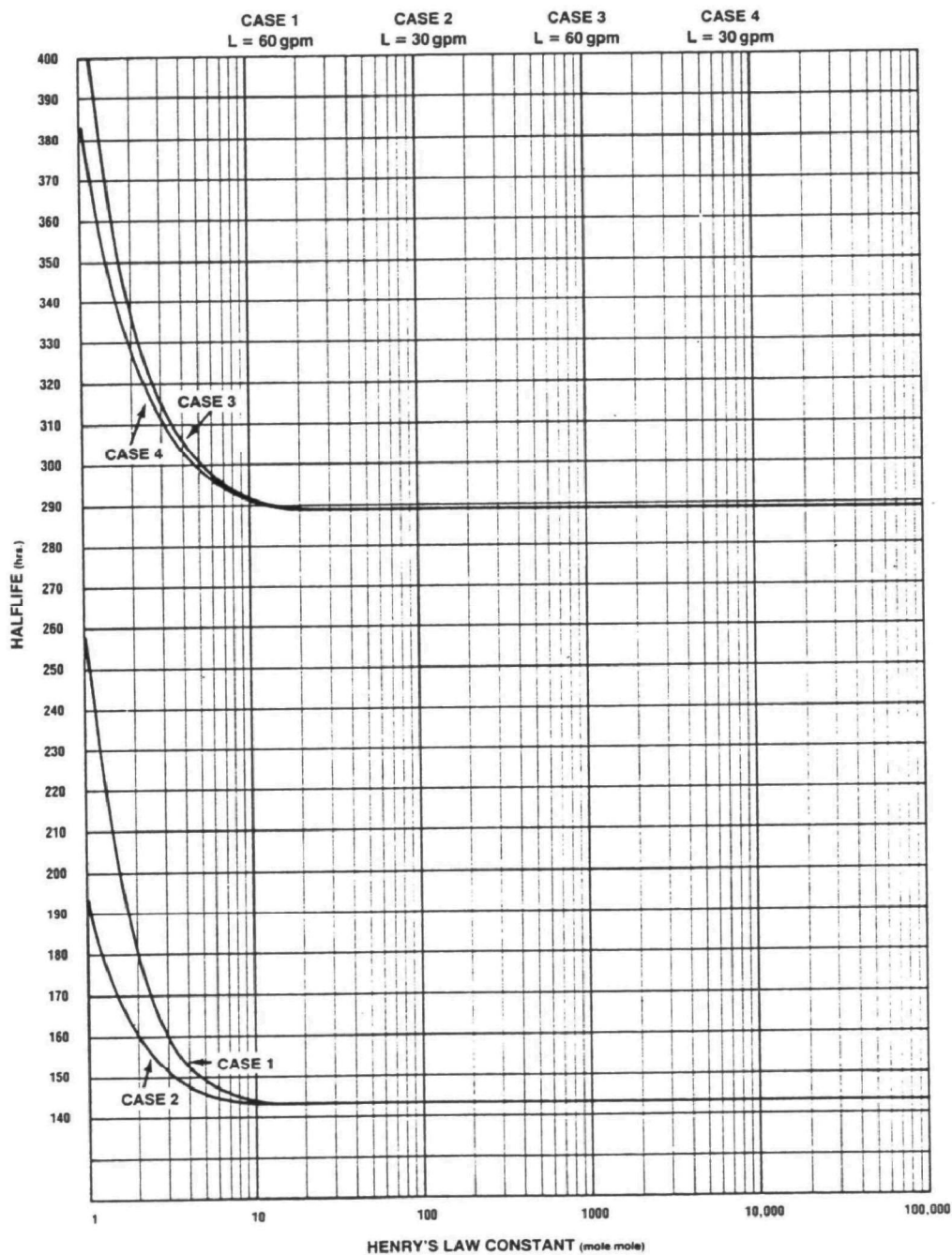
Figure 15. Half-life in model impoundment, spray column design basis, series operation

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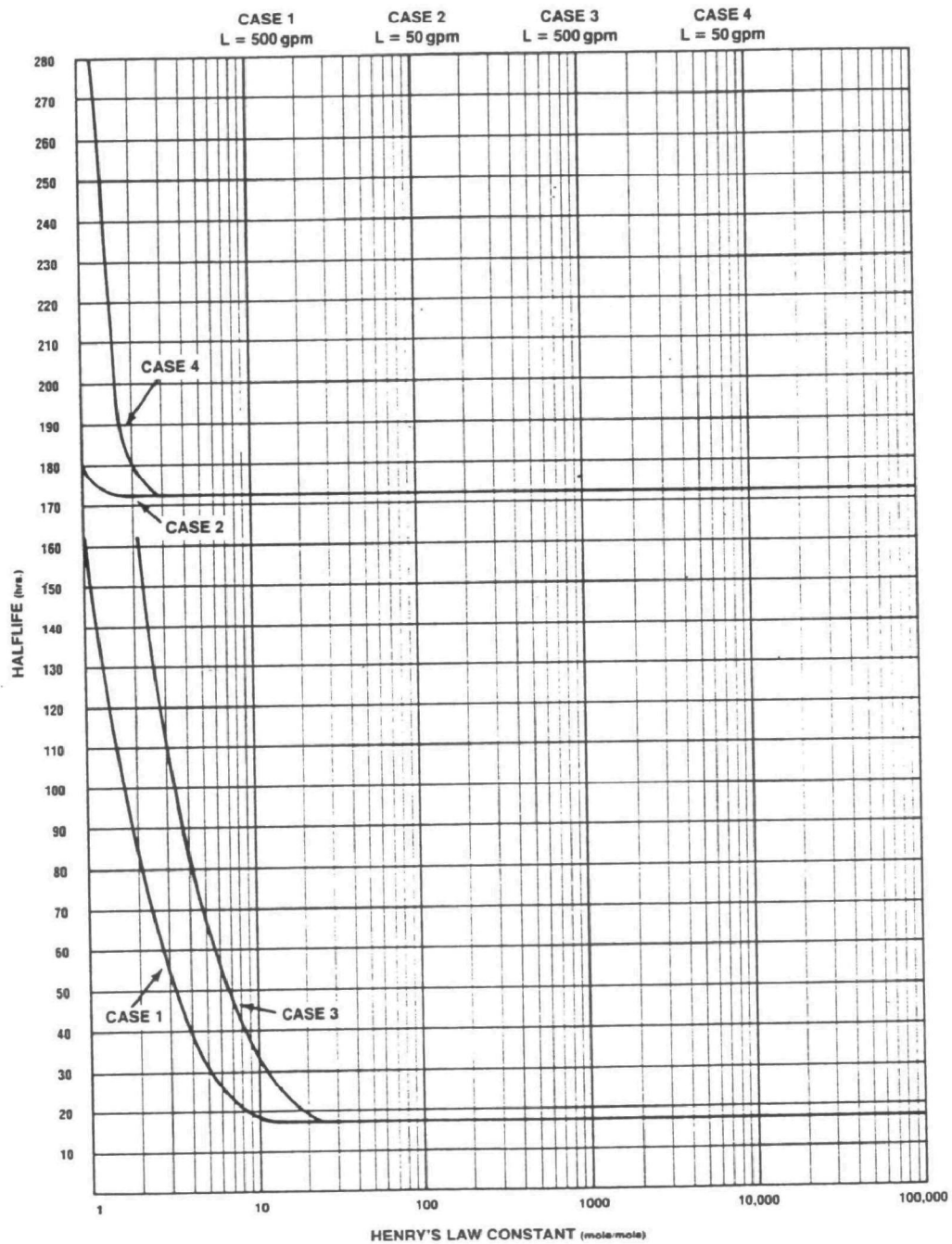
Figure 16. Half-life in model impoundment, packed column air stripper, design basis

34
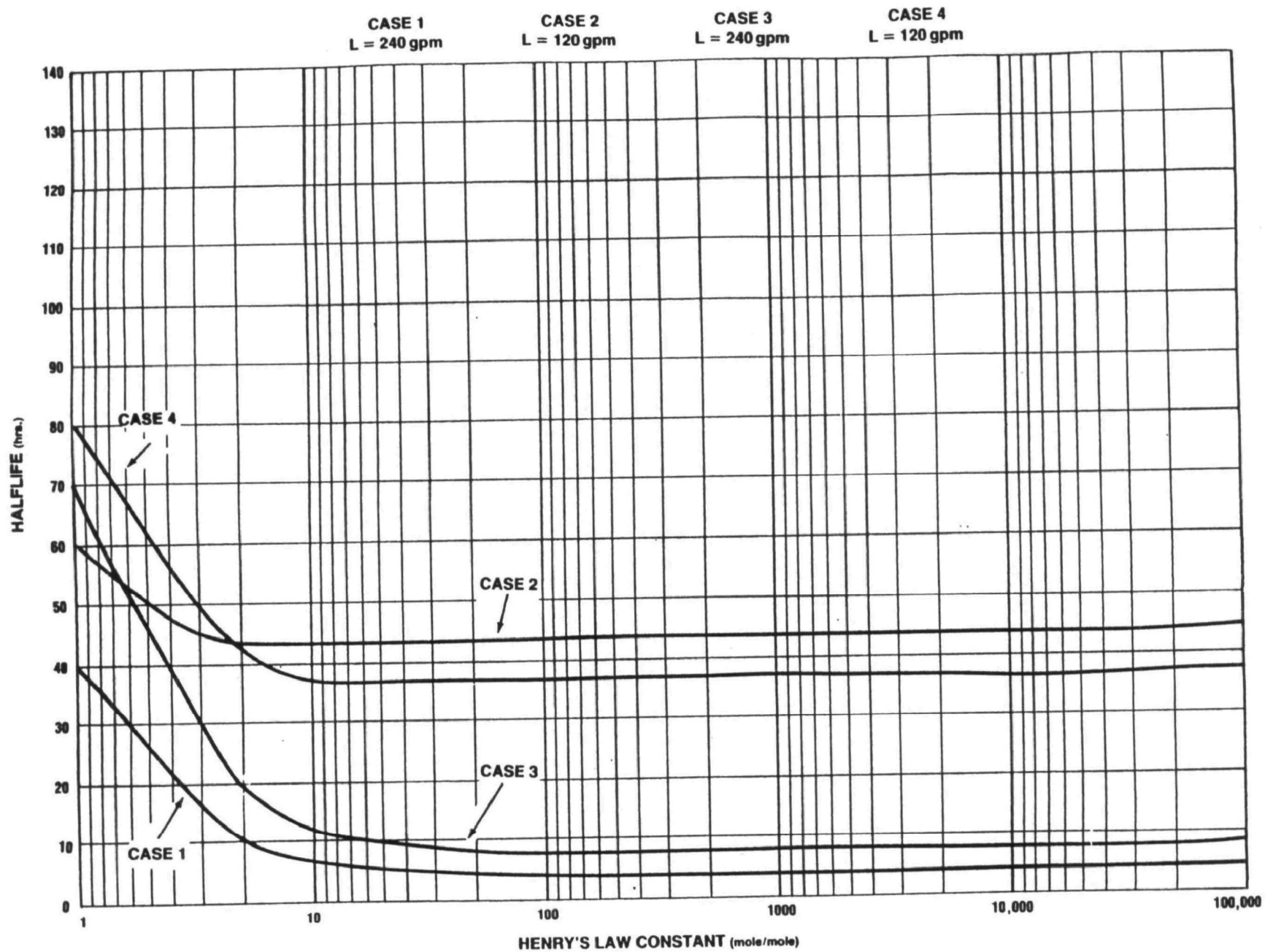
Figure 17. Half-life in model impoundment, cooling tower design basis, parallel operation

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Figure 18. Half-life in model impoundment, cooling tower design basis, series operation

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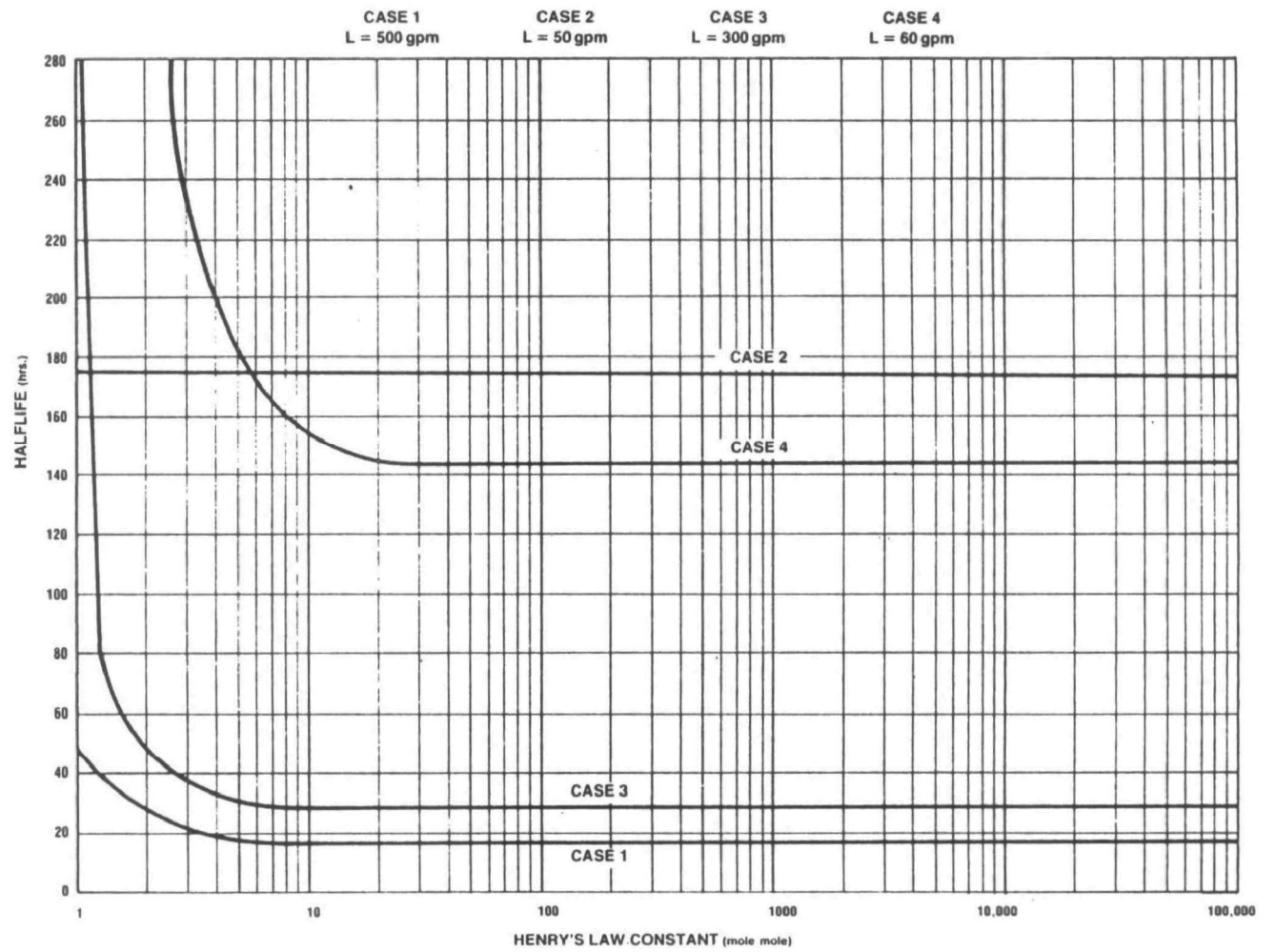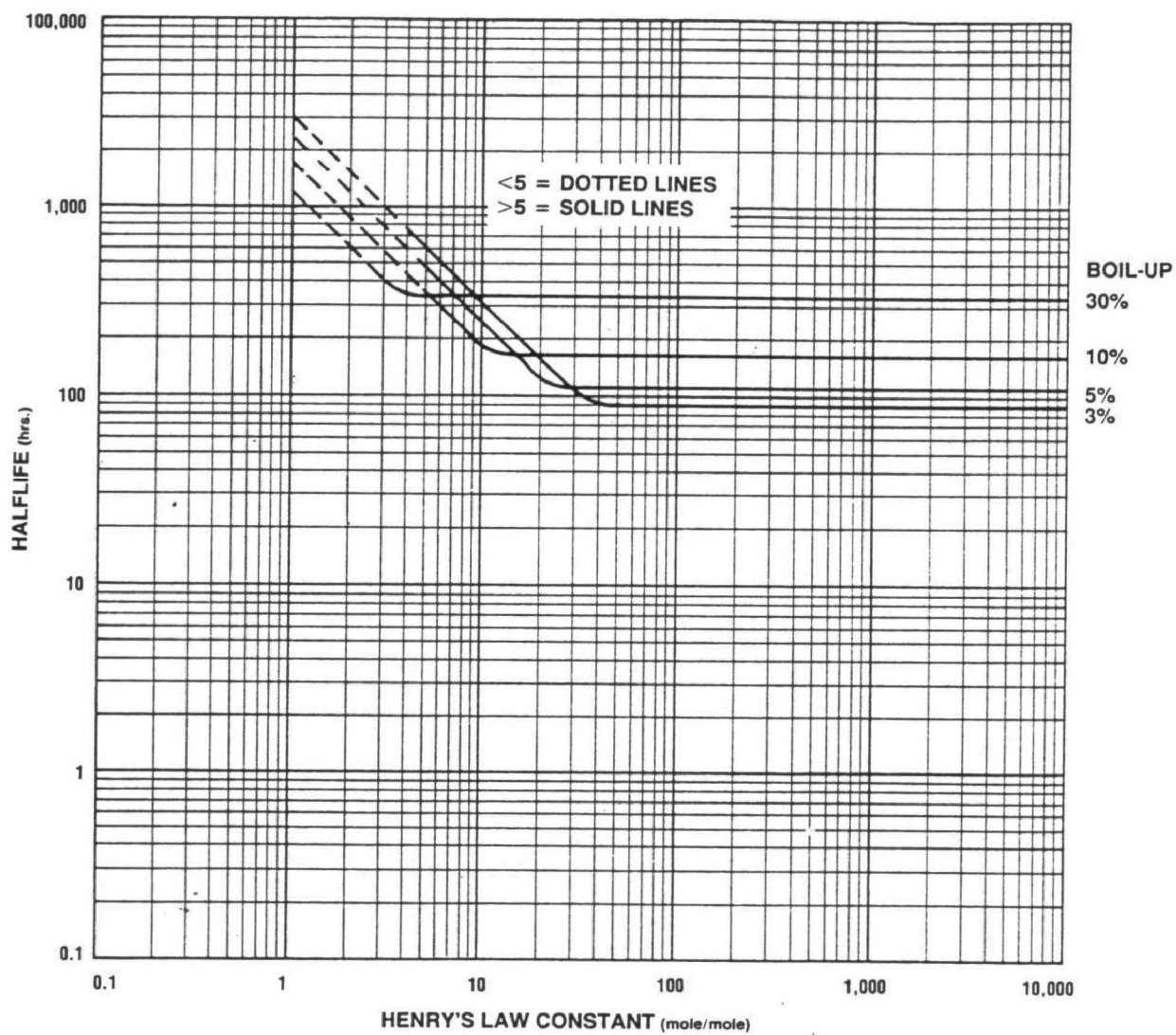
Figure 19. Half-life in model impoundment, steam stripper design basis

TABLE 3. TIME REQUIRED FOR TREATMENT OF MODEL IMPOUNDMENT, RECYCLE DISCHARGE TO POND

Technology	Case Number	Operating Mode	Liquid Flow Rate(gpm)	50% Removal H=5	H=25	H=200	H=5000	90% Removal H=5	H=25	H=200	H=5000	99% Removal H=5	H=25	H=200	H=5000	99.9% Removal H=5	H=25	H=200	H=5000
Pond, unagitated	1			197	107	87	84	656	356	290	281	1312	712	581	563	1967	1068	871	844
Pond, surface sprayer	1	25 hp		46	18	12	12	152	61	41	39	304	122	83	77	457	184	124	116
	2	50 hp		23	9	6	6	76	31	21	19	152	61	41	39	228	91	62	58
Pond, surface aerator	1	50 hp		5	1.4	0.6	0.5	17	5	2	2	34	10	4	3	51	14	6	5
	2	100 hp		0.9	0.3	0.2	0.2	2.8	1.1	0.8	0.7	5.7	2.3	1.5	1.4	8.5	3.4	2.3	21
Bubble column	1	Parallel	4000	82	18	4	2	272	60	14	7	544	120	28	15	824	182	42	??
	2		200	124	59	45	43	408	196	150	143	815	392	299	286	1235	594	453	434
	3		4000	243	50	8	2	801	166	27	8	1602	332	54	16	2428	503	82	24
	4		200	284	91	49	44	937	302	163	144	1874	603	326	287	2839	914	493	436
	1	Series	1000	86	22	9	9	283	72	30	29	566	144	60	57	857	218	92	87
	2		50	211	174	173	173	695	575	572	572	1391	1150	1143	1143	2107	1742	1733	1733
	3		1000	246	54	12	9	812	177	40	29	1624	354	81	57	2461	537	122	87
	4		50	358	188	173	173	1181	619	572	572	2361	1238	1144	1143	3578	1876	1734	1733
Spray column	1	Parallel	240	54	40	37	36	179	131	121	119	357	262	241	238	541	397	365	363
	2		120	126	92	78	73	417	303	259	242	834	607	517	484	1263	919	783	733
	3		240	51	40	36	36	420	128	120	119	840	257	239	238	1259	389	362	361
	4		120	121	84	74	72	399	279	246	239	798	557	491	478	1209	844	744	724
	1	Series	60	146	144	144	144	482	476	476	476	965	953	953	953	1462	1444	1444	1444
	2		30	299	289	289	289	986	955	953	953	1972	1910	9106	1906	2988	2894	2888	2888
	3		60	148	144	144	144	489	476	476	476	978	953	953	953	1482	1444	1444	1444
	4		30	297	289	289	289	979	953	953	953	1957	1907	1906	1906	2966	2889	2888	2888
Packed air stripping column	1	Single column	500	32	17	17	17	107	57	57	57	214	114	114	114	324	173	173	173
	2		50	173	173	173	173	572	572	572	572	1143	1143	1143	572	1733	1733	1733	1733
	3		500	64	17	17	17	212	57	57	57	424	115	114	114	642	174	173	173
	4		50	173	173	173	173	572	572	572	572	1143	1143	1143	1143	1733	1733	1733	1733
Cooling tower	1	Parallel	2000	9	5	4	4	30	15	14	14	61	30	29	29	92	46	43	43
	2		200	44	43	43	43	145	143	143	143	290	286	286	286	440	433	433	433
	3		1200	16	8	7	7	53	26	24	24	106	52	48	48	160	80	72	72
	4		240	40	36	36	36	131	120	119	119	262	239	238	238	398	363	361	361
	1	Series	500	19	17	17	17	62	57	57	57	124	114	114	114	188	173	173	173
	2		50	173	173	173	173	572	572	572	572	1143	1143	1143	1143	1733	1733	1733	1733
	3		300	32	29	29	29	105	95	95	95	210	191	191	191	318	289	289	289
	4		60	183	176	144	144	605	580	476	476	1210	1160	953	953	1834	1757	1444	1444
Steam stripper	1	3% Boil-up	96	601	121	90	90	1996	402	299	299	3993	804	598	598	5989	1206	897	897
	2	5% Boil-up	74	468	119	117	117	1555	395	389	389	3109	791	777	777	4664	1186	1166	1166
	3	10% Boil-up	50	347	173	173	173	1153	575	575	575	2305	1149	1149	1149	3458	1724	1724	1724
	4	30% Boil-up	24	362	361	361	361	1203	1199	1199	1199	2405	2398	2398	2398	3608	3598	3598	3598

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TABLE 4. TIME REQUIRED FOR TREATMENT OF MODEL IMPOUNDMENT, OFFSITE DISCHARGE AVAILABLE

Technology	Case Number	Operating Mode	Liquid FlowRate	Treatment Time (hr)	Percent Removal			
					H=5	H=25	H=200	H=5000
Bubble column	1	Parallel	4000	3	2.63	11.89	51.92	96.43
	2	"	200	63	35.06	72.97	95.58	99.81
	3	"	4000	3	0.89	4.31	26.47	90.00
	4	"	200	63	15.25	47.37	87.80	99.45
	1	Series	1000	13	10.11	39.74	94.66	99.99
	2	"	50	250	82.22	99.47	99.99	99.99
	3	"	1000	13	3.52	16.14	70.77	99.99
	4	"	50	250	48.42	92.33	99.98	99.99
Spray column	1	Parallel	240	52	66.67	90.91	98.77	99.95
	2	"	120	104	57.14	78.52	92.14	98.42
	3	"	240	52	60.00	92.71	99.61	99.99
	4	"	120	104	59.71	85.51	97.03	99.77
	1	Series	60	208	98.77	99.99	99.99	99.99
	2	"	30	417	96.63	99.79	99.99	99.99
	3	"	60	208	97.44	99.99	99.99	99.99
	4	"	30	417	97.37	99.96	99.99	99.99
Packed air stripping column	1	Single column	500	25	53.50	99.99	99.99	99.99
	2	"	50	250	99.99	99.99	99.99	99.99
	3	"	500	25	27.0	99.71	99.99	99.99
	4	"	50	250	99.99	99.99	99.99	99.99
Cooling tower	1	Parallel	2000	6	47.21	93.88	99.94	99.99
	2	"	200	63	98.55	99.96	99.99	99.99
	3	"	1200	6	45.09	90.77	99.79	99.99
	4	"	240	63	90.79	99.48	99.99	99.99
	1	Series	500	25	92.23	99.99	99.99	99.99
	2	"	50	250	99.99	99.99	99.99	99.99
	3	"	300	25	90.91	99.99	99.99	99.99
	4	"	60	250	99.99	99.99	99.99	99.99
Steam stripper	1	3% boil-up	96	130	15.00	74.47	99.99	99.99
	2	5% boil-up	74	170	25.00	98.71	99.99	99.99
	3	10% boil-up	50	250	50.00	99.99	99.99	99.99
	4	30% boil-up	24	520	99.79	99.99	99.99	99.99

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SYSTEM EMISSIONS

All processes that remove volatile organics from water will generate some uncontrolled air emissions. However, there is a difference of many orders of magnitude in the emissions from an uncontrolled technology and one designed with emission control in mind. This section presents approximations of emissions from volatilization technologies.

Emissions from an open body of water, such as an impoundment, are extremely difficult to quantify or control adequately. The total quantity of emitted volatiles is obtained directly from estimates of the quantity removed. The concentration of these compounds in the air around the impoundment is difficult, if not impossible, to quantify unless accurate data on wind speeds, directions, and mixing rates are known. In general, the concentration in air around the impoundment increases as the removal rate is increased. Therefore, it is not advisable to augment volatilization using an uncontrolled process if there are any potential problems with air emissions from either a safety or air pollution standpoint.

Air-stripping units generate an air stream containing organics that potentially could be treated. The organic concentration is very important since some air treatment technologies, such as condensers, are concentration dependent. Table 5 gives the air flowrates and organic concentrations in air exiting each of the design case systems. It includes emissions for operating each system with each design case operating mode and for both parallel and series operation if multiple columns are available.

Emission concentrations given for series operation represent the average based on a unit concentration in the influent water of 1 mg/liter. The emissions given can be multiplied by the aqueous concentration in milligrams per liter to predict emission concentrations in parts per million (wt/wt).

Steam stripping has much lower emissions than other volatilization technologies by virtue of the collection and disposal of a concentrated organic stream. Organic is emitted to the atmosphere using steam stripping in the form of fugitive emissions.

The air emission rate from the model steam stripper is estimated and summarized in Table 6. It is a function of molecular weight, the size of the decanter, and the vapor pressure of the organic at operating conditions. These estimates represent working losses from the decanter during continuous operation. Other sources, such as startup losses, are not expected to be significant.

COST DATA

Capital costs for the design case surface sprayers and surface aerators, given in Table 7, are based on similar equipment (7).

TABLE 5. EMISSIONS FROM AIR STRIPPING PROCESSES

technology	Case number	Operating mode	L (gpm)	G (cfm)	H=5	H=25	H=200	H=5000
						Volatile Emission		
Bubble Column	1	Parallel	4,000	3,600	3.2	14	63	117
	2		200	3,600	2.1	4.4	5.8	6.0
	3		4,000	1,200	3.2	16	96	327
	4		200	1,200	2.7	8.6	16	18
	1	Series	1,000	3,600	3.1	12	29	30
	2		50	3,600	1.2	1.5	1.5	1.5
	3		1,000	1,200	3.2	15	64	91
	4		50	1,200	2.2	4.2	4.5	4.5
Spray Column	1	Parallel	240	16,000	1.1	1.5	1.6	1.6
	2		120	16,000	0.47	0.64	0.75	0.80
	3		240	8,000	2.0	3.0	3.3	3.3
	4		120	8,000	0.98	1.4	1.6	1.6
	1	Series	60	16,000	0.40	0.41	0.41	0.41
	2		30	16,000	0.20	0.20	0.20	0.20
	3		60	8,000	0.80	0.82	0.82	0.82
	4		30	8,000	0.40	0.41	0.41	0.41
Packed Air Stripping Column	1	Single Column	500	9,800	3.0	5.6	5.6	5.6
	2		50	9,800	0.56	0.56	0.56	0.56
	3		500	4,900	3.0	11	11	11
	4		50	4,900	1.1	1.1	1.1	1.1
Cooling Tower	1	Parallel	2,000	39,200	2.6	5.2	5.6	5.6
	2		200	39,200	0.55	0.56	0.56	0.56
	3		1,200	24,000	2.5	4.9	5.4	5.5
	4		240	24,000	0.99	1.1	1.1	1.1
	1	Series	500	39,200	1.3	1.4	1.4	1.4
	2		50	39,200	0.14	0.14	0.14	0.14
	3		300	24,000	1.2	1.4	1.4	1.4
	4		60	24,000	0.27	0.27	0.27	0.27

* All concentrations are expressed as concentration in air (Ca) divided by concentration in water (Cw). To calculate the concentration in air in ppm wt/wt, multiply by concentration in water in mg/liter.

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TABLE 6. - AIR EMISSION RATE FROM MODEL STEAM STRIPPER*

Molecular Wt lb/lb-mol	Vapor Pressure (mm Hg)					
	10-7	10-5	10-3	0.1	10	1000
25	4 X 10-10	4 X 10-8	4 X 10-6	0.0004	0.04	4.2
50	8 X 10-10	8 X 10-8	8 X 10-6	0.0008	0.08	8.3
100	2 X 10-9	2 X 10-7	2 X 10-5	0.002	0.2	16.7
150	3 X 10-9	3 X 10-7	3 X 10-5	0.003	0.3	25.0
200	3 X 10-9	3 X 10-7	3 X 10-5	0.003	0.3	33.3

*Emissions (lb/day)

TABLE 7. MECHANICAL AGITATOR CAPITAL COSTS*

Unit	Wt(lb)	Delivered ($)
Surface sprayer, 25 hp	4,000	30,000
Surface sprayer, 50 hp	5,000	45,000
Surface aerator, 50 hp	4,000	30,000
Surface aerator, 100 hp	5,000	40,000

*All costs are based on delivered costs given in Richardson (7) and are given in 1984 dollars.

Capital costs for the bubble column, spray column, packed air stripping column, and cooling tower air strippers are in Table 8. All equipment line items are based on installed costs to account for engineering, contractors' fees, freight, contingencies, and tax.

Table 9 give the capital costs for the steam stripper. Because of the complexity of this system, equipment purchase costs were used. A factor was then applied to derive total installed costs. Individual factors, totalling 52%, were applied to the installled cost to account for tax, freight, contractors' fees, engineering, and contingencies.

All capital costs, given in mid-1984 dollars, are preliminary estimates based on conceptual design. Costs are calculated to be within + 50% of actual purchase costs. This variability is the result of the preliminary nature of the designs and differences in costs of similar systems from various manufacturers.

Table 10 shows approximate mobilization and demobilization costs for design case trailers. All costs include transporation; site preparation; trailer and auxiliary equipment rental during setup and takedown; labor for equipment assembly, hookup, and disassembly; and materials for assembly, startup, and cleanup. These costs may vary significantly from those found in the field.

In general, the design case systems are configured to minimize field assembly. Mobilization costs should, therefore, be considered as minimum numbers. If the equipment used is not designed for easy field setup, mobilization may require a much higher cost.

Table 11 give the operating costs in dollars per day and dollars per 1,000 gallons treated for each of the design case systems and operating modes. Cost-per-gallon give the best basis for comparing the technologies since it accounts for varying flowrates. Operating cost also includes captial recovery costs at a rate of 0.185% per day to allow comparison of the treatment costs for each technology, both daily and adjusted for flowrate. However, it must be noted that several of the technologies benefit from economy of scale. If a low flowrate is required, the cost-per-gallon using these technologies will increase significantly.

TABLE 8. AIR STRIPPER-CAPITAL COSTS*

Item	Installed cost (thousands of dollars)
Bubble column	
Flat-bed trailer	20.0
Columns (4)	40.0
Plumbing	23.8
Blower	9.0
Diesel engine	10.0
Demister (4)	5.2
Air diffuser (4)	2.0
Instrumentation	5.0
Railings, supports, gratings	5.0
Subtotal	120.0
Engineering, contingencies, freight, contractors' fees, and tax (54%)	64.8
Total	184.8
Spray column	
Flat-bed trailer	20.0
Columns (4)	40.0
Pumps (4)	6.2
Plumbing	10.7
Blowers (4)	4.2
Demisters (4)	5.2
Motors (8)	4.6
Electrical	7.4
Railings, supports, and gratings	5.0
Instrumentation	5.0
Subtotal	108.3
Engineering, contingencies, freight, contractors' fees, and tax (54%)	58.7
Total	167.0

TABLE 8. (CONTINUED)

	Installed cost (thousands of dollars)
Packed air-stripping column	
Column	30.0
Frame	25.0
Plumbing	3.0
Electrical	3.0
Blower	2.9
Motor (50 hp)	3.4
Demister	1.3
Packing and Liquid distributer	60.0
Sump	2.8
Instrumentation	3.0
Subtotal	134.4
Engineering, contingencies, freight, contractors fees, and tax (54%)	72.6
Total	207.0
Cooling tower	
Flat-bed trailer	20.0
Package towers	84.0
Pumps	8.1
Motors	4.6
Electrical	8.0
Plumbing	13.3
Railings, supports, and gratings	5.0
Instrumentation	5.0
Subtotal	148.0
Engineering, contingencies, freight, contractors fees, and tax (54%)	79.9
Total	227.9

*All costs are based on installed cost obtained primarily from Richardson (7) and are given in 1984 dollars.

TABLE 9. STEAM STRIPPER CAPITAL COSTS[a]

	Purchase (thousands of dollars)
1 - Column, 1.5' X 35', steel	17.0
45 ft^3 - Packing, pall rings, 1 1/2", steel	2.0
1 - Condenser, BEU, 10" X 6', 75 ft^2, steel	5.0
1 - Exchanger, BEM, 25" X 12', 850 ft^2, steel	10.0
3 - Condenser, air, 1' X 7.5' X 7.5', 15 hp, steel	22.0
2 - Reboiler, electric, 225 kW, 240V, 3, steel	25.0
1 - Decanter, 2' X 6', 150 gal, steel	1.1
2 - Accumulator, 18" X 24" X 40", steel	1.1
2 - Reflux/product pump, 10 gpm	4.0
1 - Feed pump, 125 gpm	3.0
1 - Bottoms pump, 125 gpm	3.0
1 - Trailer, hydraulic lift and stabilizers	52.0
Subtotal	145.2
Allowance - for other undefined equipment and quote precision (20)	29.0
Total estimated equipment purchase cost	174.2
Installation costs (95%)[b]	165.5
Base cost	339.7
Sales tax and freight	13.1
Contractor's fees	49.7
Toll contract	402.5
Engineering	52.0
Contingencies	60.4
Total	514.9

[a] Given in 1984 dollars.
[b] Includes structures, equipment erection, piping, insulation, paint, fire protection, instruments, and electrical work.

TABLE 10. MOBILIZATION AND DEMOBILIZATION COSTS

Design case equipment	Cost ($)[a]
Surface sprayer, 25 hp	5,400
Surface sprayer, 50 hp	6,000
Surface aerator, 50 hp	7,000
Surface aerator, 100 hp	8,000
Bubble column[b]	4,200
Spray column[b]	4,100
Packed air stripper[bc]	8,400
Cooling tower[b]	4,400
Steam stripper[bc]	11,800

[a] All costs include transportation to and from site, assumed as 500 miles at 40 miles/hour with a $52/hour cost for truck and driver, plus a $0.20 per mile fuel cost. Total transportation cost = $1,500. Costs are given in 1984 dollars.

[b] Cost includes site preparation of leveling and graveling at $700.

[c] Cost includes site preparation of placing poured footings for guy-wires at $500.

TABLE 11. OPERATING COSTS

| Technology | Operating case | | | Operating costs[a] | |
	Case number	Operating mode	Liq. flow rate (gpm)	Total (dollars/day)	Dollars/ 1,000 gal
Pond, unagitated	1		NAb	0	NA
Pond, surface sprayer	1	25 hp	NA	170[c]	NA
	2	50 hp	NA	235[c]	NA
Pond, surface aerator	1	50 hp	NA	235[c]	NA
	2	100 hp	NA	370[c]	NA
Bubble column	1	Parallel	4000	1439[d]	0.25
	2		200	1369[d]	4.75
	3		4000	1389[d]	0.24
	4		200	1319[d]	4.82
	1	Series	1000	1390[d]	0.97
	2		50	1364[d]	18.94
	3		1000	1340[d]	0.93
	4		50	1314[d]	18.25
Spray column	1	Parallel	240	1239[d]	3.59
	2		120	1239[d]	7.17
	3		240	1219[d]	3.54
	4		120	1219[d]	7.05
	1	Series	60	1239[d]	14.34
	2		30	1239[d]	28.68
	3		60	1219[d]	14.11
	4		30	1219[d]	28.22

TABLE 11. (CONTINUED)

| Technology | Operating case | | | Operating costs[a] | |
	Case number	Operating mode	Liq. flow rate (gpm)	Total (dollars/day)	Dollars/ 1,000 gal
Packed air-stripping column	1	Single column	500	1514[d]	2.10
	2		50	1367[d]	18.99
	3		500	1415[d]	1.97
	4		50	1283[d]	17.82
Cooling tower	1	Parallel	2000	1476[d]	0.51
	2		200	1449[d]	5.03
	3		1200	1333[d]	0.77
	4		240	1323[d]	3.83
	1	Series	500	1476[d]	2.05
	2		50	1449[d]	20.13
	3		300	1333[d]	3.09
	4		60	1323[d]	15.31
Steam stripper	1	3% Boilup	96	3084[c,d,e]	23.31
	2	5% Boilup	74	2739[c,d,e]	25.70
	3	10% Boilup	50	2699[c,d,e]	37.49
	4	30% Boilup	24	2830[c,d,e]	81.89

a All costs include pump rental if pump is not supplied on trailer. Fuel costs are taken as $1.50/gal. Costs include equipment rental based on purchase cost divided by 540 days (18 months). Costs for rental of auxiliary equipment are based on standard weekly rental rates. All costs are given in 1984 dollars.

b NA = not applicable.

c Costs include operator at 4 hr/day and $25/hr.

d Costs include operator at 24 hr/day and $25/hr.

e Costs include disposal costs assumed as $120/drum for 55-gal drums.

SECTION 5

DESIGN BASES

This section provides specific background information on the volatilization technologies. The equipment designs that form the basis for the data presented in the tables and graphs in Section 4 are also described. Finally, important considerations for the evaluation of available equipment are given to aid in the selection process for each technology.

VOLATILIZATION FROM SURFACE IMPOUNDMENTS

Volatile organic compounds naturally volatilize from a body of water, such as an impoundment. Volatilization rates can be increased by using mechanical agitation to enhance liquid-air contact. Three methods for removing volatile organics from an impoundment of contaminated water are:

- o Exposing the water to the outdoor environment without any mechanical agitation,

- o Spraying the water on the impoundment surface, and

- o Agitating the water surface with a high-speed mechanical surface aerator.

Principle of Volatilization from an Impoundment

The mass transfer of volatile organics from an impoundment is expressed by the normal rate equation:

$$dC/dt = -K_L sC \qquad (10)$$

where:

C = bulk average organic concentration,

t = time (hr),

K_L = the overall mass transfer rate coefficient (m/hr), and

s = the specific surface area of the liquid phase (m^2/m^3).

Integrating this equation gives:

$$-\ln C/Co = K_L s(t - t_0) \qquad (11)$$

where:

C and C_0 are the volatile organic concentrations at times t and t_0, respectively. For the condition where $C = 1/2\ C_0$, t is the half-life and Equation 11 becomes:

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$$t_h = 0.693/(K_L s) \tag{12}$$

The mass transfer constant, $K_L s$, is affected by both the liquid-and gas-phase resistance and can be estimated using the two-film concept for estimating the flux of volatiles across the air-water interface as follows:

$$1/K_L = 1/k_1 + (5.56 \times 10^4)RT/Hk_g \tag{13}$$

where:

k_1 = liquid phase mass transfer coefficient (m/hr),

k_g = gas phase mass transfer coefficient (m/hr),

R = universal gas constant $[(m^3\text{-atm/mol})(^oK)(8.2 \times 10^{-5})]$,

T = absolute temperatures ^oK (Note: $20^oC = 293^oK$), and

H = Henry's Law constant (mole fraction volatile in gas phase/mole fraction volatile in liquid phase at 1 atm).

In this equation, $1/K_L$ can be thought of as the total resistance to the transfer of a volatile from water to air, with $1/k_1$ and RT/Hk_g being the individual resistances across the liquid film and gas film, respectively, at the liquid-gas interface. Smith, et al. (8) presents a more thorough discussion of the volatilization of organic chemicals from water bodies and typical values for mass transfer coefficient.

DESCRIPTION OF MODEL IMPOUNDMENT AND VOLATILIZATION ENHANCEMENT SYSTEMS

A model impoundment with a 100-ft^2 surface area and 10-ft depth (750,000 gal) is used to evaluate the volatilization of organic from contaminated water for the described systems. The model does not have a flow into or out of the impoundment during the treatment period (this is a batch system). The model (representative of a typical body of contaminated water) is adequate in size to accommodate available commercial mechanical agitation equipment.

The following three volatilization systems (Figure 20) are considered in this guide:

   o Impoundment without mechanical agitation

   o Impoundment with surface spraying
         - 25 hp unit
         - 50 hp unit

   o Impoundment with high-speed surface aerator
         - 50 hp unit
         - 100 hp unit

IMPOUNDMENT WITHOUT AGITATION

APPROX 65'

APPROX
12'
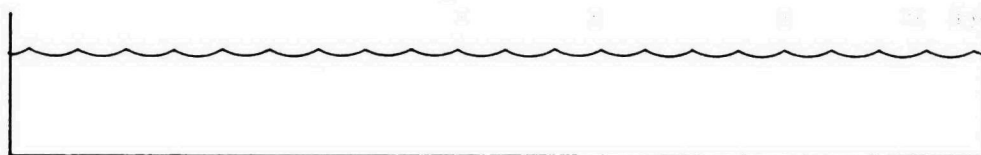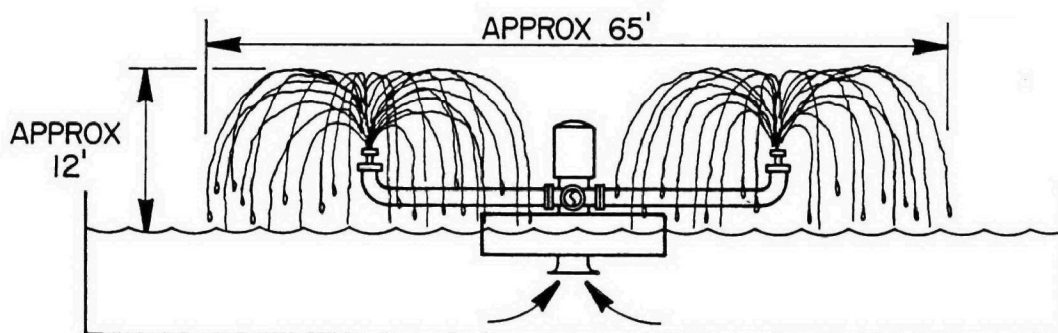
IMPOUNDMENT WITH SURFACE SPRAYER

APPROX 35'- 55'

10'

100'
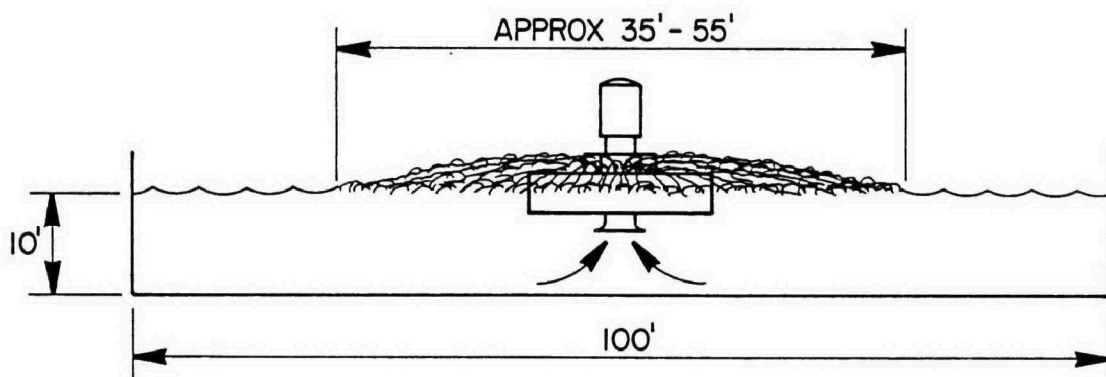
IMPOUNDMENT WITH SURFACE AERATOR

Figure 20.   Impoundment batch volatilization systems

To evaluate the systems, the organic half-life in the model impoundment is calculated for various Henry's Law constants using equations 10-13. The mass transfer rate constant, K_L, is calculated using estimates for the liquid-phase mass transfer coefficient, k_l, the gas-phase mass transfer coefficient, k_g, and the specific surface area, s, that are characteristic for the specific system and unit size (the bases for these estimates are discussed below). These are estimated values that should be typical of field conditions, but actual conditions encountered could give half-life results that vary by a factor of 2 to 3. (See Section 4 for the results of half-life calculations.)

Conditions that could cause variations in half-lives are:

    1. Climatic (temperature, wind, rainfall, etc.),

    2. Equipment design (spray-nozzle efficiency, pump efficiency, etc.), and

    3. Contaminated water conditions (presence of surfactants, other soluble contaminants, solids, etc.).

Impoundment Without Mechanical Agitation

Mass transfer coefficients for stagnant impoundments without mechanical agitation are a function of the wind conditions. The estimated value used for k_l is 0.025 m/hr and for k_g is 5 m/hr. These are selected from literature values representative of mild wind conditions, i.e., less than 2 to 3 m/sec. If field conditions have consistently higher winds, Lyman, Reehl, and Rosenblatt (9) provide more accurate estimates. The specific surface area, s, is the total surface area divided by the total volume, which is equal to 1/depth. For the model this is 0.33 m^2/m^3. This relationship makes the organic half-life directly proportional to the impoundment depth. That is, an impoundment twice as deep as another would have twice the half-life regardless of its surface area.

In evaluating organic volatilization from an unagitated impoundment, the effect of local climatic conditions must be evaluated. Half-lives are long for volatiles with low Henry's Law constants. Such conditions as the long-term ambient temperature and the net evaporation (evaporation less rainfall) could have a significant effect. Temperature effects can be accounted for by adjusting Henry's Law constant. Water evaporation will cause the organic to be concentrated.

Impoundment with a Surface Spraying System

Surface spraying systems have been developed to transfer heat from hot water sources, such as cooling water that is recycled in power plants. A typical surface spraying unit is shown in Figure 21. Heat is transferred mainly by the mass transfer of water (evaporation) to the surrounding air. The units have a large surface area, yet not so small that excessive drift loss outside of the spray pattern area can be a problem. The spray is directed up and allowed to fall back to the pond surface. This gives a large (but undefinable) gas-to-liquid contact ratio, which is a requirement for water transfer that is gas-phase (k_g) controlled.
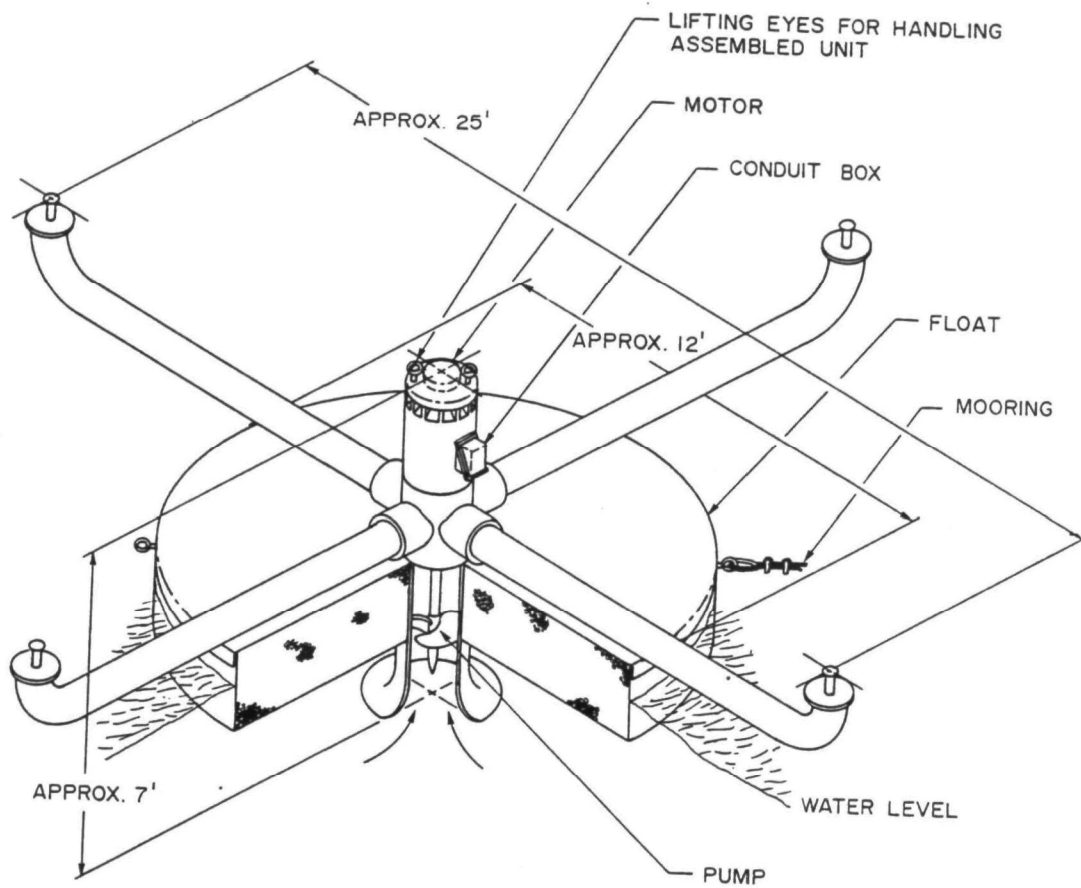
Figure 21. Typical configuration for a surface spray unit

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A surface spraying system is not as efficient as surface aeration for the same power input. The energy consumed in generating the spray droplets and projecting them into the air is not as efficiently used to stimulate mass transfer of the volatile organic.

The value estimated for k_l is 0.2 m/hr and k_g is 18 m/hr for the design case surface sprayer. These are representative for small liquid droplets being sprayed up and then falling through the air. The liquid-specific surface area in contact with the air is directly proportional to the spray drop air residence time and the spray system pumping rate. It is inversely proportional to the spray droplet diameter and the impoundment volume.

The spray droplet size produced by typical spray pond nozzles is smaller than 1/4-in in diameter and averages 1/8-in in diameter. The estimated droplet air residence time is 2 sec, which is probably typical for a 12-ft high spray pattern. The pumping rate used is 3,500 gpm for a 25-hp spraying system and 7,250 gpm for a 50-hp system. The estimated specific surface areas, for the model impoundment using these factors is 0.3 m^2/m^3 for the 25-hp system and 0.6 m^2/m^3 for the 50 hp system.

The proportion of organic that volatilizes from the impoundment surface area not directly involved in the spray pattern is normally a small percentage of that volatilized from the spray droplets, so it can be disregarded in the estimated specific surface areas.

In evaluating organic volatilization from an impoundment with a surface spraying system, the effects of local climatic conditions must be evaluated. There are three potential effects to be considered:

o   A cooling effect is encountered because the mass tranfer of water is enhanced; the impoundment water temperature probably will approach the average climatic wet-bulb temperature. This temperature should be used when calculating Henry's Law constant.

o   Because of the greater gas-to-liquid contact, the amount of water evaporated from the impoundment could be up to an estimated 20% more than from an unagitated pond subjected to the same climatic conditions.

o   The half-life is considerably lower than the half-life from an unagitated impoundment and therefore not subject to seasonal climatic conditions for as long a time.

Impoundment with a High-Speed Surface Aeration System

High-speed surface aeration systems were developed to transfer oxygen from air to water for biological treatment processes. A typical surface aeration unit appears in Figure 22. The units have integral low-head,

high-volume pumps to circulate large quantities of water designed to cause vigorous contact of this water with air. Oxygen transfer from air to water is liquid-phase (k_l) controlled, and the vigorous generation of a large liquid surface enhances this transfer.

A high-speed surface aerator is more efficient for organic volatilization than surface spraying for the same power input because it is designed to generate a large liquid surface area with an adequate gas-to-liquid ratio.

The value estimated for k_l is 0.2 m/hr and for k_g is 18 m/hr. These are considered representative for the type of liquid-gas contacts generated by high-speed surface aerators. The specific surface area, s, is estimated based on published performance testing for commercial-sized surface aerators designed to transfer oxygen from air to water (10). The relationship used to describe oxygen and organic mass transfer is:

$$K_L^{Or} s \sim 0.6 \; K_L^0 s \qquad\qquad (14)$$

where:

$$K_L^{Or} = \text{organic mass transfer coefficient}$$

$$K_L^0 = \text{oxygen mass transfer coefficient}$$

This equation holds for systems with relatively clean water and highly volatile compounds, but not for dirty suspensions and waste waters.

The estimated specific surface area, s, for the model impoundment is 6.8 m^2/m^3 for the 50-hp surface aeration system and 16.0 m^2/m^3 for the 100-hp system. The proportions of organic that would volatilize from the impoundment surface area not directly involved in the surface aeration action is small and was disregarded in this surface area estimate. As in the surface spraying system, the specific surface area for surface aeration is a direct function of the aeration equipment horsepower, and an inverse function of the volume of contaminated water in the impoundment.

In evaluating organic volatilization from an impoundment with a high-speed surface aerator, the possible effect of the local climate must be evaluated. Differences of the high speed surface aerator and surface spraying system include:

o   The specific surface area for a high-speed surface aerator is considerably larger than for a surface sprayer, even though the effective gas-to-liquid ratio may be lower for a surface aeration unit. Therefore, the impoundment water temperatures will most likely approach the average climatic wet-bulb temperatures, but

LIFTING EYES FOR HANDLING
ASSEMBLED UNIT

MOTOR

CONDUIT BOX

APPROX 10'-12'

MOORING CABLE

DISCHARGE
(TYP)

APPROX
7-9'

DEFLECTOR

FLOAT

PUMP

WATER LEVEL
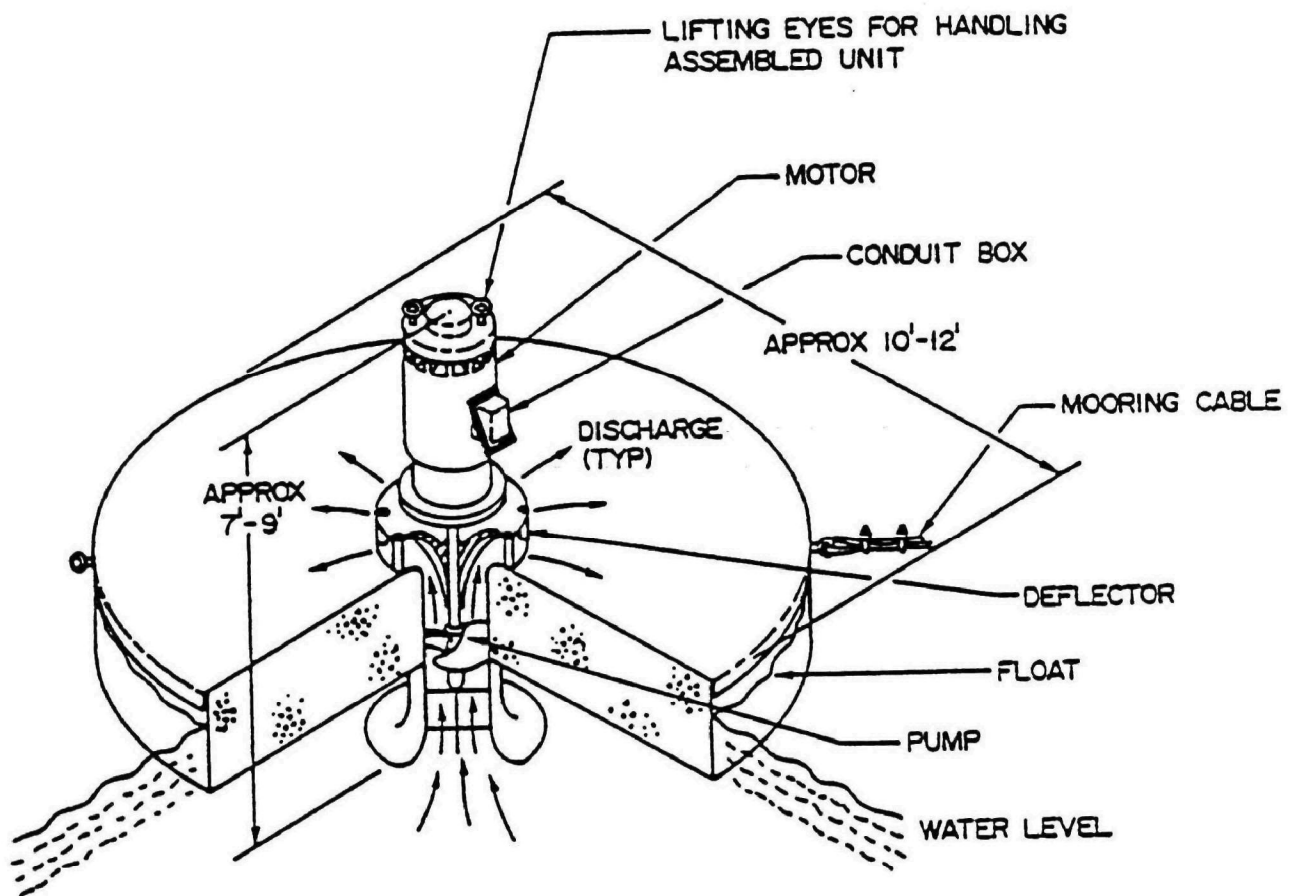
Figure 22.   Typical configuration for a floating high-speed surface
             aeration unit

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possibly not as close as a surface spraying unit. It is suggested that an average of the water temperature before treatment and the wet-bulb temperature be used to evaluate Henry's Law constant.

o The additional water evaporated over an unagitated pond is less for a surface aerator than a surface spray unit.

o The organic half-life using aeration is considerably less than the half-life using a surface spray unit system, and thus is less subject to seasonal climatic condition variations.

o Spray drift problems for surface aeration are less than for surface spraying units.

Applicability of Surface Impoundment Volatilization Technologies

Table 12 lists the characteristics of the impoundment systems discussed in this section. In considering the applicability of these or similar systems to a potential field situation, the following must be taken into account:

o A suitable impoundment should be available. It would not be cost effective to build an impoundment just for this purpose.

o The impoundment must be large enough to contain potential spray drift, to allow adequate gas-liquid contact, and to provide adequate equipment draft for proper operation.

o The shape of the impoundment should allow adequate mixing of the contaminated water during treatment.

o These model systems are batch. An inflow (steady or batch) of contaminated water to the impoundment would constitute a continuous system, and the equipment described would probably not be as efficient in treating the contaminated water as other systems discussed in this guide.

o These systems disseminate the volatile organic in the contaminated water to the surrounding air.

o Surface spraying and surface aeration units are relatively large and can transfer energy at a high rate to enhance organic volatilization from contaminated water. Even though these batch systems are not as efficient as a continuous system in removing volatile organics because of their size, they can require less time to treat a given contaminated water source and could be more cost effective in some situations.

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TABLE 12. CHARACTERISTICS OF TECHNOLOGIES FOR BATCH TREATMENT OF AN IMPOUNDMENT

Unit type	Rating (hp)	Pumping rate (gpm)	Weight (lb)	Purchase[a,b] cost ($)	Setup/ takedown time[b] (man-hours)	Normal minimum impoundment size (ft)	
						Depth	Surface
Impoundment without agitation	NA[c]	NA	NA			NA	NA
Surface sprayer	25	3,500	4,000	30,000	140	4	65 X 65
Surface sprayer	50	7,250	5,000	45,000	160	5	65 X 65
High-speed surface aerator	50	19,000[d]	4,000	30,000	200	9	35 dia.
High-speed surface aerator	100	38,000[d]	5,000	40,000	240	10	55 dia.

[a] Includes the basic unit with stainless-steel or steel-coated construction, fiberglass floats, freight to storage base, and waterproof electric cable for hookup on mid-1984 basis.

[b] No costs are included that are associated with the impoundment. These must be added if known.

[c] Not applicable.

[d] The actual pumping rate of the units; the induced flow caused by the pumping rate is 4 times larger.

AIR-STRIPPING COLUMNS

Principle of Air Stripping

Air stripping is the controlled contact of a liquid phase containing volatile contaminants with a clean air stream. The volatile component transfer from the liquid to the vapor phase. Liquid-vapor contactors may be designed to operate with a continuous vapor phase, as is found in a spray column or packed column, or with a continuous liquid phase, as in a bubble column. In either case, mass transfer is controlled by the equilibrium partitioning of the compound between water and air, which is represented by Henry's Law constant of that compound.

The removal efficiencies of air-stripping columns can vary widely, depending on theoretical stages in the column, air flow rate, and liquid flow rate. The height of a theoretical stage represents the height of a column required to reach equilibrium between the liquid and vapor phases. A theoretical stage is also known as an equilibrium stage, or a theoretical plate.

The effect of the air flow rate, liquid flow rate, Henry's Law constant, and number of theoretical stages on material removal is described mathematically for a continuous isothermal stripper in the Kremser equation (4):

$$f = \frac{1 - (G/L)(H)}{1 - [(G/L)H]^{(N + 1)}} \qquad (15)$$

where:

f   = fraction of material left in liquid phase,

G   = molar flow rate of gas (in moles/min, for air: $G = 0.0026 \times cfm$),

L   = molar flow rate of liquid (in moles/min, for water: $L = 0.46 \times gpm$),

H   = Henry's Law constant of strippable component (mole fraction/mole fraction), and

N   = number of stages in column.

For the derivation of this equation, the reader is referred to Smith (4). It should be noted when (G/L)(H) = 1 this equation takes on the indeterminate form, 0/0. To find f at (G/L)(H) = 1, the numerator and denominator should be differentiated and the new fraction used for evaluation.

$$f = 1/(N + 1), \text{ when } (G/L)(H) = 1 \qquad (16)$$

An important consideration in evaluating the performance of any air-stripping column is its operating temperature. This temperature

determines the Henry's Law constant of the strippable compound and thereby the amount of organic removed. Evaporation during normal operations causes the operating temperature to be lower than the ambient water temperature. The system operates at the influent water temperature when water enters the air stripper at the wet-bulb temperature of the ambient air, as in the case of an isothermal stripper.

In some cases, ambient air may heat cold influent water. An air-stripping column theoretically can be operated isothermally by adding steam to the dry air stream, thereby increasing the wet-bulb temperature. This method is recommended to permit control of an air stripper under a variety of seasonal conditions.

If the air-stripping column is not operated isothermally, organic removal is calculated using the air and water temperature in each stage, based on water evaporation at that point of the column. The removal achieved in each stage may then be calculated based on the Henry's Law constant at the calculated temperature. Although this can easily be done on a computer with the proper software, it is very tedious to do by hand. Isothermal stripping can be assumed to occur at a temperature that is the arithmetic mean of the feed water and the wet-bulb temperature (6) adjusted for relative mass flow and heat capacities of the air and water. This method should yield satisfactory results when the temperature difference is small (20°C). Reference (6) also gives an excellent treatment of the proper method for calculating adiabatic air stripping, giving the method for calculation of temperature drop in each stage.

The wet-bulb temperature is attainable by using the psychrometric chart in Figure 23. Relative humidity and ambient air temperature need to be assumed to obtain the wet-bulb temperature to be used in performance calculations; conservative values should represent close to the minimum wet-bulb temperature for the particular location and season.

The number of stages in a column depends on numerous factors, such as column geometry, contacting surface, liquid-surface tension with the packing, liquid and vapor dispersion and mixing, and resistance to mass transfer in both the liquid and vapor phases. Many of these factors are dependent on the specific column used, mass flow, and properties of the air/water system.

The prediction of column performance is a complex, time-consuming process. However, for quick estimation of column performance, a conservative value can be estimated for a number of stages in a particular column. For further discussion of this field, the reader is referred to many references on the subject (1,4,6,9).

For a cocurrent column, the maximum number of theoretical stages is one. As long as a cocurrent column is at least one theoretical stage in height, adding additional height does not increase compound removal. In a countercurrent column, additional column height almost always increases the number of stages, and hence, the amount of compound removal. However, a point of diminishing returns is reached when column height is added to an already-tall column.

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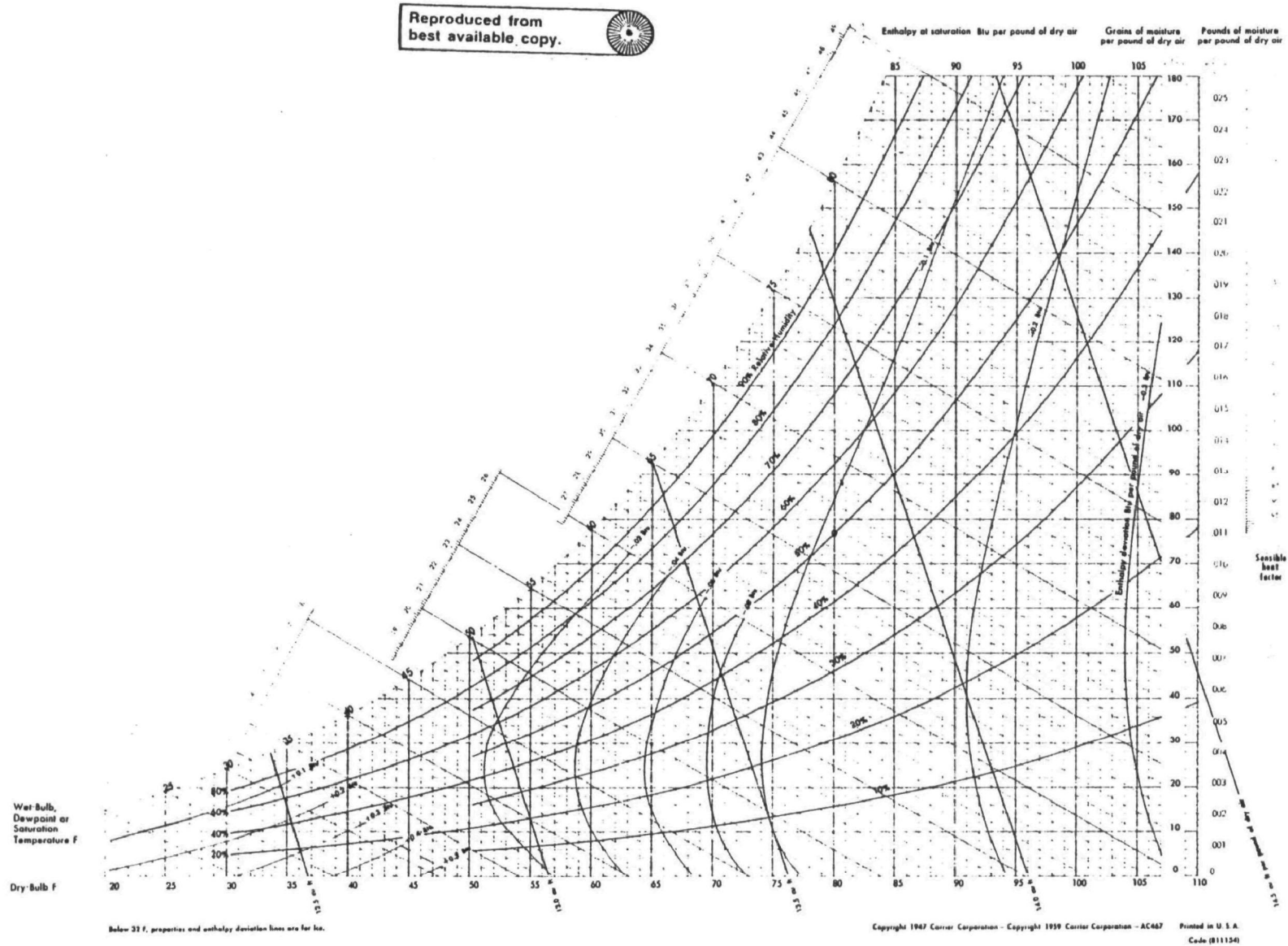
Figure 23.   Psychrometric chart (reproduced courtesy of Carrier
             Corporation)

The presence of surfactant, salts, oils, and biomass alter the stripping rate and vapor-liquid equilibrium. Recent proprietary studies have demonstrated that this effect will vary the stripping rate no more than ± 50% when compared with pure water. Conservative estimation of height per theoretical stage should allow these factors to be ignored during preliminary performance estimates.

Description of Model Air-Stripping Systems

Four types of model systems representing the broad field of air-stripping systems are discussed: cocurrent bubble column, countercooling spray column, countercurrent packed column, and countercurrent cooling tower.

Cocurrent Bubble Column--
A bubble column operates with a continuous liquid and discontinuous vapor phase. As the name implies, air is bubbled through water by means of a diffuser at the bottom of the column. Mass transfer is a function of bubble size, and bubble size in the column is primarily controlled by mass flow rates. Initial distribution of bubble sizes from the diffuser has little to do with mass transfer rate, as long as the bubbles are evenly distributed and within an order of magnitude of the steady-state size distribution. Bubbles of a size distribution other than steady state will rapidly coalesce or break apart to reach the steady-state size distribution.

Bubble columns may be run in a cocurrent or countercurrent fashion. Cocurrent devices are limited to one stage . Countercurrent devices may have more than one stage, but back- mixing prevents good stage efficiency. Most countercurrent columns operate as single-stage devices. A theoretical stage is reached rapidly in cocurrent bubble columns. Recent experimentation (11) has demonstrated that a contact height of 5 ft or less is, in most cases, sufficient to achieve a single stage.

Maximum air-flow rates in bubble columns are limited by the mass flow required to achieve the bubble flow pattern. As air flow is increased, the column will enter the regime of a slug-flow pattern and, eventually, a froth-flow pattern. Calculation of maximum flow rates is further complicated by the uncertainty of the vapor-to-liquid ratio of the mixture actually in motion.

The mixture differs from that admitted to the column due to slip, known as holdup. In general, the gas phase tends to slip past the liquid phase, reducing the gas-to-liquid ratio in the column over that of the entering or exiting mixtures. For further information on flow in bubble columns, the reader is referred to many sources (2,12,13,14).

Since flow is unrestricted by column internals, the theoretically allowable water-flow in a bubble column is relatively great, particularly for cocurrent systems. For large-diameter columns (4 ft), practical

limitations in water- handling systems become more important than flow considerations in the column. For cocurrent systems, the most practical consideration for large columns is the method for air-water separation at the top of the column. The presence of surfactants in water causes foaming in air space over the column. This limits the ability of the demister to prevent spray from being emitted with exiting air. Water flow is limited by the size of the weir over which the water must travel. To a lesser extent, flow may be limited by piping, blower, or pumping limitations.

Minimum air-flow rates in bubble columns are limited by the ability of the air diffuser to distribute low air flows evenly. This should not be a problem in a properly designed system. The turndown requirement (i.e., the minimum capacity of the system that can be used efficiently) for air flow are dictated by the presence of surfactants in the water. It is not expected that a turndown of greater than 10:1 would ever be necessary; properly designed diffusers should be able to provide turndown in this range. There are no limitations on turndown for liquid flow, so this enables column operation with a wide range of gas-to-liquid ratios.

Cocurrent Bubble Column Design Basis--
The design basis selected for a bubble column is a cocurrent upflow device with a single stage. A cocurrent device was selected over a countercurrent device because columns may be operated in series without pumps between the columns. This is possible since the density of the air-water mixture in the columns is less than the water in lines running between columns. Also, cocurrent columns have a slightly greater throughput since gas holdup is less than in a countercurrent column.

Figure 24 shows the schematic of the design case column. The water enters at the base of the 6-ft column. The air diffuser is positioned at the lowest practical point in the column to maximize the contact volume. Water exits the column by means of an overflow weir which breaks up any fro# formed by the bubbling action. A demister section (as large as the column to maximize its ability to break any foam) at the top of the column breaks foam and surface bubbles and eliminates mist from the exiting air.

Figure 25 is a process flow diagram (PFD) of the design case system, including valving. A single-turbine blower (B-1001) supplies air to all four columns. This high-pressure blower (5 psig) requires a 150-hp motor. The four columns (T-1001, T-1002, T-1003, T-1004) are arranged so that they can be operated in parallel, two in series, or four in series.

Figure 26 gives the side, top, and rear views of the design case system. The four columns, which must be drained when transporting, are mounted on a 45-ft long, 13 1/2-ft high, and 8-ft wide low-boy trailer. The blower, mounted on the front of the trailer, is powered by a 150-hp diesel motor. Water must be pumped to the trailer using a pump rented for that purpose.

Design case operating conditions are in Table 13. The water flow rate of 1,000 gpm is the maximum able to exit the column over the weir,
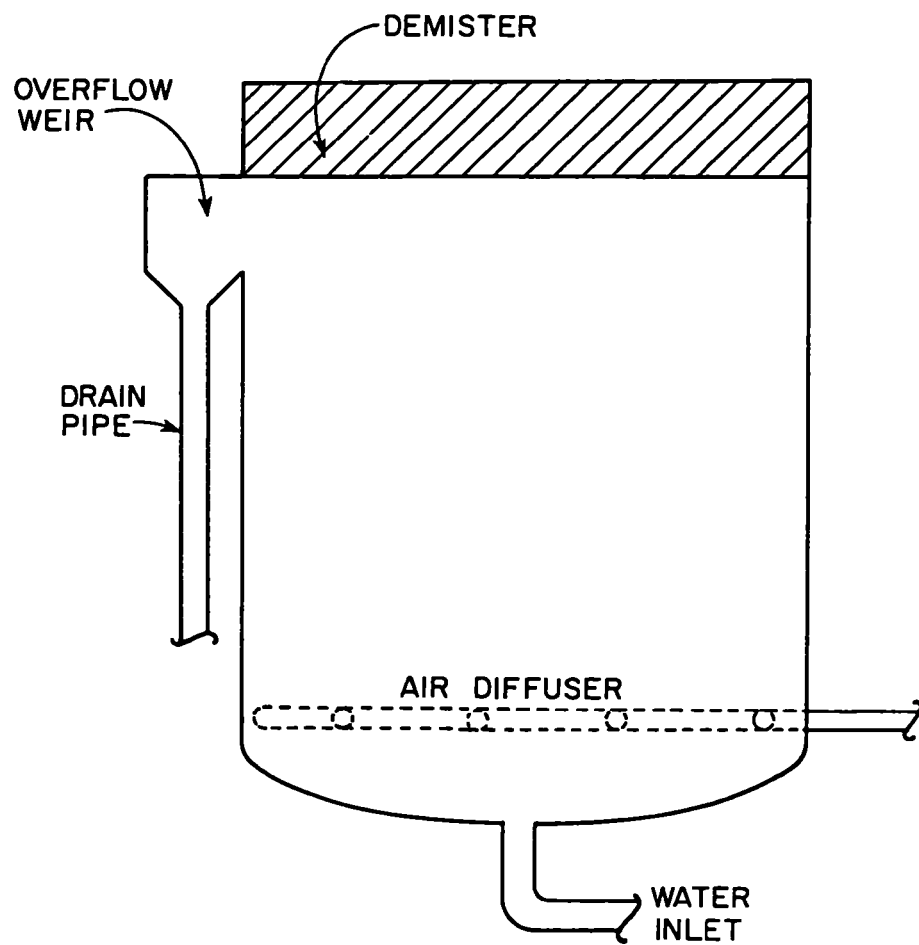
Figure 24. Bubble column design, schematic
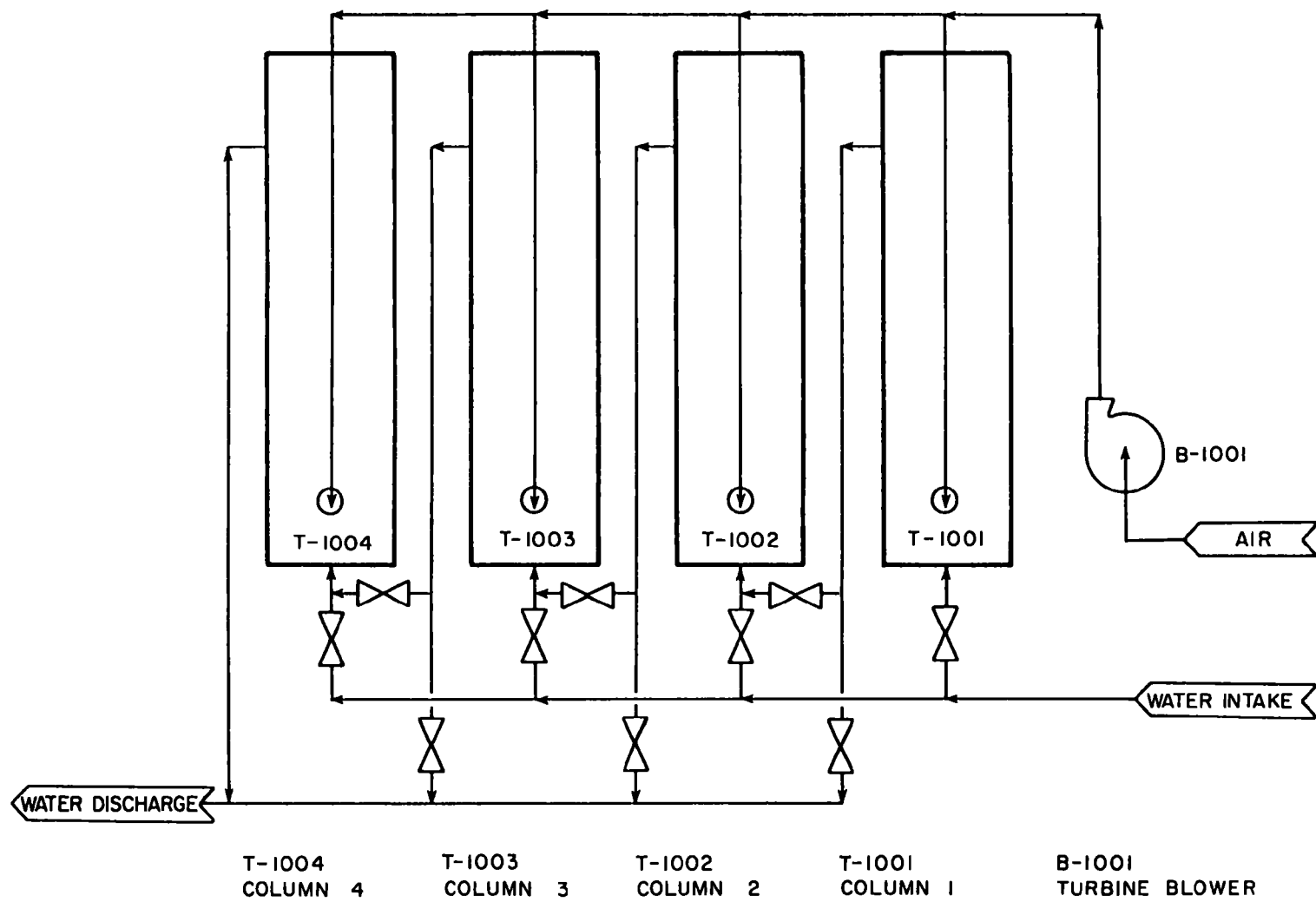
Figure 25. Bubble column design basis, process flow diagram

0 2½' 5' 10'
scale
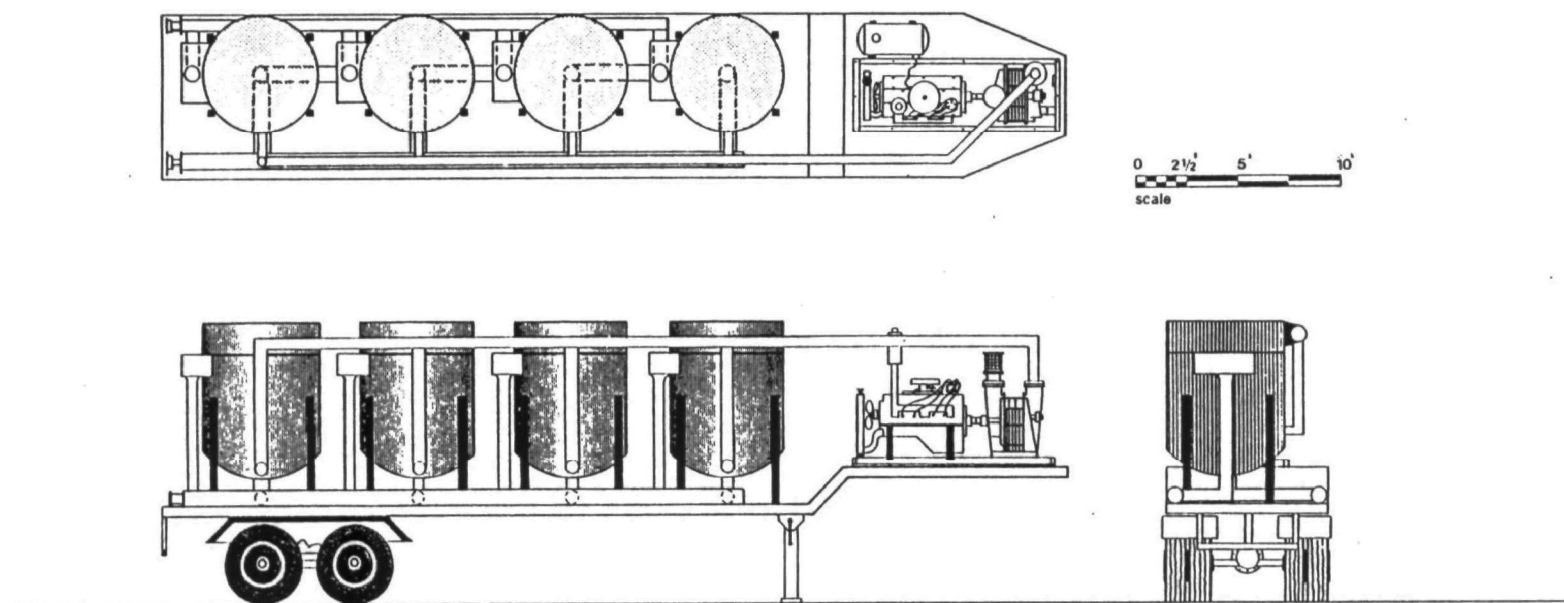
Figure 26. Bubble column design basis, side, top, and rear views

TABLE 13. BUBBLE COLUMN DESIGN CASE OPERATING CONDITIONS

Case No.	Gas flow moles/hr (cfm)	Liquid flow moles/hr (gpm)	G/L moles/mole	Column Stages
1	150 (900)	28,000 (1,000)	0.0054	1
2	150 (900)	1,400 (50)	0.108	1
3	50 (300)	28,000 (1,000)	0.0018	1
4	60 (300)	1,400 (50)	0.036	1

assuming an 8-in head for the air-water mixture and no surfactants in the water. The 900-cfm airflow represents an estimate of the maximum flow rate that could be sent through a demister, considering the potential for foaming in a clean water stream.

The selected airflow is about 30% of the maximum possible airflow rate for a bubble flow pattern to be maintained in the column with a 1,000-gpm water flow. The 50-gpm water flow was chosen to demonstrate the turndown potential of a bubble column. Water flow could be further reduced for a more advantageous G/L ratio. The lower airflow rate of 300 cfm represents the estimate at a practical operating flow using water containing some surfactants. Water flows of 1,000 and 50 gpm were used as they were with the 900 cfm air flow.

Spray Column--
A spray column, which sprays water into air through spray nozzles, operates with a continuous vapor phase and discontinuous liquid phase. Mass transfer is a function of the droplet size, turbulence in the column, and distribution of water in the column. Droplet size is, in turn, a function of liquid flow rate.

It has been suggested that the number of stages in a spray tower is approximately proportional to the liquid flow rate (2,15). This is true for a limited flow regime and is dependent on the material being stripped and the nozzle used. The same sources suggest that the number of column stages decreases approximately as the square root of the gas velocity. Well-designed spray columns generally have between 0.5 to 3 stages, depending on the size of the column, mass flow rate, and spray nozzles used. Theoretical stages are not proportional to column height because of backmixing of the spray, less-efficient droplet distribution in a taller column, and a greater influence of spray collection on the walls. Columns taller than about 10 ft should have spray redistributed at an intermediate point.

Generally, two types of spray towers are used: countercurrent and cyclone. Cocurrent columns have also been designed for certain applications, but are less efficient than the other types. Countercurrent spray columns are arranged with nozzles at the top and a collection sump at the bottom. Air enters at the bottom and exits through a demister at the top.

Cyclone columns have a tangential air inlet at the side along its base. Air travels in a spiraling motion up the column and exits at the top. Water, introduced via a manifold running about half-way up the center of the column, collects at the bottom and exits out a drain.

The type of spray nozzles is an important consideration in spray column design since the nozzle will affect turndown potential, droplet size, horsepower requirement, potential for fouling, and spatial pattern of the spray.

Droplet size and spatial pattern, in turn, affect the column's mass transfer characteristics. For a discussion of different nozzle types, refer to Perry (2).

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The maximum gas flow rate in a spray tower is limited by the entrainment of liquid droplets. An accepted maximum flow rate is 800 lb/hr ft^2, which may be converted to 106 cfm per ft^2 of column area (2,15). A second consideration when choosing gas flow rates is the decrease in number of stages as the gas rate is increased. Increasing the gas flow rate will therefore not give as great an improvement in compound removal as might be expected, although some increase in removal should occur. Liquid flow is limited by the characteristics of the spray nozzles. The spray must be distributed evenly throughout the column, with a minimum of spray striking the walls of the column. The nozzles must also maintain proper distribution of droplet sizes at the maximum flowrate. The maximum liquid flow should be in the range of 1 to 3 gpm/ft^2. The actual value will depend on column size, nozzle type, and gas flow rate.

There is no minimum air flowrate for spray towers, although there is little reason to run at low air flows for stripping, unless a greater organic concentration in the exiting gas is desired. Minimum liquid flow is determined by the spray nozzle used. The technology is limited in this respect since turndown ratios of 5:1 are considered good and turndown ratios of 3:1 are not uncommon for many nozzles. However, the column will operate most efficiently at maximum nozzle flow. Turndown of the liquid flow will not give a great increase in organic removal. Nozzles with greater turndown ratios are available, but are of limited utility due to the droplet sizes and spatial distributions possible with these nozzles. However, nozzles can be successfully substituted into a spray column to operate in different liquid-flow regimes.

Spray Column Design Basis--
A countercurrent spray column was selected over a cyclone column since it will allow more than one stage, whereas the cyclone column is limited to one stage. Also, a countercurrent column requires less maintenance and a smaller area-per-liquid flow than the cyclone. The columns may be operated in series for improved organic removal or parallel for higher liquid flow. The trailer was designed with four short columns transported upright.

Figure 27 gives the schematic for the design case column. Water is pumped to spray nozzles through a dedicated pump (5-hp electric motor) that can supply a relatively high-pressure (40 psi) stream. Water collects in the sump at the column's base.

A main drain controls the water level and an overflow drain protects the blower from process upset conditions. Each column has its own blower requiring a 5-hp motor. Air enters the column through a duct, is directed downward to allow even flow, and exits through a demister at the top.

Figure 28 gives the PFD for the design case trailer, including the valving arrangement. The four columns (T-1001, T-1002, T-1003, T-1004) may be run in parallel, or two or four in series. Four pumps (P1001, P1002, P1003, P1004) supply water to the columns, which have individual blowers (B-1001, B-1002, B-1003, B-1004) to supply air.

DEMISTER

SPRAY NOZZLES

BLOWER

OVERFLOW

DRAIN   SUMP

PUMP

WATER
INLET
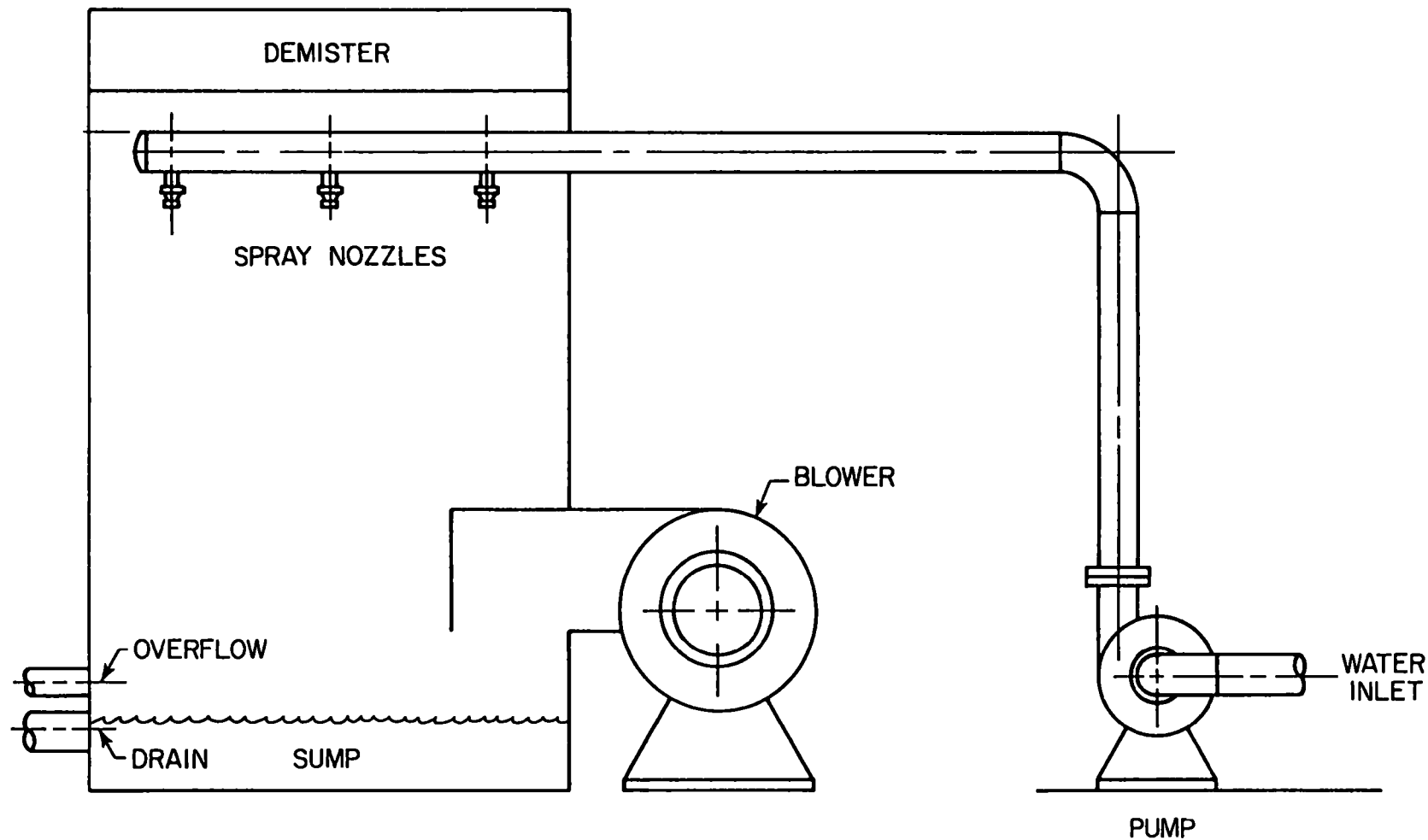
Figure 27.   Spray column design basis, schematic
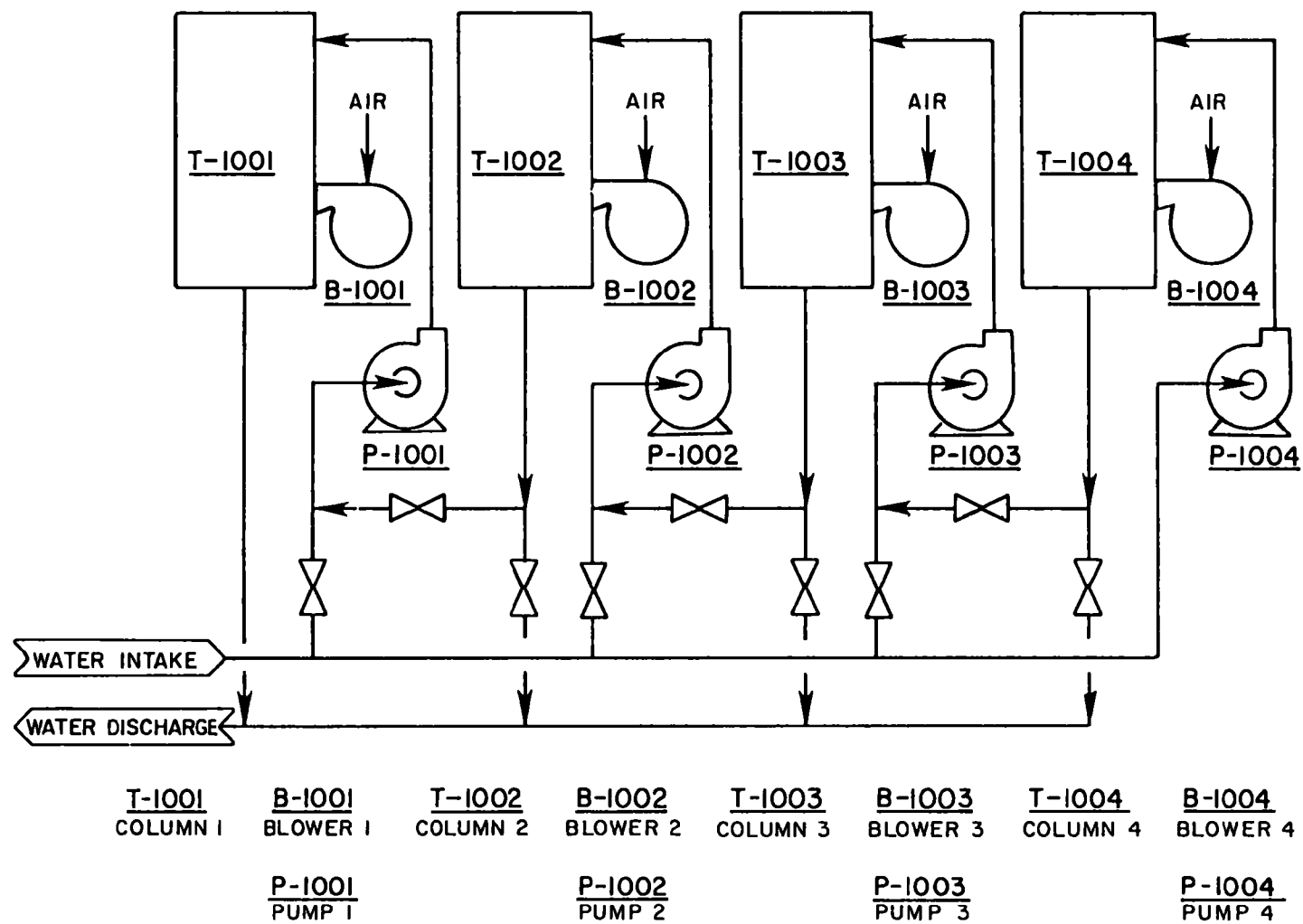
Figure 28. Spray column design basis, process flow diagram

A side, top, and rear view of the trailer are shown in Figure 29. Pumps on the trailer are sized to handle design flows for pumping between columns, or from a source directly beside the trailer. The four columns, each 6 ft in diameter, 9-1/2 ft high, are mounted on a 45-ft long trailer with a 4-ft bed height. Overall height of the trailer is 13-1/2 ft and it is 8 ft wide.

Design case operating conditions for a spray column are given in Table 14 along with column stages calculated for each flowrate. Water flow of 60 gpm (1,060 lb/hr ft^2) represents an estimate of the maximum flow for good distribution through 40 psi nozzles in a 6-ft diameter column. Maximum design air flow of 4,000 cfm represents the maximum that could be used before excessive entrainment occurs. The maximum air and liquid flows were halved to demonstrate the effect on column stages and removal efficiencies.

Packed Column Air Stripper--
A packed air-stripping column operates with a continuous vapor phase and discontinuous liquid phase. Packing in the column is designed to expose liquid surface area, limit backmixing, and allow an even distribution of liquid and vapor over its cross section. The characteristics of the packing, the most important consideration in column design, will determine overall performance.

Countercurrent columns can have either packing or trays. Packed columns yield a lower pressure drop per stage and have a lower liquid holdup. This gives them lower operating costs and sharp separation between water and organics.

Packings are able to operate over a wider range of gas-to-liquid ratios than trays, and perform better than trays when surfactants are present because they are more resistant to entrainment.

Trays are generally made of metal and are subject to corrosion, while packings can be made from metal, plastics, or ceramics. However, trays are generally better for handling streams with high solids contents. They also lend support to the column and are not subject to loss of efficiency in transport as are many packings.

Column packings, which come in a myriad of materials, forms, and sizes, are of three basic types: random dump, structured grid, and high efficiency mesh. Random dump packing, normally 0.5-3-in in diameter, may be shaped in a ring, saddle, or other configuration. As their name implies, random dump packings are loaded into a column in a random fashion. They are generally aceptable for mobile air stripping, although they may settle during transport, reducing column perfomrance. It is advisable to load random dump packings into the column on site to avoid this problem.

Structured packings consist of a solid latticework of either metal or plastic. Designs vary according to the size of slats in the lattice, perforations and crimpings in the slats, and geometric arrangement of the
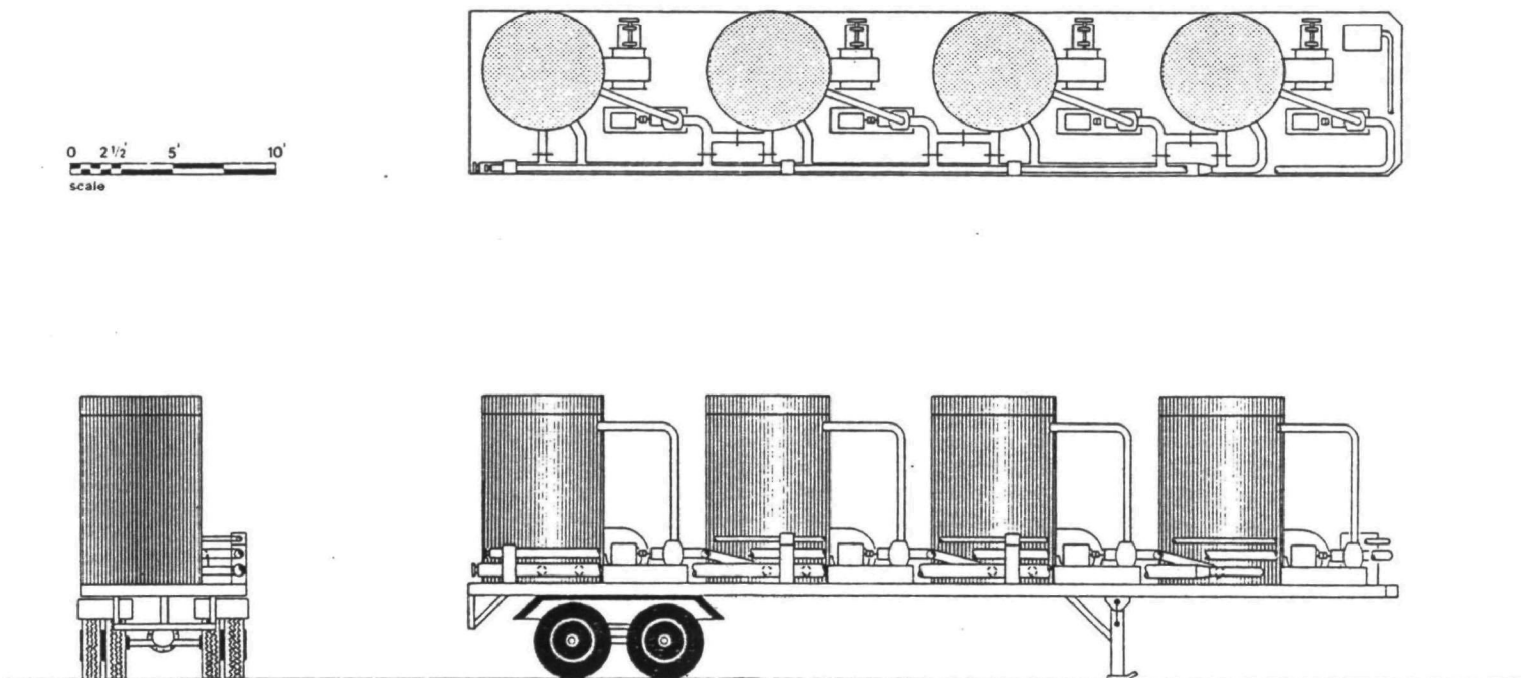
Figure 29.   Spray column design basis, side, top, and rear views

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TABLE 14. SPRAY COLUMN DESIGN CASE OPERATING CONDITIONS

Case No.	Gas flow moles/hr (cfm)	Liquid flow moles/hr (gpm)	G/L moles/mole	Column Stages
1	660 (4,000)	1,660 (60)	0.40	1.0
2	660 (4,000)	830 (30)	0.80	0.5
3	330 (2,000)	1,660 (60)	0.20	1.5
4	330 (2,000)	830 (30)	0.40	0.8

lattice. The surface area in the lattice will vary from 40 to 200 ft^3 per ft^2 of packing. As the surface area is increased, the volume of holdup, pressure drop, and number of stages per foot of column height increase, thus sacrificing mass. High surface area packings sacrifice mass flow for staging in a column. Structured packings are ideal for mobile systems, for they maintain their shape during transport. They also give high removal efficiencies with reasonably low pressure drop.

High-efficiency packings, made of metal wound into a tight mesh, are extremely efficient in many industrial applications requiring difficult separations. They have very small heights per theoretical stage and, although they tend to have a higher pressure drop per foot than do random dump or structured beds, often have a lower pressure drop per stage. However, these packings are of limited utility in mobile applications due to their: (1) startup problems, (2) potential for fouling, and (3) sensitivity to placement in the column. In addition, high-efficiency packings cost more than random dump or structured packings.

Evaluation of packings is an engineering field unto itself, and cannot be sufficiently covered in this manual. For further information on packings, consult packing manufacturers or the literature (2,16,17).

In order for a packing to perform properly, the liquid must be evenly distributed over the column's area. Often, when a column fails to perform as expected, the problem stems from problems with liquid distribution. A variety of distributors are available, each with its own advantages and disadvantages.

A "V"-notched distributor has a high potential turndown, low fouling potential, and high maximum flow rate. Water is distributed by means of troughs with "V" notches along their sides. The "V"-notched distributor is suitable for columns with a diameter of 3 ft or greater. For smaller-diameter columns, an orifice distributor is preferred, although turndown is normally limited to about 4:1. Liquid is distributed through orifices set either in a pan holding vapor risers, or in an array of pipes. Both "V"-notched and orifice distributors operate by gravity flow and are very sensitive to levelness.

A mobile column containing these distributors must be perfectly leveled before operation to perform properly. To avoid the leveling problem, liquid distribution can be accomplished by means of spray nozzles. However, spray nozzles are often subject to fouling, have low turndown ratios, low maximum flowrates, and high pressure drop in the nozzles.

Several sources can provide more information on liquid distributors (e.g., 1,3,16). Liquid distributors are not perfectly efficient. Therefore, some packing height is necessary to distribute liquid throughout the column. A rule of thumb is to have approximately one column diameter in packing height over and above the packing heights estimated by the methods in this guide.

Air distribution may also be a factor in an improperly operating column. The most common problem is air bypassing the packing by flowing between the packing and column wall. This is a particular problem with structured packings, and can be prevented by using tabs to reduce flow up the walls of the column.

Packed Column Air Stripper Design Basis--

The design basis selected for a packed column is a 6-ft diameter column with 25 ft of packing height. A structured grid packing with a surface area of 120 ft^2/ft^3 was selected. Liquid distribution is with a "V"-notched distributor. In our opinion, this type of design should give the best overall performance in a variety of mobile applications.

Figure 30 gives the schematic for the design case packed air-stripping column. Water is pumped to the top of the column by an external pump, rented for the flow needed. The liquid distributor sits at the top of the column. Additional "wall wiper" distributors are placed along the sides of the packing to redistribute flow running down and air up the walls of the column. Water collects in a sump positioned below the packing and exits out a drain. A blower sits at the base of the column. Air enters the column through a duct and is directed downward to improve its distribution. Air travels upward through the packing and exits through a demister at the top of the column.

Figure 31 is the process flow diagram (PFD) for the system. It shows the blower (B-1001) supplying air to the countercurrent packed column (T-1001). The blower may be controlled by alteration of pulley arrangement, reduction in amperage, or by means of a damper in the ductwork.

Side view of the column during transport, and side and top views during operation are shown in Figure 32. The high-density polyethylene column rests in a metal framework 8 ft wide, 9-1/2 ft deep and 36 ft high. The frame is moved by crane during setup. The column is secured with four guy wires coming from each top corner of the frame. The 6-ft diameter column rests on a 7-ft by 8-1/2 ft sump. The blower rests on top of the sump, supported by the metal frame, and directs air flow downward into the sump.

A 50-hp electric motor powers the blower. A fuse block and control box are mounted on the side of the sump for ease of setup. The 36-ft height permits room on the trailer for support supplies, such as hoses, guy-wires, tools, and spare motor pulleys.

The design case operating conditions are given in Table 15. Flow is limited by increased pressure drop caused by liquid holdup. Data on structured packings were used to determine the maximum C factor for this column of 0.2 ft/sec. The C factor is defined as $V_s[D_v/(D_l - D_v)]^{0.5}$. ($V_s$ is the superficial vapor velocity taken as the velocity of air flow in a column without packing or liquid flow.) D_v and D_l are the vapor and liquid densities, respectively. This equals 0.0343 V_s for an air/water system at standard temperature and pressure. A C factor of 0.2 corresponds to an air flow of 9,800 cfm in the design case column.
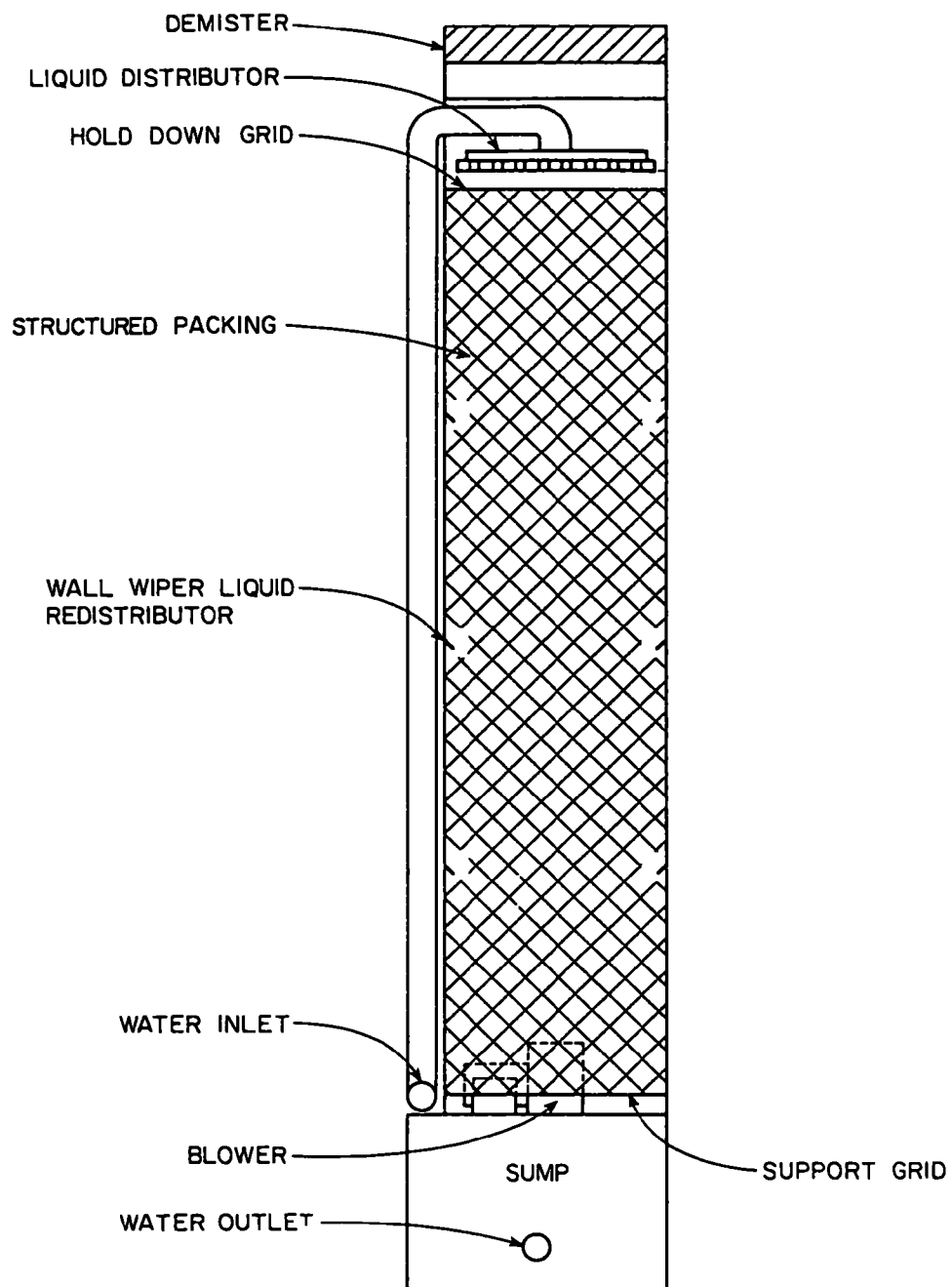
Figure 30. Packed-column air stripper, design basis schematic

T-1001

COUNTER-CURRENT
PACKED COLUMN

B-1001

BLOWER
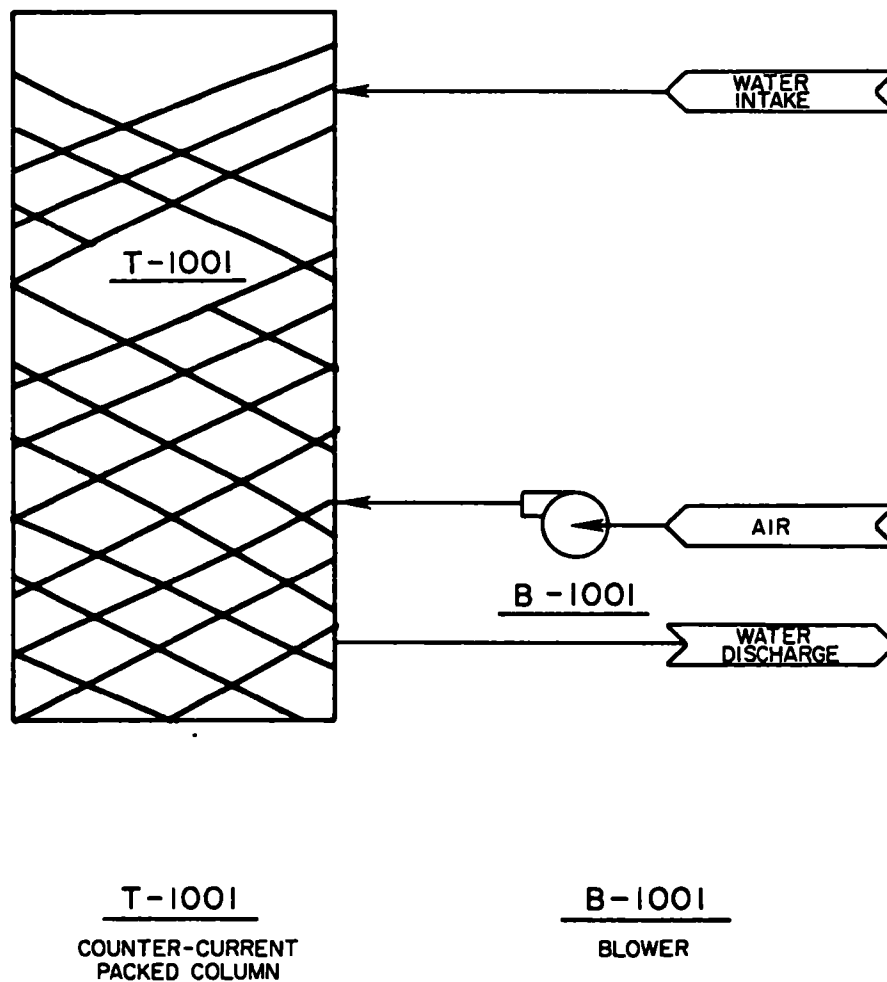
Figure 31.   Packed-column air stripper, design basis, process flow
diagram
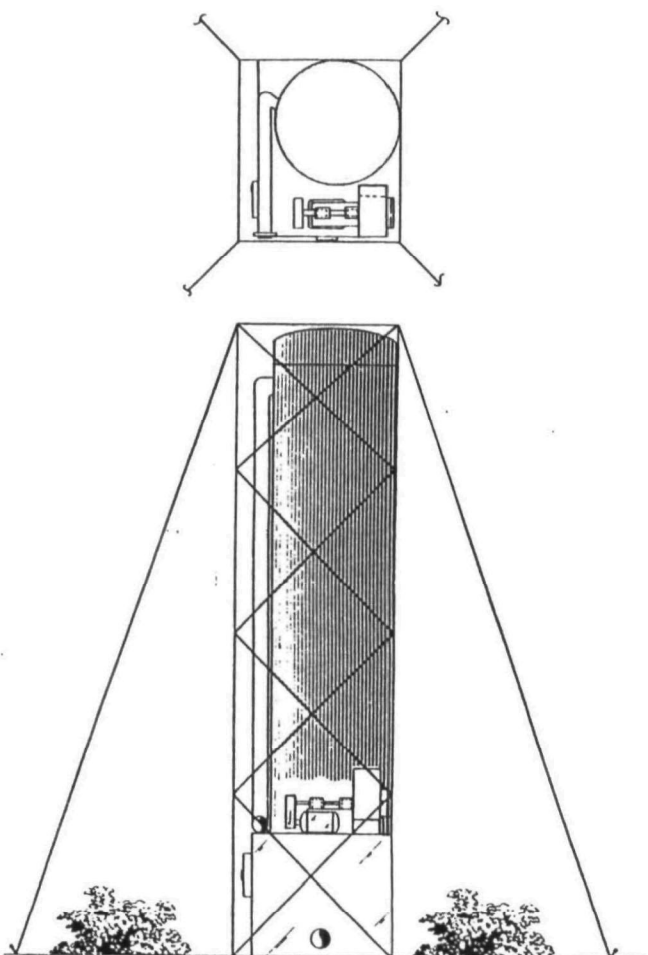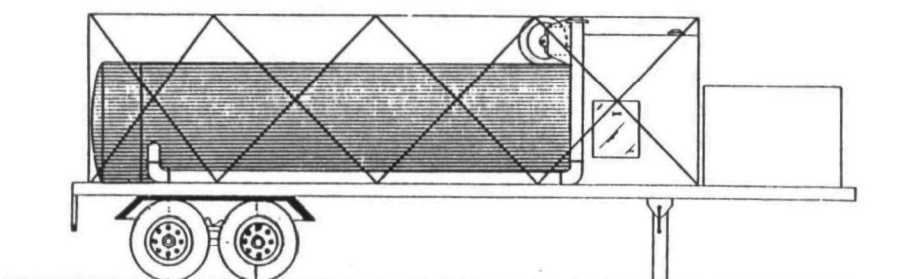
Figure 32. Packed-column air stripper, design basis, side, top, and on-road views

0   2½'   5'   10'
scale

TABLE 15. PACKED AIR STRIPPING COLUMN DESIGN CASE OPERATING CONDITIONS

Case Number	C Factor	Stages	Superficial Vapor Velocity (ft/sec)	Superficial Liquid Velocity (ft/sec)	Gas Flow (G) (moles/hr) (cfm)	Liquid Flow (L) (moles/hr) (gpm)	G/L $\frac{(mole)}{(mole)}$	Pressure Drop $\frac{(in\ water)}{(ft\ packing)}$	Pressure Drop Total (in water)	Volume Hold-up (%)
1	0.20	15	5.8	0.045	1,500 (9,800)	14,000 (500)	0.107	0.41	12.25	8.0
2	0.20	15	5.8	0.0045	1,500 (9,800)	1,400 (50)	1.071	0.18	0.5	6.6
3	0.10	15	2.9	0.045	750 (4,900)	14,000 (500)	0.054	0.12	4.2	2
4	0.10	15	2.9	0.0045	750 (4,900)	1,400 (50)	0.536	0.056	2.4	2

The maximum liquid flow, which was obtained by reviewing pressure drop curves for structured packing, corresponds to a value close to flooding. Air flow was halved and water flow was reduced by a factor of 10 to yield three other design cases to demonstrate the effect of varying mass flow.

The number of stages given represents a conservative estimate based on packing efficiency found for other organics. The column may operate with more stages in actual field situations.

Cooling Tower--

Design and function of cooling towers for air stripping closely parallels packed columns. As of this writing, fabricators of cooling towers are generally new in the field of air stripping. As cooling tower manufacturers become more sophisticated in the application of their units to air stripping, the packings, column geometries, and column internals they build for cooling towers are becoming like those used for packed columns. These manufacturers have a number of advantages for building mobile air-stripping units. The use of plastics in their designs, experience with manufacturing transportable "turnkey" systems, and facilities for inexpensive production of small units may give cooling tower manufacturers a competitive edge in production of mobile systems.

At present, most manufacturers use a structured packing similar to that for the packed column design. However, packing supplied by cooling tower manufacturers will not be as efficient as that of packings manufacturers. In the future, these manufacturers will probably continue to gain understanding of the subtleties of mass transfer and may equal traditional packing manufacturers in this respect.

Cooling Tower Design Basis--

We have selected two types of packing and liquid distribution systems. The first is the same packing and liquid distribution system as for the design case of packed columns. The second is a system found in cooling towers. The packing supplied by packed column manufacturers is slightly more efficient than that produced by cooling tower manufacturers in our survey.

The cooling tower design case gives an interesting contrast to the packed tower design, since it compares four short columns to one tall column. The design case cooling tower system uses a column arrangement common to several manufacturers. Four 6-ft diameter columns with 4 ft of packing are transported vertically on a 45-ft trailer. Blowers are placed directly on the side of each column.

For the first two design cases, liquid distribution is accomplished by a "V"-notch distributor. The second two design cases employ spray nozzles common to many cooling towers. This was done to demonstrate the greater maximum liquid flow and greater turndown allowed by the "V" notch distributor.

Figure 33 gives the schematic for the cooling tower design basis. Water is pumped to the top of the column with a 10-hp pump mounted on the trailer. Pumps are sized to pump water between columns or from a source beside the trailer. For pumping from any significant distance, an external pump would be necessary. Water flows from the distributor, down through 4 ft of packing and then collects in a sump. The distributor pictured is a "V"-notch distributor, and is used in the first and second desired cases. The water outlet may be directed to the next column or discharged to the sewer. Figure 34 is a design sketch of the cooling tower unit.

If the normal outlet becomes blocked, an overflow drain is provided to protect the blower. Air is blown into the column with a 25-hp blower and directed downward via ducting. Exiting air passes through a demister at the top. The valving is arranged so that the columns can operate in parallel, or two or four in a series. Discharge is directed to a common drain line that also takes water from the overflow drain. Four blowers supply air to the columns.

The four columns each have a 6-ft diameter and 9-1/2 ft overall height. With a 4 ft high trailer bed, the overall trailer height is 13-1/2 ft. The trailer is 45 ft long and 8 ft wide. All blowers and pumps are controlled from a panel mounted at the front of the trailer.

The design case operating conditions are shown in Table 16. The first two operating conditions are the same as two of the conditions used in the packed column. The second two operating conditions are for the less efficient packing. Use of the spray nozzles reduces the maximum air flow to 6,000 cfm due to entrainment of the liquid droplet.

Applicability of Air Stripping

Air-stripping columns are for treatment of water containing low- to medium-hazard materials. Potential emissions from air stripping limit its application. Control devices can be placed on the exiting air to reduce emissions; however, the added cost of an air control device may make air stripping less cost effective than other water treatment options, such as steam stripping or aqueous-phase carbon adsorption.

The potential for fugitive emissions may require additional design considerations for an air stripper to be used for removal of extremely hazardous substances, regardless of the emission control device used.

Limitations on the applicable concentration ranges for air stripping are extremely variable. At low organic concentrations, adsorption and absorption of the organic onto oils, biological material, and suspended solids present in natural waters may begin to limit the ability of an air

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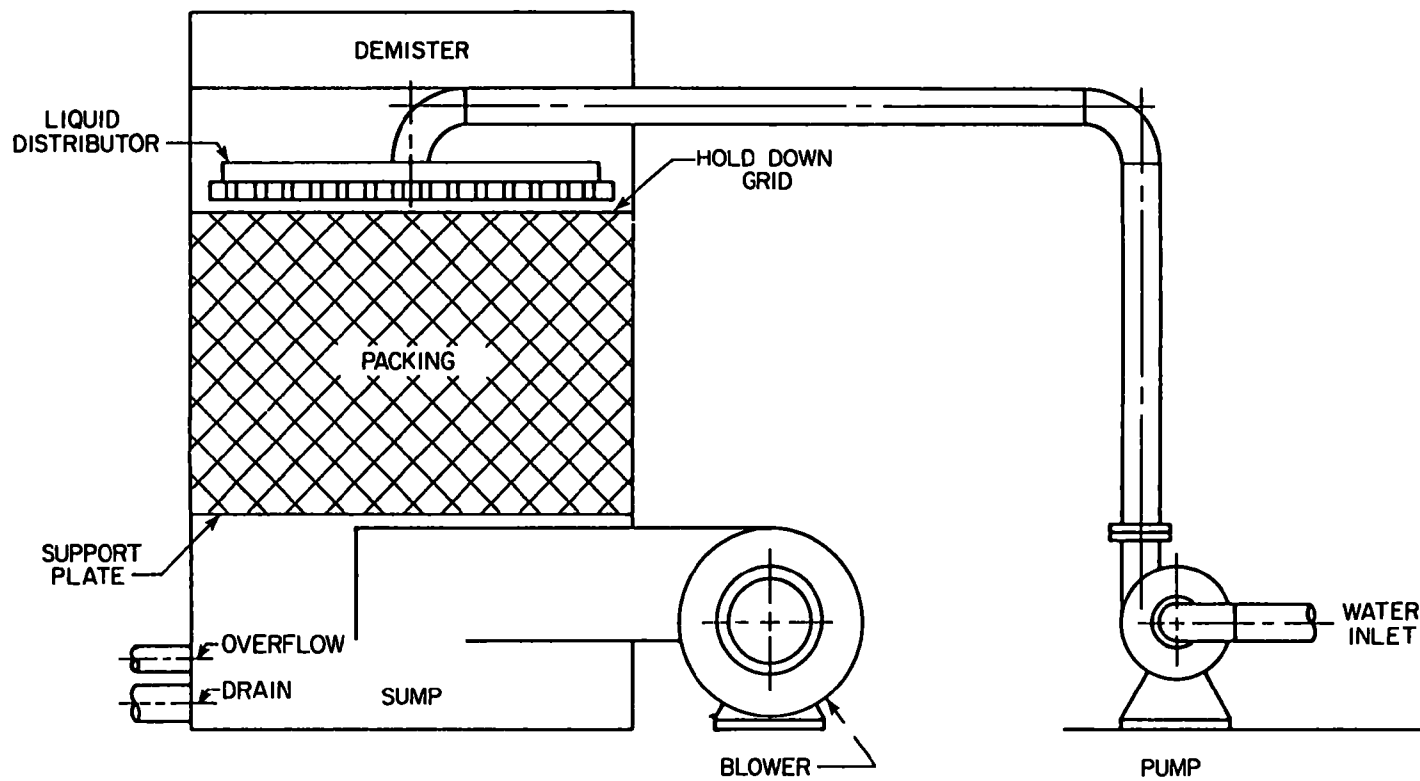
Figure 33. Cooling tower design basis, schematic
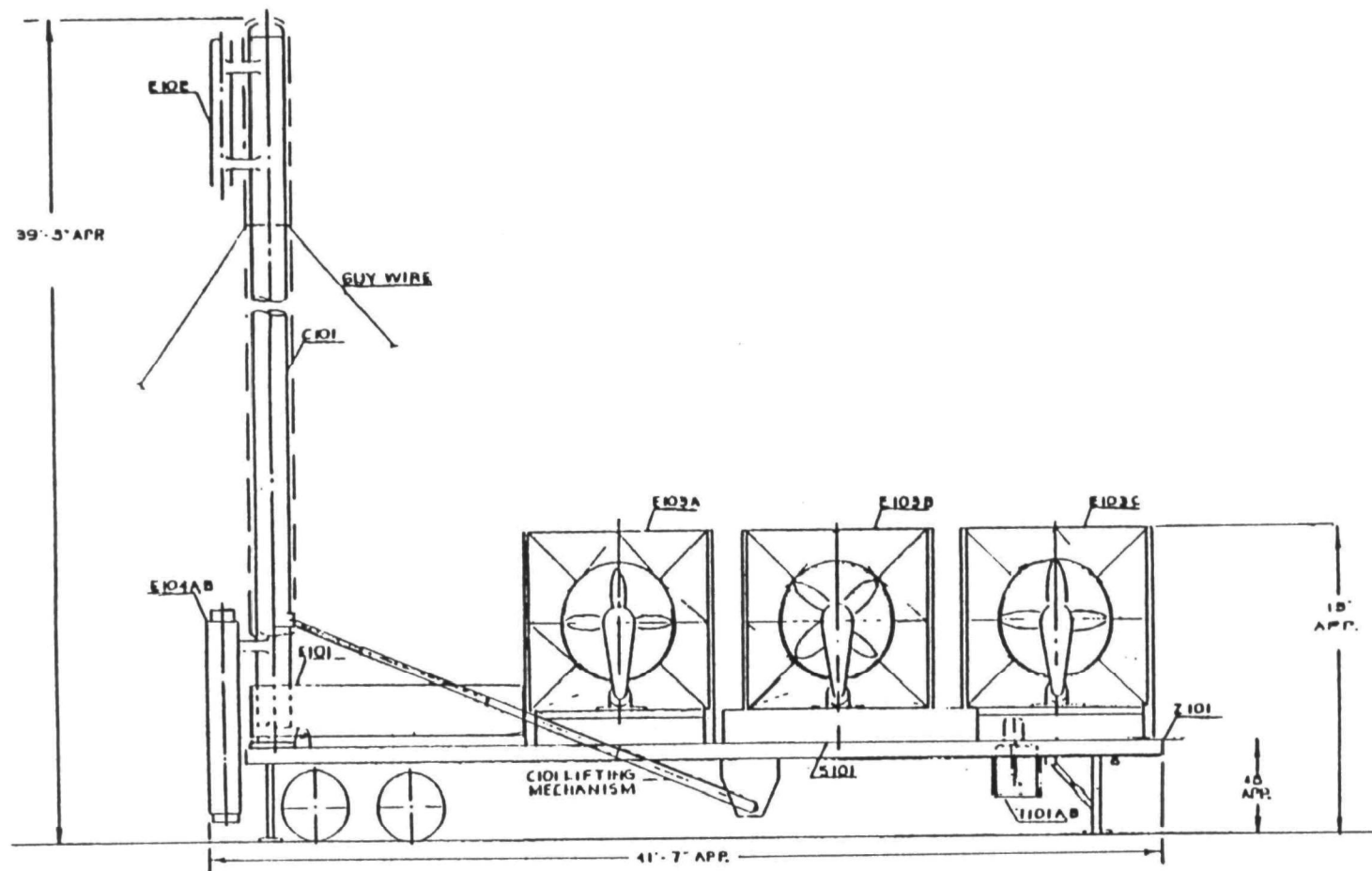
Figure 34.   Cooling tower design basis, side view

TABLE 16. COOLING TOWER DESIGN CASE OPERATING CONDITIONS

Case Number	C Factor	Stages	Superficial Vapor Velocity (ft/sec)	Superficial Liquid Velocity (ft/sec)	Gas Flow (G) (moles/hr) (cfm)	Liquid Flow (L) (moles/hr) (gpm)	G/L (mole) (mole)	Pressure Drop (in water) (ft packing)	Pressure Drop Total (in water)	Volume Hold-up (%)	Packing
1	0.20	2.4	5.8	0.045	1,500 (9,800)	14,000 (500)	0.107	0.41	3.0	8.0	a
2	0.20	2.4	5.8	0.0045	1,500 (9,800)	1,400 (50)	1.071	0.18	2.2	6.6	a
3	0.12	2.0	3.6	0.027	900 (6,000)	8,400 (300)	0.107	0.09	1.4	2.5	b
4	0.12	2.0	3.6	0.0054	900 (6,000)	1,680 (60)	0.536	0.07	1.3	2	b

a Structured packing typical of packed towers.
b Structured packing typical of cooling towers.

stripper to volatilize the organic. However, this is an extremely variable concentration limit, depending on the organic to be stripped, contaminants present in the water, and organic removal desired. At high concentrations of organic, the air emissions or safety considerations begin to limit the use of air stripping. This is also extremely variable and is dependent on toxicities, flammabilities, and stripping rates.

The primary safety consideration for air stripping is the treatment of flammable organics since a combustible mixture could be formed in the air exiting the stripper. This is likely with flammable organics having a high Henry's Law constant. Aqueous phase organic concentrations in the range of 100 ppm can often result in air concentrations above the lower flammability limit (LFL).

Whenever air-stripping is used, anticipated air emissions should be calculated and compared with data on the LFL. Organic concentration in air must be maintained below 25% of the LFL to meet the safety standards in the EPA Standard Operating Safety Guidelines. Explosion-proof equipment is required on all air stripping units used with any flammable materials. A table of LFL values for various organics is given in Appendix C as a reference.

In addition to general considerations on the applicability of air stripping, each type of stripping column has its own applications, as discussed below.

Applicability of Bubble Columns

Generally bubble columns are best applied to situations requiring high liquid throughput with a relatively low requirement for material removal.

They are ideal for situations where there are solids in the water that might cause fouling, but do not adapt well to situations requiring difficult separations or treatment of water with high surfactant concentrations. Mobile units can have a very simple design requiring a short setup time.

The advantages of bubble columns include:

- High potential liquid throughput

- High liquid turndown ratio

- Wide range of G/L ratios

- Low potential for fouling

- Short columns, may be transported vertically

- Low liquid pressure drop

- Simple device, low maintenance

- Adaptability to field situations

- Short setup time

- Design adaptable to available tankage and equipment

The disadvantages include:

- Surfactants in water limit flow rate

- Single-stage device, low removal percentage

- High gas-pressure drop requires high-horsepower blower

Applicability of Spray Columns

Of the air-stripping columns covered in this manual, spray columns are the most limited in range of application. The only relative advantage spray columns have over other air-stripping devices is a low pressure drop for the gas which reduces blower horsepower requirements. In certain low pressure distillations, this advantage justifies their use, although it is not as important in air stripping.

Spray columns, which are not as efficient as packed columns, have limited throughput and turndown potential, and can be prone to fouling at the nozzles.

The advantages of spray columns include:

- Low pressure drop for gas

- Simple operation

- No packing, reduced potential for fouling and channeling

- Short setup time

- Design adaptable to available tankage and equipment

The disadvantages include:

- High pressure drop for liquid

- Gas flow limited by liquid entrainment

- Limited number of stages, low removal percentage

- Number of stages not proportional to column height

- Possibility of fouling in nozzles

- Low turndown ratio (unless nozzles are changed)

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Applicability of Packed Air-Stripping Columns

A packed air-stripping column, as described for the design case, is useful for difficult separations requiring a high percentage removal. However, the treatment potential in this column may not be required for removal of many organics, particularly those having a high Henry's Law constant or in situations where high percentage removal is not required. In many cases, a shorter column gives adequate treatment for a lower operating cost.

A major advantage is the extremely high removal allowed in a tall packed bed. The disadvantages presented are a function of column design, packing, and mass flow.

The potential for fouling should normally not be a problem with proper packing selection. Fouling problems may also be eliminated by pretreatment of wastewater with a sand filter or other device. Column setup requirements will vary, but a tall column will either be transported horizontally or in sections, thus requiring greater field setup time. Other advantages of a packed air-stripping column include:

- Excellent removal efficiency (multistage device)

- High rate mass flow

- High turndown potential

- Large range of G/L ratios

- Low liquid pressure drop

The disadvantages include:

- Potential for fouling (depends on column internals)

- Difficult to transport and set up

- Significant gas pressure drop

- Difficult to adapt to available tankage and equipment

Applicability of Cooling Towers

Applications for this device are similar to those for the taller packed column. Shorter columns are a better choice than tall columns if they can give the desired treatment for they require a lower-horsepower blower than a tall column for the same mass flows, thus reducing operating costs.

Also, short multiple columns (four per trailer) can be transported vertically, thus reducing setup time and permitting a higher treatment rate. Operated in series, the four columns would give treatment at least

as good as the tall column, although the tall column will have a lower operating cost than four short columns. In addition, a trailer with multiple short columns is more versatile than a single tall column, since both series and parallel operation are possible.

The advantages of short columns, such as cooling towers, include:

- High rate of mass flow
- High turndown potential
- Large range of G/L ratios
- Low liquid pressure drop
- Compact device - easily transported
- Short setup time
- Low gas pressure drop

The disadvantages include:

- Potential for fouling (depends on column internals)
- Relatively new application by manufacturers
- Two- or three-stage device, may not give enough removal
- Difficult to adapt to available tankage and equipment

CONSIDERATIONS FOR AIR-STRIPPING EQUIPMENT EVALUATION

Considerations for selecting a particular piece of air-stripping equipment are: Number of stages in the column, mass flow rates, utility requirements, and setup requirements.

The number of stages in a column is determined by the packing in the column, and, to a lesser extent, the air and water flow rates and Henry's Law constant of the organic. The vendor should be questioned on column performance at various air and water flowrates. The vendor should be able to give data on the packing in his column, including ranges of height per theoretical stage, pressure drop for various flowrates, and liquid holdup for various flowrates. A conservative estimate of height per theoretical stage for use during preliminary performance calculations should be taken as the upper end of the range given by the vendor.

Bubble columns should be treated as having a single stage. The number of stages in a spray column is difficult to obtain, but may be assumed to be one for preliminary estimates.

The type of packing and column diameter determine mass flow rates. The vendor should be able to provide a flooding curve (which defines the limits at which the column can no longer support a discontinuous liquid phase due to the mass flow) for the column. To estimate maximum column performance, mass flows that represent 80% of flooding should be used.

The Kremser equation (Eq. 5), can be used to estimate material removal at several flowrates. Pressure drop data should be used to determine blower horsepower requirements. The blower provided with the column should be examined to determine whether it will perform as required. New pulley arrangements, different horsepower motors, and adjustment of amperage will allow a range of performance from the same blower.

The design case systems assume columns of the maximum diameter transportable on one trailer. Smaller columns of the same height and packing will have lower maximum mass flows. To estimate the mass flow in a smaller diameter column, multiply the mass flow by the square of the smaller diameter, and divide the result by the square of the design case diameter.

DISTILLATION SYSTEMS

Principle of Distillation

Distillation is a method of separating the components of a liquid solution and depends on the distribution of the substances between a vapor and a liquid phase. Instead of introducing a new substance into the mixture in order to form the second phase, as is done in air stripping, the new phase is created from the original solution by vaporization (1).

Distillation columns are divided into stripping and rectification sections. Stripping sections operate at a higher concentration of the lower-volatility component. Rectification sections operate at a higher concentration of the higher- volatility component. Generally, water columns have only a stripping column with no rectification section.

The vapor and liquid phases in contact in a distillation column are at essentially the same temperature and pressure. Various kinds of devices (plates, trays, or packings) are used to bring the two phases into intimate contact. Trays or packings are stacked and enclosed in a cylindrical shell to form a column. Feed material is introduced at one or more points along the column shell. Because of the difference in specific gravity between the vapor and liquid phases, the liquid runs down the column, cascading from tray to tray, while the vapor goes up the column, contacting the liquid at each tray.

The liquid reaching the bottom of the column is partially vaporized in a heated reboiler to provide reboil vapor which is sent back up the column. The remainder of the bottom liquid is withdrawn as the bottom product. The vapor reaching the top of the column is cooled and condensed to a liquid in the overhead condenser. Part of this liquid is returned to

the column as reflux. The remainder of the overhead stream is withdrawn as the overhead or distillate product. In some instances, the distillate product consists of an organic-rich phase that is separated from the aqueous phase. The overall flow pattern in a distillation column provides countercurrent contacting of vapor and liquid streams throughout the column.

The lighter (lower boiling) components tend to concentrate in the vapor phase, while the heavier (higher boiling) components tend toward the liquid phase. The result is a vapor phase that becomes richer in the lighter components as it passes up the column, and a liquid phase that becomes richer in the heavy components as it cascades downward. If the feed is introduced at one point along the column shell, the column is divided into an upper section, called the rectifying section, and a lower section, referred to as the stripping section.

The overall separation achieved between the overhead product and the bottom product depends primarily on the:

1. Relative volatilities of the components

2. Number of contacting trays or stages

3. Ratio of the liquid-phase rate to the vapor-phase rate

By appropriate manipulation of the two phases, repeated vaporizations or condensations, or variation in column height, it is possible to make as complete a separation as desired by using distillation (except for azeotropes, see below). Both components of a two-component mixture can then be recovered in as pure a state as desired.

Distillation is an energy-intensive separation process (1,2). In a mobile system the limitations imposed by energy requirements are the primary limitations on removals and flowrates. Limits on column height may also be important in some cases.

Treatment of Aqueous Organic Solutions by Distillation

Application of distillation to dilute aqueous organic solutions of limited solubility is confined to steam stripping. (Steam stripping uses steam as a heat source instead of a reboiler and is in contact with the waste liquid.) Because we are interested only in purifying the water stream and not the organic stream, the desired distillation should contain only a stripping section to remove the more volatile organic from the water. Descriptions of theory for the removal of volatile organics from wastewaters is contained in other sources (6,18,19).

The application of other distillation techniques, such as multicomponent, azeotropic, extractive, vacuum, fractionation, and molecular distillation, are applicable to specific systems where vapor-liquid equilibrium data are experimentally determined or known, and specific equipment and methods are needed to obtain a specific product.

These applications are therefore beyond the scope of a generally applicable distillation technique for the removal of many volatile organic compounds from wastewater.

Relative Volatility

Relative volatility in a binary system is a measure of the degree to which the more volatile component concentrates in the vapor phase and the less volatile component concentrates in the liquid phase. Also, relative volatility is the ratio of vapor to liquid composition for the two components under consideration.

For steam stripping of a single volatile organic from water, the relative volatility can be related to the Henry's Law constant after making some simplifying assumptions. Henry's Law constant is used exclusively throughout the manual for steam stripping. For further information on the relationship between the relative volatility and Henry's Law constant, see Section 1.

Azeotropes

In a binary system, an azeotrope is a system in which the organic concentration is the same in the vapor as in the liquid. An azeotrope represents a limit to which a separation can be conducted. In general, when dealing with dilute insoluble organics in water, azeotropic formation will not affect the separation. If, however, the organic is soluble in water and requires rectification, then an azeotrope will be more likely to affect the degree of separation in a particular system. The exact effect depends on the materials being separated and the operating conditions. Each system should be evaluated for the possibility of azeotropic formation before a full-scale system is designed or operated.

Azeotropic data are available; (20) these data should be used to verify the existence of the azeotrope, and a design engineer should do a final calculation. If azeotropic data are not found, it will be necessary to attain vapor-liquid equilibrium data for the system before a design is initiated. Structure-activity methods for the prediction of azeotropes are available, but their accuracy will vary depending on the system of interest. Data should be obtained from published experimental data, if available, or from laboratory distillation of the specific compound(s) of interest.

Steam-to-Feed Ratio

Distillation is an energy-intensive separation process. A major portion of the operating cost of a steam stripper is the energy necessary to make steam. For a given column with a fixed column height and packing to produce a given separation, the steam-to-feed ratio (also called gas to liquid ratio, G/L, boilup, or percentage boilup) is fixed by Henry's Law constant. The degree of separation is increased by selecting a higher steam-to-feed ratio. The steam-to-feed ratio can be raised and lowered in a given column, within limitations. The range used for this manual is

a minimum steam-to-feed ratio of 0.03 and a maximum of 0.30. These limits are imposed because of equipment limitations, and should be generally applicable to mobile steam-stripping systems.

Mass Transfer Equations and Estimation Procedures

As in air stripping, the performance of a steam stripper can be described mathematically by the Kremser equation (Eq. 15). It should also be noted that this equation assumes dilute isothermal solutions. The Henry's Law constant used should be evaluated at $100^\circ C$. All other terms have identical meaning and application as those stated for air stripping.

In cases where Henry's Law does not apply, the Kremser equation yields an estimate, but the detailed methods of McCabe-Thiele or Ponchon-Savarit should be used if a better estimate is desired for design purposes. These methods, requiring specific vapor-liquid equilibrium data on the specific compounds being separated, are described in various texts (1,2). The reader should also use caution when applying the Kremser equation for more soluble compounds.

DESCRIPTION OF MODEL SYSTEM

A process flow of the model steam stripping system is shown in Figure 35. It also includes major control instrumentation for clarity. A plan view is shown in Figure 36.

The steam-stripping system consists of a packed column with two packing sections. Feed inlets are located above each of the sections. These sections have ~5 ft of packing in the upper section and ~20 ft of packing in the lower section. A multistage operation is required to provide an overhead organic concentration higher than the organic's concentration in water. The rectification section provides for column operation at organic concentrations higher than the feed organic concentrations. In general, rectification will be necessary only if the ratio of the organic solubility and the feed concentration is greater than the Henry's Law constant evaluated at $100^\circ C$, assuming dilute solutions. Or:

$$\frac{C_{os}}{C_{of}} > H_{100^\circ C} \tag{17}$$

where:

C_{os} = Concentration of organic in water at solubility,

C_{of} = Concentration of organic in the feed water, and

$H_{100^\circ C}$ = Henry's Law constant at $100^\circ C$.

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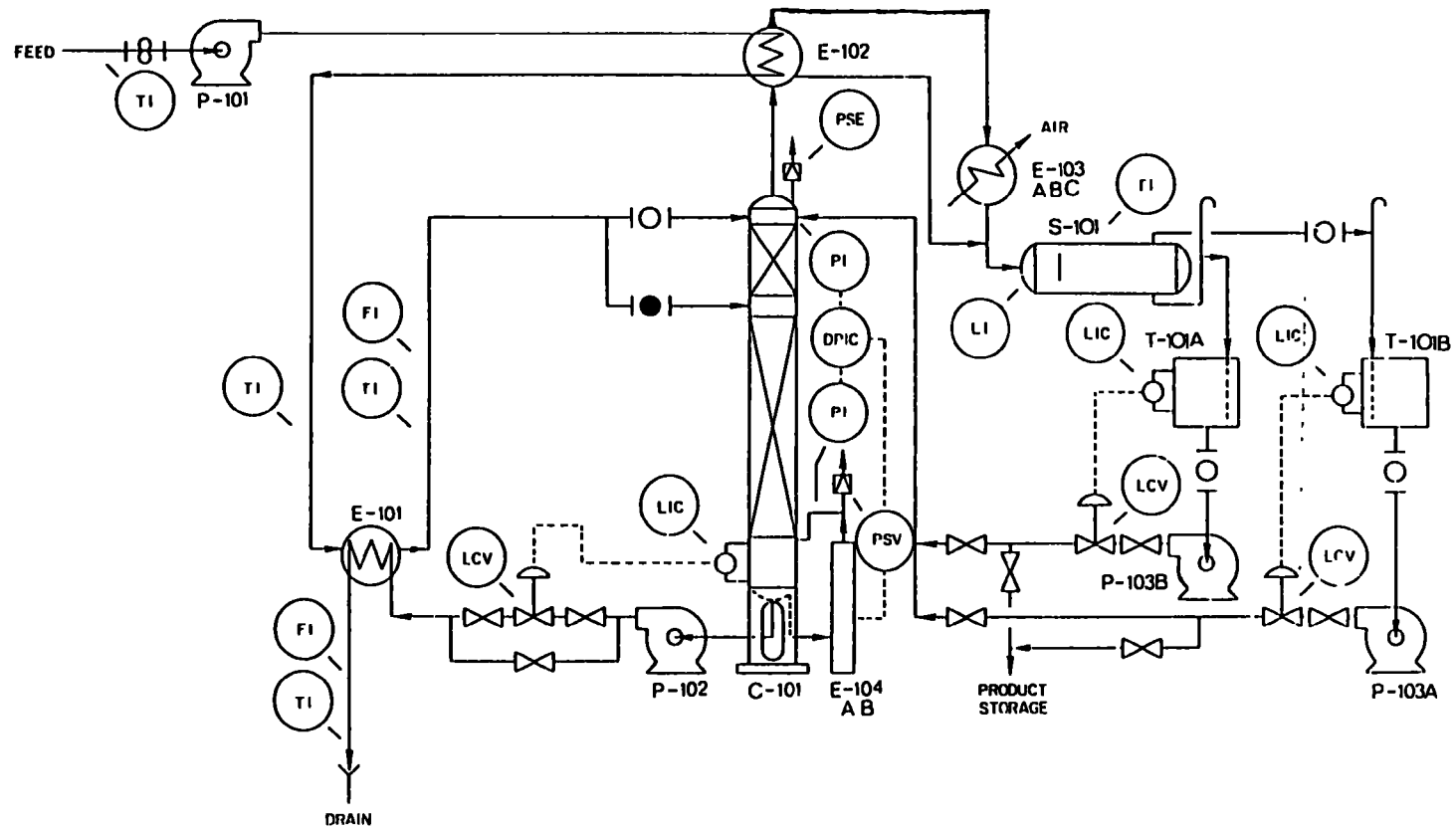
Figure 35.   Steam stripper design basis, process flow diagram

If rectification is necessary, the final design or application should be determined by a design engineer. In most instances a dilute, insoluble organic will enter the top of the column and will not require a rectification section.

The column diameter of the model system is limited by the physical size and weight of the auxiliary system equipment required to operate the column. This was apparent in the sizes of required heat exchangers diagrammed in Figure 36. The largest standard column diameter (determined by the maximum heat duty) that can be placed on a packed trailer is 1.5 ft. The packing used is 1.5-in metal pall rings. Random dumped packing was chosen over trays because of easier cleaning, and over rigid packing because of availability. The height of packing was chosen to be 25 ft. This was due to the overall size of the column shell of 35 ft, which is a realistic size for a single flatbed trailer.

The feed is pumped from the waste location, through a strainer, and used as cooling water for the overhead condenser. From there the feed exchanges heat in the bottoms heat exchanger with clean water from the bottom of the column. The preheated feed enters the top of the distillation column. Preheating the feed reduces energy input required to operate the column. The total energy required can be estimated as the differences in enthalpy between the feed in and the bottoms out (the project out will usually be a small fraction of the feed). Another advantage of preheating is that cooling water for condensation may not be available, so some of this heat duty can be handled by the feed stream, thus reducing the size of air condensers required on the trailer.

The practical liquid and gas flowrates are fixed by the column diameter due to the limits of flooding. Flooding in a packed tower is an unstable operating region in which the vapor rising up the column interferes with the liquid traveling down the column, causing a sharply increased pressure drop over the column. Flooding causes a reduction in mass transfer resulting in lower effluent quality. The flooding flowrates for the design case steam stripper removing dilute organic compounds from a wastewater stream are shown in Figure 37. In this figure, column diameter is plotted against flooding liquid rates for different boil-ups (gas-to-liquid ratios). Different sizes of metal pall rings are used in a range of diameters to conform with standard rules-of-thumb used in industry. Standard practice is to operate at 80% of flooding. Therefore, the operating conditions for a 1.5-ft diameter column are as follows:

Boil-Up (G/L)	Maximum Liquid Rate (gpm)
3% or 0.03	96
5% or 0.05	74
10% or 0.10	50
30% or 0.30	24

These rates will yield pressure drops in the column of 0.75 to 1.75 in of water per foot of packing or ~1.5 psi maximum over the entire column.
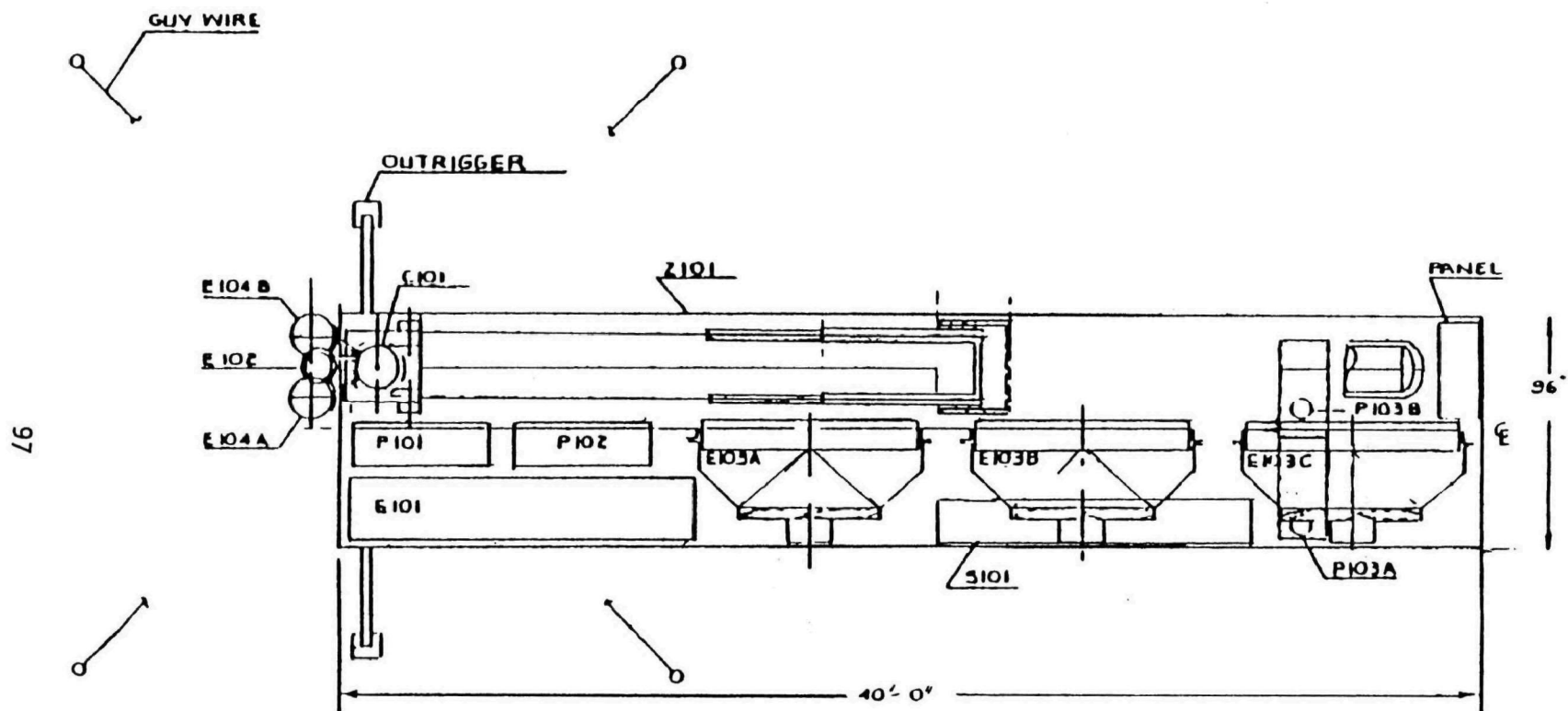
Figure 36.   Steam stripper design basis, plan view
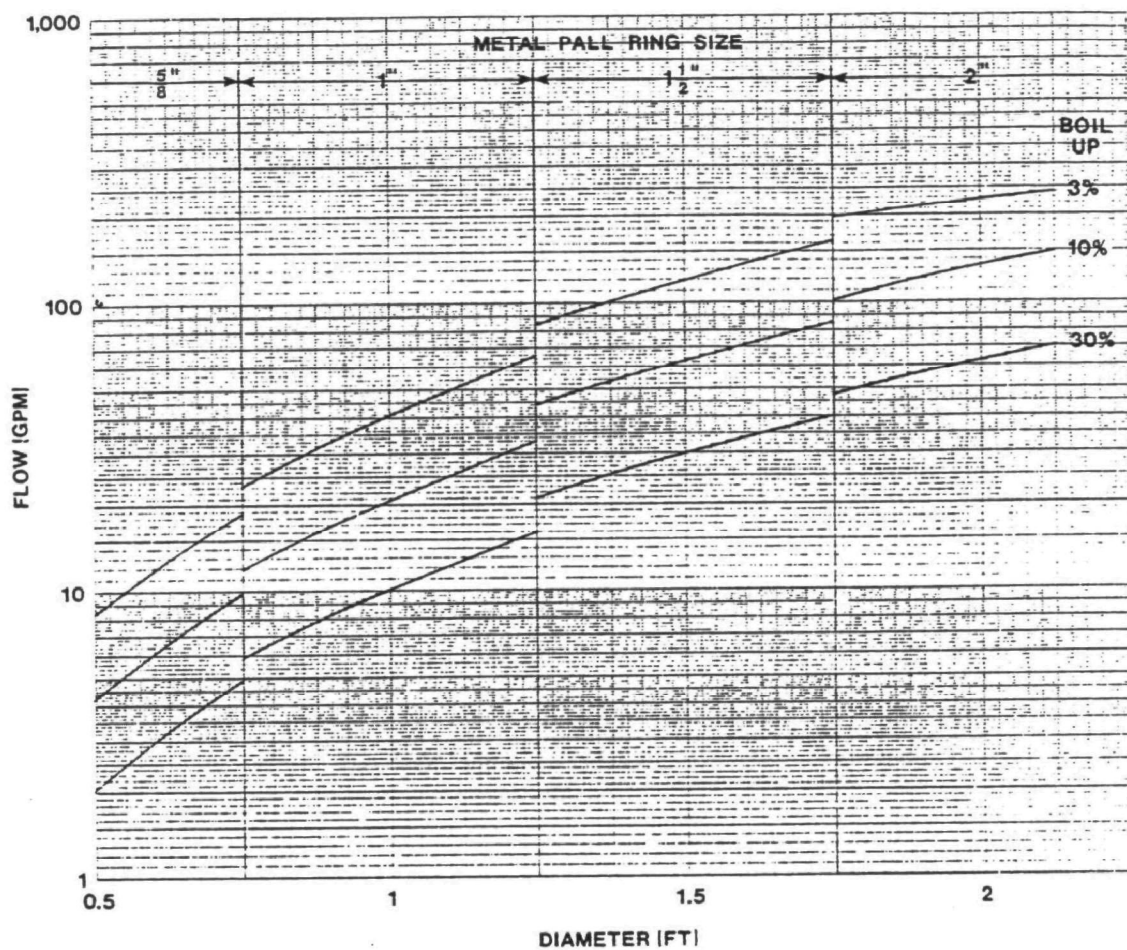
Figure 37. Flooding in a packed tower stream stripper

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The four heat transfer surfaces were sized to reduce the energy consumption of the system over the entire range of operating conditions. The range of heat duty for the reboiler and condensers is as follows:

Boil-Up (G/L) (%) Heat Duty (10^6 Btu)/hr)

Boil-Up (G/L) (%)	Heat Duty (10^6 Btu)/hr)
3	1.4
5	1.8
10	2.4
30	3.5

This range represents practical operating limits and operation should not deviate from these ranges.

The reboiler consists of two 225-kW electric steam generators. This will yield ~1.4 X 106 Btu/hr of low-pressure steam for boilup of 3%. For larger boilup the system operator could rent a portable diesel-powered steam generator to hock into the bottom of the column. A combination of the boil-up required and the standard size of available equipment in the area would determine the size of boiler rented. When using the electric steam generators supplied with the design case system, the operator would select a rental electric generator based on the electric demand of the reboiler.

The bottoms exchanger is sized such that the temperatures of the feed on either side of it are similar in order to reduce boiler requirement and minimize the heat released if the bottoms were returned to the environment. A hot stream returned to a lagoon, for example, would release more organic material to the atmosphere. This exchanger has a heat transfer area of 850 ft^2.

The overhead condenser is sized based on a 3% boilup, and has a heat transfer area of 75 ft^2. If a higher boilup is selected, then the additional heat duty would be taken by the extended surface air condenser. This is sized based on using 85^{0}F air to condense 3.5 x 10^6 Btu/hr of atmospheric steam and has a total heat transfer area based on a bare tube area of 385 ft^2. For some operating conditions, the condensers provide some subcooling of the liquids. The temperature is a function of boilup, organic concentration, and vapor-liquid equilibrium. Some degree of subcooling of the organic is required to reduce vent losses. The water phase returned to the top of the column should be as close as possible to boiling to reduce energy costs of the reboiler. The design case heat transfer system represents a compromise over the range of operating conditions.

Four different operating regions were envisaged that would influence the design of the product storage/reflux area. These are summarized as follows:

Number of Phases Formed in the Decanter	Liquid Organic	Reflux
2	More dense than H_2O	All of the H_2O
2	Less dense than H_2O	All of the H_2O
1	Miscible with H_2O	None if stripping only
1	Miscible with H_2O	A fraction of the H_2O if stripping and rectifying

The first two operating modes cover most of the organic systems encountered. Condensate from both condensers flows by gravity to the accumulator/gravity separator. Separation occurs by allowing a minimum of 0.5 hr residence time in the accumulator (150 gal). A light and heavy liquid stream are drawn off with a movable standpipe, which permits the two-phase interface to be adjusted inside the accumulator. Both streams then flow by gravity to individual levee control tanks. These allow 15-min residence time (75 gal). Individual reflux/product pumps are used to return the water stream to the top of the column or to send organic product to a storage location. This tank would be rented at the site. Fifty-five gallon drums may also be used for product storage. Ultimately, the choice will depend on the available organic disposal.

In the case of a single phase forming in the decanter, a single-level control tank and pump is used to send part of the organic-rich stream back to the column as reflux and part to an organic-rich storage tank. The flowrate of this organic-rich stream is the product of boilup and the feed flowrate divided by the reflux ratio. The product-rich storage tank should be sized with this flowrate in mind. The column is transported in a horizontal position with packing in place. At the treatment site the column is raised by means of a hydraulic arm to an upright, vertical position. The column is then interconnected with the rest of the system. The trailer is also equipped with hydraulic stabilizer feet to form a base of support for the column. Finally, the column is secured with four guy-wires for added wind stability.

As designed, the model system is primarily a steam-stripping unit. Provisions were made to operate the unit with rectification to provide some flexibility to operate the system as a distillation unit. However, it is anticipated that most field situations will involve organic contaminants that will only require stripping to remove them from a wastewater stream. The system represents a compromise so that as many compounds as possible can be treated with the mobile steam-stripping system.

Applicability of Distillation Systems

In industry, steam stripping is used to remove compounds from water in the concentration range of 1 - 10%. The application of steam stripping to lower level of organic compounds has been proposed (6,19). Generally, at concentrations below 100 ppm organic, other treatment alternatives become more economically attractive, such as carbon adsorption (21). The lower treatment concentration limit depends on the specific design of the steam-stripping equipment, including such equipment details as liquid and vapor distributors, wall effects, and gas-liquid contacting. Treatment levels for some compounds were proposed down to 1 ppb (5).

Steam stripping is not generally applicable to certain classes of compounds such as glycols, amides, acids, phenols, and glycol ethers because they are the less volatile compounds. However, certain individual compounds within those classes might be treatable by steam stripping.

If air emissions are not acceptable, steam stripping allows the organic to be removed from water and discharged as a liquid phase. with appropriate vent controls, air emission could be greatly reduced over treatment technologies, such as air stripping, that discharge the organic directly to the air. However, a concentrated organic stream may become a disadvantage from a flammability and health standpoint. These factors must be considered when a steam stripper will generate an extremely flammable liquid or extremely toxic concentrated organic. Each situation will have unique requirements that must be evaluated individually.

Compared with other systems in this manual, the advantages of steam strippers include:

- Recovery of a concentrated organic (reduced disposal volume)

- Air emissions from tank vents only

- Availability of many equilibrium stages

The disadvantages of steam strippers include:

- Low G/L ratio

- High energy consumption, high operating costs

- Not easily adapted outside of industrial plants

- Moderately complicated device, high maintenance

- Extended setup time

- High potential for fouling

- Low treatment rates

- Recovery of a concentrated organic (health and safety exposure)

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- Difficult to adapt to available tankage and equipment

In general, steam stripping is applied to situations requiring high removal efficiencies with mandatory recovery of organic (low air emissions).

Utility requirements are the principal factors limiting possible treatment rates in a steam-stripping system. This is demonstrated in the design case system by the relative sizes of equipment on the trailer. The physical sizes of heat transfer equipment and associated heat duty are the primary factors influencing the treatment rates through the system. If cooling water is available from other sources, then a larger system could be designed to fit a single flatbed trailer.

The model system previously described was designed to be a quick response/emergency treatment system. Before operating this type of unit, some study of available equilibrium data is required to evaluate whether treatment criteria will be met. Certain design modifications may need to be implemented in each specific case, such as vent controls, fire proofing, special holding tanks, or high-hazard training courses for operators and others. Also, a steam stripping unit requires evaluation and extra setup time as compared with the other treatment technologies covered in the manual.

CONSIDERATIONS FOR STEAM-STRIPPING EQUIPMENT EVALUATION

Equipment associated with a steam-stripping system is standard chemical processing equipment. Although most of it is custom fabricated, the specifications are standard designs used throughout the chemical industry. In some cases, a vessel fabrication and packing manufacturer may be able to build the entire system. Several package distillation systems are available in the marketplace. However, it is generally not practical to configure a steam-stripping system from available equipment.

For heat transfer equipment, most reputable manufacturers follow standard design practices. Any heat exchanger can be designed using any standard text (22). Pumps are standard designs available from vendors and suitable for the required service. All packing manufacturers have literature on the performance and specifications of their packing; however, such data from vendors tend to be optimistic.

The design case system assumes a column of the maximum diameter transportable on a trailer with all associated equipment. A smaller-diameter column of the same height and packing has a correspondingly lower treatment rate. However, smaller columns that were designed to be pilot plants for demonstration purposes may be available. These columns may have flows in the 1-10 gpm range. If this flow rate is acceptable, these systems could provide an attractive option for water treatment.

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SECTION 6

FACTORS AFFECTING EVALUATION

A variety of factors affect the performance of treatment systems under actual field conditions. Many of these factors have effects that are difficult to quantify on a theoretical basis. Further data to apply the theory may often be difficult or impossible to gather in the field. Normally, these factors taken together will not influence system performance by more than a factor of 2 to 3. Therefore, they generally fall within the accuracy of the predictive methods outlined in this guide and can be ignored during preliminary evaluations. This section describes some of these factors and qualitatively predicts their effects.

MATERIAL-SPECIFIC FACTORS

Multicomponent Mixtures

Effects of multicomponent mixtures become more profound as the organic concentration is increased. The presence of organic contaminants affect the volatilization of the compound(s) of interest by introducing competitive interactions into the vapor-liquid equilibrium. These effects are extremely complex and normally cannot be predicted accurately without specific experimental data.

The volatilization technology most affected by multicomponent mixtures is steam-stripping due to the concentration effect of rectification in a steam stripping column. Air in an air-stripping unit normally will not become saturated with organic, resulting in reduced interaction between organic components in that technology.

We estimate the effect of multicomponent mixtures can be ignored for a routine evaluation of performance, particularly when organic concentrations are low. Volatilization of each organic component should be estimated independently, as if it were the only organic present. This gives a very rough estimate if no supporting data are available. The effects of multicomponent mixtures are system specific, however, and may be very significant, particularly at high concentrations of organics.

Safety Considerations

Two important safety considerations are the flammability and toxicity of organic contaminants. By nature, air stripping creates a mixture of air and organic vapor that could be explosive. Additionally, emissions from airstripping devices may be difficult to treat to low concentrations. Emission controls may not prevent a hazardous atmosphere in the area around an airstripping operation, particularly if the process involves very toxic organics or flammable organics that tend to collect in low-lying areas. Generally, safety and emission restraints limit the applicability of air-stripping devices, including surface aerators and surface sprayers placed in a pond.

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Although steam stripping does not necessarily create a potentially explosive or toxic mixture of air and organic vapors, these mixtures may occur if precautions are not taken. Strict handling procedures must be followed when handling potentially toxic or flammable materials. The potential for unsafe conditions is increased by the elevated operating temperatures of steam stripping and the formation of a concentrated organic stream for disposal.

Safety practices must include: Vent condensers, LFL monitoring, special fire suppression systems, operator respiratory protection, and protective clothing.

Whenever evaluating treatment technologies for potentially hazardous materials, a qualified industrial hygienist should determine if the process can be run safely, draft safety precautions for operating the process, and develop cost estimates for the safety program. Regardless of the urgency of the cleanup process, there is no substitute for appropriate safety planning and determination of the limitations of the equipment and technology.

Absorption and Adsorption

Absorption is the dissolution of a material into another material. In natural water, oils associated with solids or freely floating oils form a separate nonpolar phase. The measure of the equilibrium partitioning between water and a nonpolar phase is the octanol-water partition coefficient. A relatively small amount of oils in natural water can greatly influence the behavior of an organic with a high octanol-water partition coefficient.

Adsorption is the binding of a material to the surface of a solid. The tendency of organics to adsorb is greater for low-molecular-weight organics and organics with low aqueous solubilities.

The absorption and adsorption of a compound on suspended solids, sediments, oils, and biological tissue can reduce the stripping rate, particularly for organics with low solubilities. This effect is the result of the equilibrium and kinetics of organic transfer between water and solid materials.

Decomposition in Water

Many organics will decompose in water by such mechanisms as hydrolysis, photolysis, reaction with other substances in the water, and biological degradation. These factors will compete with volatilization for the disappearance of the organic from water. In some cases, decomposition will yield products that are relatively innocuous. In other cases, the decomposition product(s) may be hazardous in their own right and require treatment.

The scope of this manual does not include the decomposition of organics. However, Appendix B lists some compounds suspected to hydrolyze

or photolyze in water. If decomposition by any means is suspected, the mechanism should be studied to determine the competing rate. The properties of decomposition products should then be analyzed to determine if their removal should be considered in the evaluation of treatment alternatives.

SITE-SPECIFIC FACTORS

Season

Season mainly influences the operating temperatures of the treatment system. For air stripping and volatilization from a pond, the volatilization rate will decrease as ambient temperature decreases. For stream stripping, the ambient temperature mostly affects the size of air condensers and heat exchangers necessary to operate the column. If proper insulation is not used, very cold ambient temperatures can cause freezing in lines and excessive heat loss from a steam stripper.

For volatilization from a pond, seasonal effects other than temperature can be important. For a pond without agitation, increased wind speeds increase the volatilization rate. Incident radiation affects pond temperature, thus increasing volatilization rates. Precipitation, or lack of it, affects the concentration of the organic in the water, although it may not affect the actual amount in it. The effects of precipitation are not due just to rainfall, but also include runoff.

Expected seasonal variation must be considered as part of the initial technology evaluation. If a unit is to be run in the winter, provisions for insulation, steam injection into air strippers, and protection of equipment and work areas from excessive condensation and ice formation must be implemented.

Water Quality

Water quality can affect system performance through reduction of volatilization rate, limitation of gas and liquid flow rates, and fouling of equipment. Reduction in rates influences compound removal. Adsorption and absorption are primary causes of reduction of volatilization rates.

The presence of surfactant can limit the gas and liquid flowrates possible for proper operating of treatment systems. Agitation, a primary characteristic of all methods, increases volatilization. If surfactants are present, foaming can become a problem in agitated systems. Flow rates must then be reduced to limit foaming. To overcome this problem, additives can be used to help prevent foaming.

Fouling can be caused by suspended solids, biological material or growth, or water hardness. It can reduce the effective surface area of packing, diminish the effectiveness of spray nozzles, and increase pressure drop in columns. It is difficult to predict the potential for fouling in heating natural water. Use common sense to determine the potential for fouling in specific situations. If any of these factors are

present in abundance, the potential for fouling must be considered before using any system that might be prone-to-foul.

In many instances, pretreatment will be necessary before application of air- or steam-stripping columns. Warning signs are the presence of solids, algae, or salts in the water to be treated, or any application using water contaminated with an organic that will support bilogical growth. Pretreatment methods could include sand filtration, treatment with an oil absorbent, addition of additives to prevent growth, and flocculation followed by sedimentation.

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APPENDIX A
EXAMPLE

STATEMENT OF PROBLEM

A city drinking water field is contaminated with trichloroethylene (TCE), with levels from the well field as high as 15 ppb. A contamination assessment was performed around a manufacturing site 2 miles from the well field. This assessment showed the presence of contaminated groundwater migrating beyond the extent of monitoring wells at levels as high as 250 ppb. A temporary system is needed for approximately 1 year until new water supply wells are installed into a deeper uncontaminated aquifer. The flow rate from this well field is 1 mgd (700 gpm). The drinking water standard for TCE is 5 ppb. The water temperature is 20°C.

EVALUATION

Figure 1 of this guide is used to direct the selection process. As described in Phase 1 (Section 1, Introduction), volatilization is an appropriate technology because the contaminant level is low and TCE volatilizes faster than water evaporates. The second phase is the site characterization (Section 2, Site Characterization), using the checklist in Table 2. The extent of treatment needed and the treatment requirements are defined in the statement of the problem. The maximum concentration (250 ppb) found in the contamination assessment is used as the basis for groundwater contamination. This will ensure that the system will operate adequately if levels increase to the higher concentration.

The properties of the spilled material are then obtained from Section 3, Material Properties and Estimation Methods, and the appendices. The Henry's Law constant and solubility of TCE are obtained in Appendix B; they are 490 and 1110 ppm, respectively. The lower flammability limit of 12% is obtained from Appendix C. An azeotrope for TCE at 5.4% water is obtainable (20). The fact that TCE solubility is much greater (an order of magnitude) than the Henry's Law constant indicates that a column can run very efficiently. Because the level of contamination is in the ppb range, the lower flammability limit of 12% will not be reached; so an air stripping column is also feasible. Finally, the azeotrope at 5.4% water indicates a reasonably pure product. Based on these facts, no technology is eliminated.

The water temperature of 20°C is confirmed with the well operators, who confirm that this temperature remains fairly constant throughout the year. The site is accessible and has utilities.

The calculation of material properties as listed in Figure 1 is unnecessary for this example because all essential information is available in the guide. If this step were necessary, explanations are provided in Section 1.

The required removal is 98%, obtained from influent and effluent criteria of 250 ppb and 5 ppb, respectively (1 - 5/250 = 0.98).

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Inspection of Figures 2-9 (Section 3) reveals that all technologies except bubble columns and spray columns operated in parallel are applicable. Bubble columns and spray columns are batch systems, and the requirement is for a continuous system. Impoundments are not practical for a city water supply. This preliminary evaluation is based on the Henry's Law constant of TCE and the lowest removal rate plotted in the figures.

The flow rates are then compared for the model systems. It is seen from this comparison that to obtain a 700 gpm flow, two model packed air stripping towers or one cooling tower system would be needed. Although larger systems could be constructed on site, spray tower and steam stripping systems have flow rates too low to be applicable for this service. They are therefore dropped from consideration, leaving only the packed air stripping column and cooling tower systems.

Air emissions are obtained from Table 5 (Section 4, Technology Evaluation) for the two remaining technologies. Putting the two systems on the same basis of pounds of TCE per hour, the emissions from the two systems are very similar. This similarity should be expected because both the packed air stripping column and cooling tower system provide greater than 98% removal. To obtain the total emission rate, it is assumed that all of the TCE in water is emitted. The daily TCE emission is then:

$$(10^6 \text{ gpd}) \ (8.2 \text{ lb water/gal}) \ [(250 \times 10^{-9} \text{ lb TCE}) \ /\text{lb water}] = 2 \text{ lb TCE/day}.$$

This rate is permissible in some states for an air stripper. The concentration of TCE in air emissions is calculated from Table 5 for the packed air stripper column as 2.75 ppm (wt/wt) or 0.6 ppm (mole/mole). These values would be compared to any applicable air quality criteria to determine if these air emissions are acceptable. For the purposes of our example, it is assumed that these emission rates are acceptable.

The final criterion for selection is cost (Section 4). Costs of the air stripping column and cooling tower systems are compared on the basis of dollars per 1000 gallons of water treated. Cost for packed air stripping columns range from $1.97 to $18.99 per 1000 gallons, while cooling tower prices in parallel operation range from $0.51 to $5.03 per 1000 gallons.

CONCLUSION

Either a packed tower air stripper or cooling tower should be selected for this service. The height, diameter, and packing will need to be evaluated in detail as a part of the vendor selection process.

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CERCLA Compound Chemical Formula (Synonym)	CERCLA Class	Solubility in H₂O (ppm)	Temperature (°C)	Source	Vapor Pressure mm Hg Pure Solute	Temperature (°C)	Source	Henry's Law Constant Theoretical (at 1 Atm)	Units	Temperature (°C)	Source	Henry's Law Constant Experimental (at 1 Atm)	Units	Temperature (°C)	Source
Acetic acid CH₃COOH (ethanoic acid)	III	-		23	760 10	118 17	23 23	1.29 0.01	N U N U	100 17	6 Calc	0.73	N U	100	28
Acetic acid, ethyl ester, CH₃COOC₂H₅ (ethyl acetate)	V	89,800	25	24	760 95	77 25	24 5	6 3	N U	25	Calc.				
Acetic anhydride (CH₃CO)₂O	III	Hydrolyzes (forms acetic acid)		23	760 214 5.3	139 100 25	24 5 5								
Acetone CH₃COCH₃ (propanone)	III	-		5	760 227.1 200	56 25 25	5 25 26	0.28 6 8 x 10⁻⁶	N.U b	25 25	Calc. 26	15 5	N.U.	100	29
Acetone cyanohydrin (CH₃)₂C(OII)·CN	III	v s Hydrolyzes (forms hydrogen cyanide)		24	15 760	81 95	24 24								
Acrylic acid CH₂ CHCOOH (propenoic acid)	III	-		5	760 200 40 5	142 103 66 27	5 24 24 24	0 01	N.U.	27	Calc.	1.0	N U	100	30
Aniline C₆H₅NH₂ (aminobenzene)	VI	34,000 60,000	100	24 24	50 760	102 184	5	1.8 3 07 x 10⁻⁶ 5 4	Atm b N.U.	75 25 101	27 26 Calc.				
Benzal chloride C₆H₅CHCl₂ (benzylidene chloride)	VI	(Hydrolyzes)			760 1.05	205 35	23 25	1 70 x 10⁻⁴	b	25	26				
Benzenethiol C₆H₅SH (mercaptobenzene)	VI	1		24	760 87 8 15.0	169 100 60	22 5 5	3.10 x 10⁻⁴	b	25	26				
Benzonitrile C₆H₅CN (phenyl cyanide)	III	10,000	100	5	760 100 10 1	191 124 89 28	24 24 24 24	30	N U	100	Calc.				
Benzotrichloride C₆H₅CCl₃ (phenyl chloroform)	III	Hydrolyzes to benzoic and hydrochloric acid		24	760 60 25 10	221 129 105 89	23 24 24 24	1 12 x 10⁻⁴	b	25	26				
Benzoyl chloride C₆H₅COCl	I	Decompos		5	760 35 3	192 100 49	24 24 24								
2,2-Bioxirane C₄H₆O₂ (Erythritol Anhydride) (1,2 3,4-diepoxybutane)	III	S Hydrolyzes to Erythritol		23	760 23	144 51	23 24								

CERCLA Compound (Synonym) Chemical Formula	CERCLA Class	Solubility in H₂O (ppm)	Temperature (°C)	Source	Vapor Pressure in Hg Pure Solute	Temperature (°C)	Source	Henry's Law Constant Theoretical (at 1 Atm)	Units	Temperature (°C)	Source	Henry's Law Constant Experimental (at 1 Atm)	Units	Temperature (°C)	Source
Bis(2-chloroethyl) ether ClC₂H₅OC₂H₅Cl (2,'2'-dichlorodiethyl ether)	III	10,200	25	19	760	179	5	15.0	N.U.[a]	100	6,19				
		Decomposes in hot water		23	57	100	19	2.58 x 10⁻⁵	b	25	26				
					1.2	25	26	1.2	N.U.	25	Calc.				
		11,000	20	5											
Bis(2-chloroisopropyl) ether [ClCH₂CH(CH₃)]₂O (2,B-dichlorodiisopropyl ether)	VI	1700	25	19	45	100	19	1.1 x 10⁻⁴	b	20	26,35				
					760	187	6,19,23	14.7	N.U.	25	Calc.				
								58.3	N.U.	100	6,19				
Bis(chloromethyl) ether (CH₂Cl)₂O (1,1'-dichlorodimethyl ether)	III				30	25	19	2.50 x 19⁻⁴	b	25	26				
		Decomp. to formaldehyde and HCl			760	106	24								
								1.17 x 10⁻⁷	b	25	26				
Bromoacetone BrCH₂COCH₃	VI	v.sl.s		5	725	137	24								
		Photolyzes			50	64	23								
Bromomethane CH₃Br (methyl bromide)	VI	17,500	20	24	760	4	24	9.3 x 10⁻²	b	20	35				
		Forms hydrate			1420	20	23	0 106	b	25	26				
		13,200	25	25	1633	25	6,25	12,400	N U.	25	6,34				
								14,800	N U.	100	6,34				
1-Butanol C₂H₅CH₂CH₂OH (n-butyl alcohol)	V	90,000	15	5	3	15	5	0.02	N.U.	15	Calc.	27.5	N.U.	100	36
		9.1 ml/10 mg		25	6	25	5	7.0 x 10⁻⁶	b	25	26				
		69,000	25	24	760	118	24								
		180,000	30	31											
2-Butanol peroxide C₂H₅CH(OOH)CH₃ (sec-butyl hydroperoxide)	V				11	42	33								
Butyric acid C₂H₅CH₂CO₂H (butanoic acid)	III	-		5	72	100	5	0.09	N.U.	100	Calc.	1.0	N.U.	100	37
					760	164	5								
Carbonochloridic acid	III														
Carbon tetrachloride CCl₄ (tetrachloromethane)	VI	800	25	24,32	113	25	26,32	3200	N.U	100	6,19				
		800	20	5,19	760	77	5	1600	N.U	25	32				
		970	0	5	1500	100	6,19	1600	N.U	25	Calc				
Chloroacetaldehyde ClCH₂CH.O (chloroethanol)	III	Forms hydrate		24	760	86	23,24	4.7 x 10⁻⁶	b	25	26				
					317	25	26								
Chlorodibromomethane ClCHBr₂	VI	1		23	50	25	34	44	N U.	25	6				
					428	100	19	235	N.U.	100	6,19				
					760	120	19,23	0 783 x 10⁻³	b	25	26				
Chloroethane C₂H₅Cl (ethyl chloride)	IX	5700	25	19,32	760	12	17,23,24	811	N.U	25	6				
		4500	0	5	1190.0	25	6,24	625	N U.	25	32				
					8900	100	6,19,24	1282	N U.	100	6,19				
								980	N.U.	25	Calc.				

CERCLA Compound (Synonym)	Chemical Formula	CERCLA Class	Solubility in H₂O (ppm)	Temperature (°C)	Source	Vapor Pressure in Hg Pure Solute	Temperature (°C)	Source	Henry's Law Constant Theoretical (at 1 Atm)	Units	Temperature (°C)	Source	Henry's Law Constant Experimental (at 1 Atm)	Units	Temperature (°C)	Source
Chloroform CHCl₃ (trichloromethane)		VI	7840 8200	25 20	32 19,23	182 760 2300	25 62 100	26,32 19,18 19	217 636 3200 3 39 x 10⁻³ 182	N.U [a] N.U N.U b N.U.	25 100 100 25 25	32 19 6 26 Calc.	177	N.U.	25	32
Chloromethane CH₃Cl (methyl chloride)		IX	5380 280 mL/100 7250	25 16 25	32 5 19	760 4700 30,300	-24 25 100	23 19 19	1480 0.38 2800	N U. b N.U.	100 25 25	6,19 26 Calc.				
Chloromethoxymethane (ClCH₂OCH₃ (chlorodimethyl ether)		VI	Decomp.	25	23	760	59	23								
Cyanogen NC·CN (oxalic nitrile)		IX	450 cc (gas) 100 g H₂O Hydrolyzed slowly	20	5 24	760	-21	2,23	9.91	b	25	26				
Dibromomethane CH₂Br₂ (methylene bromide)		VI	11,400 11,900	20 30	5 38	12 340 760	0 25 97	2 26 5,23	360 820 3 16 x 10⁻⁶	N.U. N.U. b	25 97 25	Calc. Calc. 26				
Dichlorobromethane BCHCl₂ (bromodi-chloromethane)		VI	1		23	760 1010	90 100	19,23 19	118 262 2.12 x 10⁻⁵	N.U. N U b	25 100 25	6 6,19 26				
1,4-Dichloro-2-butene (CCH₂CH CHCH₂Cl		VI	1		23	758 (cis) 3 (cis) 758 (trans) 20 (trans)	153 23 156 56	23 23 39 23	6.78 x 10⁻⁵	b	25	26				
Dichlorodifluoromethane Cl₂CF₂ (Freon 12)		IX	28 7.6 mL/100g H₂O	25 26	19 5	1700 25,000 160	25 100 -30	19,23 19 23	641,000 537,000 2 75	N.U N.U. b	100 25 25	19 Calc. 26				
Dichloromethane CH₂Cl₂ (methylene chloride)		VI	19,400 20,000	25 20	32 19,24	438 760 4500	25 40 100	6,26,32 23 6,19	136 178 941 1800 3.19 x 10⁻³	N U. N.U N.U. N.U. b	25 25 100 100 25	32 6 19 6 26	149	N.U.	25	32
Dichloromethylbenzene C₇H₆Cl₂ (2,6-dichlorotoluene)		VI	1		23	760	198	23					112	N U	25	40
N,N-diethylhydrazine (C₂H₅)₂NNH₂		V	v s.		23	756	99	23								

CERCLA Compound (Synonym) Chemical Formula	CERCLA Class	Solubility in H2O (ppm)	Temperature (°C)	Source	Vapor Pressure in Hg Pure Solute	Temperature (°C)	Source	Henry's Law Constant Theoretical (at 1 Atm)	Units	Temperature (°C)	Source	Henry's Law Constant Experimental (at 1 Atm)	Units	Temperature (°C)	Source
Dipropylamine $(C_2H_5CH_2)_2NH$	III	S Forms hydrate	24	5 24	760	110	5,23	3.32×10^{-4}	b	25	26	279	N.U.	89	38
Ethion $C_4H_{22}O_4P_2S_4$ (Niagara 1240, Nialate)	VI	S		24											
Ethylene bromide BrC_2H_4Br (1,2-dibromoethane)	VI	4300 4300	25 30	41 5	760 10 11 280	131 29 25 100	23 23 26,41 6	49 32 204 6.25×10^{-4}	N.U.[a] N.U. N.U b	25 25 25 25	6 Calc 6 26				
Formic acid HCOOH (methanoic acid)	III	-		5,23	33 120 743 760	25 50 100 101	26 23 5 23	0.04 1.0 4.4×10^{-7}	N.U. N.U. b	25 100 25	Calc. Calc 26	0.45	N.U.	100	43
Hexachlorobutadiene CCl_2 $CClCCl \cdot CCl_2$ (hexachloro,1,3-butadiene)	VI	2 1	20 25	19,34 23	0,15 20 760	20 101 215	24 19,23 19,23	150 25.7×10^{-3} 1431 580 4200	N.U. b N.U. N.U. N.U.	100 20 20 25 100	19 34 Calc. 6 6				
Hexachlorocyclopentadiene C_5Cl_6	VI	13	25	19	5.4 0.3 753	100 49 239	19 23 19,23	36.2×10^{-3} 34 900 2500 512	b N.U. N.U. N.U.	25 25 25 100 100	34 6 6 6 19	16.4×10^{-3}	b		25
Iodomethane CH_3I (methyl iodide)	III	18,000	15	5,24	760 281 400	42 15 25	5,22,24 2 26	33 5.0×10^{-3}	N.U. b	15 25	Calc. 26				
Isobutyl alcohol $(CH_3)_2CHCH_2OH$ (2-methyl-1-propanol)	V	100,000	10	5	4.6 760	10 108	2 24	0.23 1.03×10^{-5}	N.U. b	10 25	Calc. 26				
Isophorone $C_9H_{14}O$ (3,5,5-trimethyl-2-cyclohexen-1-one)	V	9,600	25	19	0.2 19 760	20 100 215	42 19 19,42	5.2 4.2 0.32	N.U N.U. N.U.	100 100 25	19 6 6				
Methacrylonitrile $(CH_2.C(CH_3)C:N$ (isopropenylnitrile)	V	25,700	20	24	760 56.5	90 20	24 2	10.6	N.U.	20	Calc.				
Methanol CH_3OH (methyl alcohol)	III	-		5,23	760 400 100 73	65 50 21 15	23 24 24 24	0.13 1.1×10^{-6}	N.U. b	21 25	Calc. 26				

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CERCLA Compound Formula (Synonym)	CERCLA Class	Solubility in H₂O (ppm)	Temperature (°C)	Source	Vapor Pressure in Hg Pure Solute	Temperature (°C)	Source	Henry's Law Constant Theoretical (at 1 Atm)	Units	Temperature (°C)	Source	Henry's Law Constant Experimental (at 1 Atm)	Units	Temperature (°C)	Source
Methapyrilene C₁₄H₁₉N₃S (Lullamin)	III	670,000	25	24	3 0.45	173 130	23, 42 24	7.6 x 10⁻⁵	b	25	26				
1-methyl ethyl benzene C₂H₅C₆H₄CH₃ (o,m,p-ethyl toluene)	V	1		23	760 (O) 760 (M) 760 (P) 20 (O) 10 (M) 10 (P)	165 161 162 62 46 46	23 23 23 23 23 23					173	N.U.	25	40
Methyl Isobutyl ketone CH₃COC₄H₉ (MIBK, Isopropylacetone)	III	20,000	20	5	5 16 760	20 38 118	23 23 23, 24	1.8	N.U.ᵃ	20	Calc	95	N.U.	100	39
2-Methyl-5-nitrobenzeneamine C₇H₈N₂O₂ (2-amino-4-nitro toluene)	VI	S		23				1.80 x 10⁻⁷	b	43	35				
Methylthiouracil C₅H₆N₂OS (6-methyl-2-thiouracil)	III	6600	100	24											
2-Nitropropane CH₃CH(NO₂)CH₃	V	17,000	20	5	13.4 760	20 120	2 23	5.1	N.U.	20	Calc.				
Paraldehyde C₆H₁₂O₃ (paracetaldehyde)	III	60,000 125,000	100 25	24 24	25 760	25 128	43 23, 24	1.7 3.66 x 10⁻⁵	N.U. b	25 25	Calc. 26				
Phthalic anhydride C₆H₄(CO)₂O	VI	v.sl.s	25	5	0.0002	25	26	1.0 x 10⁻¹⁰	b	25	26				
2-Picoline C₅H₄N(CH₃) (2-methylpyridine)	III	v.s.		5	760 10	129 25	23, 42 43, 24, 42	2.4 x 10⁻⁵	b	25	26				
Propargyl alcohol HC:CCH₂OH (2-propyn-1-ol)	III	s		5	760 490 21 12	114 100 50 20	23, 24, 42 24 23 24								
Propionic acid CH₃CH₂COOH (Propanoic acid) (methylacetic acid)	III	-		23	760 10	141 42	23, 42 23	1 0.45	N.U. N U	100 80	6 6	1.19	N.U.	100	44
Propionic anhydride (C₂H₅CO)₂O	III	Decomp.		5	760 1	167 20	42 42								
Propyleneimine C₃H₇N (propylenimine)	III	-		23	760 748	67 63	42 23								

CERCLA Compound (Synonyms)	Chemical Formula	CERCLA Class	Solubility in H2O (ppm)	Temperature (°C)	Source	Vapor Pressure in Hg Pure Solute	Temperature (°C)	Source	Henry's Law Constant Theoretical (at 1 Atm)	Units	Temperature (°C)	Source	Henry's Law Constant Experimental (at 1 Atm)	Units	Temperature (°C)	Source
Pyrethrins I: $C_{21}H_{28}O_3$ II: $C_{22}H_{28}O_5$		VI	I		24	0.0005 (I) 0.0070 (II)	148 193	24 24								
1,1,1,2-Tetrachloroethane (Cl_3CCH_2Cl)		VI	1100 200	25 20	32 5	760 13.9 10 6.5 187	131 25 22 25 100	23 32 24 6 6	150 155 24 156 2.76 x 10⁻³	N.U.[a] N.U. N.U. N.U b	25 25 25 100 25	32 Calc. 6 6,19 26				
1,1,2,2-Tetrachloroethane $Cl_2CHCHCl_2$ (acetylene tetrachloride)		VI	3000 2850	25 25	32 24	6 5 760 10 188	25 146 34 100	23 19, 23, 24 23 19	25 27 4.7 x 10⁻⁴	N.U. N U. b	25 25 25	23 Calc. 26				
Tetraethyl lead $(C_2H_5)_4Pb$		VI	0.2	25	45	1 760 14	28 200 80	26, 45 42 42	120,000	N.U.	25	Calc.				
Tetraethylpyrophosphate $(C_2H_5)_4P_2O_7$ (TEPP)		VI	-, Hydrolizes with H2O Decomp	170	24 24	0.00047	30	24								
Tetrahydrofuran C_4H_8O (diethylene oxide)		III	s		23	760 162	66 25	24 24	0 08 x 10⁻⁴	b	25	26	1.0	N.U.	64	46
Tribromomethane $CHBr_3$ (bromoform)		VI	3130 1000 2890	25 (cold) 25	34 5 19	5.6 760 165 15	25 150 100 46	24 5, 19, 24 19 23	0.595 x 10⁻³ 30 34 190	b N.U N.U. N.U.	25 25 25 100	34 6 Calc. 6, 19	0 532 x 10⁻³	a	25	34
1,1,1-Trichloroethane CH_3CCl_3 (methyl chloroform)		VI	730 4400	20 25	32 19	126 99 760 760 1600	25 20 74 134 100	6 32 5, 23 19 6 19	1335 800 273	N.U. N U. N.U.	20 25 25	23 6, 19 6	1870	N.U.	20	32
1,1,2-Trichloroethane Cl_2CHCH_2Cl		VI	4420 4500	25 25	32 19	23 760 760 495	25 114 134 100	32 23 19 6, 19	52 51 241 1.18 x 10⁻³	N.U N.U. N.U. b	25 25 100 25	32 Calc. 6.19 26				
Trichloroethylene $ClCH CCl_2$ (trichloroethene) (ethylene trichloride)		VI	1100	20	5,19,32	59 760 1125	20 87 100	32 19, 23 19	535 1675 8.92 x 10⁻³	N.U. N.U. b	20 100 25	32 19 26	490	N.U.	20	32
Trichlorofluoromethane CCl_3F (Freon 11)		VI	1100	25	19, 34	6300 633 760 400 200	100 25 25 7 -9	6, 19 34 5,6,19,24 24 24	104 x 10⁻³ 34 9700 5.8 x 10⁻² 3250 5000	b N.U. b N U. N U.	25 100 25 25 100	34 19 26 6 6	58.3 x 10⁻³	a		25
Trichloromethanethiol CCl_3SH (trichloromethyl mercaptan)		VI														

*Summary of limits of flammability,
lower temperature limits (T_L), and minimum
autoignition temperatures (AIT) of individual
gases and vapors in air at atmospheric pressure*

Combustible	Limits of flammability (volume-percent) L_u	U_u	T_L (°C)	AIT (°C)
Acetal	1 6	10	37	230
Acetaldehyde	4 0	60	-----	175
Acetic acid	1 5 4	------	40	465
Acetic anhydride	2 2 7	1 10	47	390
Acetanilide	4 1 0	----	----	545
Acetone	2 6	13	----	465
Acetophenone	1 1	----	----	570
Acetylacetone	4 1 7	----	----	340
Acetyl chloride	4 5 0	----	----	390
Acetylene	2 5	100	----	305
Acrolein	2 8	31	----	235
Acrylonitrile	3 0	----	-6	----
Acetone Cyanohydrin	2 2	12	----	----
Adipic acid	1 1 6	----	----	420
Aldol	1 2 0	----	----	250
Allyl alcohol	2 5	18	22	----
Allyl amine	2 2	22	----	375
Allyl bromide	1 2 7	----	----	295
Allyl chloride	2 9	----	-32	485
o-Aminodiphenyl	66	4 1	----	450
Ammonia	15	28	----	----
n-Amyl acetate	1 1 0	1 7 1	25	360
n-Amyl alcohol	1 1 4	1 10	38	300
tert-Amyl alcohol	1 1 4	----	----	435
n-Amyl chloride	3 1 6	1 8 6	----	260
tert-Amyl chloride	1 1 5	----	-12	345
n-Amyl ether	4 7	----	----	170
Amyl nitrite	4 1 0	----	----	210
n-Amyl propionate	4 1 0	----	----	380
Amylene	1 4	8 7	----	275
Aniline	7 1 2	2 8 3	----	615
Anthracene	4 65	----	----	540
n-Amyl nitrate	1 1	----	----	195
Benzene	1 3	1 7 9	----	560
Benzyl benzoate	4 7	----	----	480
Benzyl chloride	1 1 2	----	----	585
Bicyclohexyl	1 65	4 5 1	74	245
Biphenyl	9 70	----	110	510
2-Biphenylamine	4 8	----	----	450
Bromobenzene	4 1 6	----	----	565
Butadiene (1,3)	2 0	12	----	420
n-Butane	1 8	8 4	-72	405
1,3-Butandiol	4 1 9	----	----	395
Butene-1	1 6	10	----	385
Butene-2	1 7	9 7	----	325
n-Butyl acetate	4 1 4	1 8 0	----	425
n-Butyl alcohol	1 1 7	1 12	----	----
sec-Butyl alcohol	1 1 7	1 9 8	21	405
tert-Butyl alcohol	1 1 9	1 9 0	11	480
tert-Butyl amine	1 1 7	1 8 9	----	380
n-Butyl benzene	1 82	1 5 8	----	410
sec-Butyl benzene	1 0 77	1 5 8	----	420
tert-Butyl benzene	1 77	1 5 8	----	450
n-Butyl bromide	1 2 5	----	----	265
Butyl cellosolve	1 1 1	10 11	----	245
n-Butyl chloride	1 8	1 10	----	----
n-Butyl formate	1 7	8 2	----	----
n-Butyl stearate	4 3	----	----	355
Butyric acid	4 2 1	----	----	450
a-Butyrolactone	1 2 0	----	----	----
Carbon disulfide	1 3	50	----	90
Carbon monoxide	12 5	74	----	----
Chlorobenzene	1 4	----	21	640
m-Cresol	1 1 1	----	----	----
Crotonaldehyde	2 1	11 16	----	----
Cumene	1 88	1 6 5	----	425
Cyanogen	6 6	----	----	----
Cycloheptane	1 1	6 7	----	----
Cyclohexane	1 3	7 8	----	245
Cyclohexanol	4 1 2	----	----	300
Cyclohexene	1 1 2	----	----	----
Cyclohexyl acetate	4 1 0	----	----	335
Cyclopropane	2 4	10 4	----	500
Cymene	1 85	1 6 5	----	435

Combustible	Limits of flammability (volume-percent) L_u	U_u	T_L (°C)	AIT (°C)
Decaborane	2	----	----	----
Decalin	1 74	1 4 9	57	250
n-Decane	12 75	11 5 6	46	210
Deuterium	4 9	75	----	----
Diborane	8	88	----	----
Diesel fuel(60 cetane)	----	----	----	225
Diethyl amine	1 8	10	----	----
Diethyl analine	4 8	----	80	630
1,4-Diethyl benzene	1 8	----	----	430
Diethyl cyclohexane	75	----	----	240
Diethyl ether	1 9	36	----	160
3,3-Diethyl pentane	1 7	----	----	290
Diethyl ketone	1 6	----	----	450
Diisobutyl carbinol	1 82	10 6 1	----	----
Diisobutyl ketone	1 79	1 6 2	----	----
2-4, Diisocyanate	----	----	120	----
Diisopropyl ether	1 4	7 9	----	----
Dimethyl amine	2 8	----	----	400
2,2-Dimethyl butane	1 2	7 0	----	----
2,3-Dimethyl butane	1 2	7 0	----	----
Dimethyl decalin	1 69	4 5 3	----	235
Dimethyl dichlorosilane	3 4	----	----	----
Dimethyl ether	3 4	27	----	350
n,n-Dimethyl formamide	1 1 8	1 14	57	435
2,3-Dimethyl pentane	1 1	6 8	----	335
2,2-Dimethyl propane	1 4	7 5	----	450
Dimethyl sulfide	2 2	20	----	205
Dimethyl sulfoxide	----	----	84	----
Dioxane	2 0	22	----	265
Dipentene	4 75	4 6 1	45	237
Diphenylamine	4 7	----	----	635
Diphenyl ether	4 0 8	----	----	620
Diphenyl methane	4 7	----	----	485
Divinyl ether	1 7	27	----	----
n-Dodecane	4 60	----	74	205
Ethane	3 0	12 4	-130	515
Ethyl acetate	2 2	11	----	----
Ethyl alcohol	3 3	11 19	----	365
Ethyl amine	3 5	----	----	385
Ethyl benzene	1 1 0	1 6 7	----	430
Ethyl chloride	3 8	----	----	----
Ethyl cyclobutane	1 2	7 7	----	210
Ethyl cyclohexane	14 2 0	14 6 6	----	260
Ethyl cyclopentane	1 1	6 7	----	260
Ethyl formate	2 8	16	----	455
Ethyl lactate	1 5	----	----	400
Ethyl mercaptan	2 8	18	----	300
Ethyl nitrate	4 0	----	----	----
Ethyl nitrite	3 0	50	----	----
Ethyl propionate	1 8	11	----	440
Ethyl propyl ether	1 7	9	----	----
Ethylene	2 7	36	----	490
Ethyleneimine	3 6	46	----	320
Ethylene glycol	4 3 5	----	----	400
Ethylene oxide	3 6	100	----	----
Furfural alcohol	15 1 8	16 16	72	390
Gasoline				
100/130	1 3	7 1	----	440
115/145	1 2	7 1	----	470
Glycerine	----	----	----	370
n-Heptane	1 05	6 7	-4	215
n-Hexadecane	4 43	----	126	205
n-Hexane	1 2	7 4	-26	225
n-Hexyl alcohol	1 1 2	----	----	----
n-Hexyl ether	4 6	----	----	185
Hydrazine	4 7	100	----	----
Hydrogen	4 0	75	----	400
Hydrogen cyanide	5 6	40	----	----
Hydrogen sulfide	4 0	44	----	----
Isoamyl acetate	1 1 1	1 7 0	25	360
Isoamyl alcohol	1 1 4	1 9 0	----	350
Isobutane	1 8	8 4	-81	460

Combustible	Limits of flammability (volume-percent)		T_L (°C)	AIT (°C)
	L_u	U_u		
Isobutyl alcohol	[1]1 7	[1]11	......	....
Isobutyl benzene	[1] 82	[10]6 0	......	430
Isobutyl formate	2 0	8 9		
Isobutylene	1 8	9 6		465
Isopentane	1.4			....
Isophorone	84			460
Isopropyl acetate	[4]1 7			....
Isopropyl alcohol	2 2			
Isopropyl biphenyl	[4] 6			440
Jet fuel				
JP-4	1 3	8	......	240
JP-6				230
Kerosine				210
Methane	5 0	15 0	-187	540
Methyl acetate	3 2	16		....
Methyl acetylene	1 7			
Methyl alcohol	6 7	[1] 36		385
Methyl amine	[4]4 2			430
Methyl bromide	10	15		
3-Methyl butene-1	1 5	9 1		....
Methyl butyl ketone	[5]1 2	[1]8 0		
Methyl cellosolve	[13]2 5	[7] 20		380
Methyl cellosolve acetate	[1]1 7		46	....
Methyl ethyl ether	[4]2 2			
Methyl chloride	[4]7			
Methyl cyclohexane	1 1	6 7		250
Methyl cyclopentadiene	[1]1 3	[1]7 6	49	445
Methyl ethyl ketone	1 9	10		
Methyl ethyl ketone peroxide			40	390
Methyl formate	5 0	23		465
Methyl cyclohexanol	[4]1 0			295
Methyl isobutyl carbinol	[4]1 2		40	....
Methyl isopropenyl ketone	[5]1 8	[4]9 0		
Methyl lactate	[1]2 2			
α-Methyl naphthalene	[4] 8			530
2, Methyl pentane	[4]1 2			....
Methyl propionate	2 4	13		
Methyl propyl ketone	1 6	8 2		
Methyl styrene	[4]1 0		49	495
Methyl vinyl ether	2 6	39		....
Methylene chloride				615
Monoisopropyl bicyclohexyl	52	[11]4 1	124	230
2-Monoisopropyl biphenyl	[10] 53	[11]3 2	141	435
Monomethylhydrazine	4			....
Naphthalene	[19] 8S	[20]5 9		526
Nicotine	[1] 75			
Nitroethane	3 4		30	
Nitromethane	7 3		33	....
1-Nitropropane	2 2		34	
2-Nitropropane	2 5		27	....
n-Nonane	[21] 85		31	205
n-Octane	0 95		13	220
Paraldehyde	1 3			
Pentaborane	42			
n-Pentane	1 4	7 8	-48	260
Pentamethylene glycol				335
Phthalic anhydride	[7]1 2	[22]9 2	140	570

Combustible	Limits of flammability (volume-percent)		T_L (°C)	AIT (°C)
	L_u	U_u		
3-Picoline	[4]1 4			500
Pinane	[23] 74	[23]7 2		....
Propadiene	2 16			
Propane	2 1	9 5	-102	450
1,2-Propandiol	[4]2 5			410
β-Propiolactone	[3]2 9			
Propionaldehyde	2 9	17		....
n-Propyl acetate	1 8	8		
n-Propyl alcohol	[12]2 2	[1] 14		440
Propyl amine	2 0			....
Propyl chloride	[4]2 4			
n-Propyl nitrate	[17]1 S	[17]100	21	175
Propylene	2 4	11		460
Propylene dichloride	[4]3 1			
Propylene glycol	[24]2 6			
Propylene oxide	2 8	37		
Pyridine	[11]1 S	[23]12		....
Propargyl alcohol	[3]2 4			
Quinoline	[4]1 0			
Styrene	[26]1 1			....
Sulfur	[27]2 0		247	
p-Terphenyl	[4] 96			535
n-Tetradecane	[4] 5			200
Tetrahydrofurane	2 0			....
Tetralin	[1] 84	[4]5 0	71	3S5
2,2,3,3-Tetramethyl pentane	0 8			430
Tetramethylene glycol				390
Toluene	[1]1 2	[1]7 1		4S0
Trichloroethane				500
Trichloroethylene	[4]12	[14]40	30	420
Triethyl amine	1 2	8 0		....
Triethylene glycol	[4] 9	[23]9 2		
2,2,3-Trimethyl butane	1 0			420
Trimethyl amine	2 0	12		
2,2,4-Trimethyl pentane	95			415
Trimethylene glycol	[4]1 7			400
Trioxane	[3]3 2			
Turpentine	1 7			....
Unsymmetrical dimethylhydrazine	2 0	95		
Vinyl acetate	2 6			
Vinyl chloride	3 6	33		
m-Xylene	[1]1 1	[1]6 4		530
o-Xylene	[1]1 1	[1]6 4		465
p-Xylene	[1]1 1	[1]6 6		530

[1] t=100° C.
[2] t=47° C.
[3] t=75° C.
[4] Calculated.
[5] t=50° C.
[6] t=85° C.
[7] t=140° C.
[8] t=150° C.
[9] t=110° C.
[10] t=175° C.
[11] t=60° C.
[12] t=53° C.
[13] t=86° C.
[14] t=130° C.
[15] t=72° C.
[16] t=117° C.
[17] t=125° C.
[18] t=200° C.
[19] t=78° C.
[20] t=122° C.
[21] t=43° C.
[22] t=195° C
[23] t=160° C
[24] t=96° C.
[25] t=70° C.
[26] t=29° C.
[27] t=247° C.
[28] t=30° C
[29] t=203° C.

L_{25} = Lower flammability limit at 25 °C

U_{25} = Upper flammability limit at 25 °C

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