



A Burlington
Environmental Inc.
Company

CHEMICAL PROCESSORS, INC.

Northern California Division

May 18, 1990
Project No. 1051

Lisa Marinaro
Chevron U.S.A., Inc.
P.O. Box 5004
San Ramon, California 94583

Re: **RESPONSE TO ALAMEDA COUNTY INFORMATION REQUEST**
Former Chevron Service Station No. 9-1026
3701 Broadway, Oakland, California

Dear Ms. Marinaro:

As requested by the Alameda County Department of Environmental Health (ACDEH), Chemical Processors, Inc. (Chempro) has assembled the following information: (1) aquifer test procedures, (2) air stripper operation specifics, (3) details of system maintenance and performance testing, and (4) agency reporting frequency.

1.0 **Aquifer Test Procedures**

A pumping test is needed in the southern portion of the site. If boring logs and well completion details are obtained for Well "B" (see Figure 1), and B is suitable for extraction, then well B will be used for the pumping test. Otherwise, a new 4-inch diameter well will be installed to the east of well B in the southern corner of the lot. Once the well has been installed and developed, an aquifer test will be performed. A description of the aquifer test can be found Appendix A. Results of the aquifer test will be used to (a) evaluate the hydraulic properties of the aquifer, (b) locate additional extraction wells if they are needed, and (c) determine the expected continuous pumping rate for pump selection.

2.0 **Air Stripper Operation Specifics**

The air stripper unit to be used at this site is a Chempro model SB-10. The unit is mounted on a skid and contained in fiberglass enclosure for minimal visual impact. The unit is currently operating at a number of sites throughout Northern California and typically achieves 99% removal efficiency.

Operating details of the air stripper unit can be found in Appendix B. The sampling results from a site with an operating SB-10 air stripper is also attached in Appendix B.

950 Gilman Street, Suite B
Berkeley, California 94710
(415) 524-9372

3.0 System Maintenance and Performance Testing

Optimal system performance is insured through periodic sampling and site visits by Chempro maintenance personnel. Site visits for sampling will be performed weekly for the first month of operation, bimonthly for the next two months, and then at least once per month thereafter. Sampling of the water will occur between the two carbon units to determine breakthrough of the first series-connected carbon unit. To check the air stripper performance, sampling before and after the stripper will be performed once at start-up and then once per quarter throughout the system operation. The samples will be analyzed for total petroleum hydrocarbons as gasoline (TPH), benzene, toluene, ethylbenzene, and xylenes (BTEX) by a State Certified Analytical Laboratory. Sample taps are provided before and after the air stripper and also between and after the two aqueous carbon units.

Maintenance of the system will be performed as needed. The system is designed to operate continuously. If the system shuts down for any reason, an automatic telephone dialer summons maintenance personnel.

4.0 Agency Reporting Frequency

The sampling results will be reported to the appropriate agency monthly for the first three months of operation and then quarterly thereafter. In addition to the sampling results, Chempro will report total gallons treated for that period and average flow rate. Site visit and maintenance records will be recorded on a "Facility Inspection Log" (FIL). Copies of the FILs can be forwarded to the appropriate agency if needed.

We trust we have provided the information requested by ACDEH. As always, we are available to answer any questions you may have. Please feel free to contact us at your convenience.

Yours very truly,
CHEMICAL PROCESSORS, INC.



James R. Phillips
Staff Engineer



Dave C. Tight
Site Remediation Manager

REMEDIATION SCHEDULE
Former Chevron Service Station No. 1026
3701 Broadway, Oakland, California

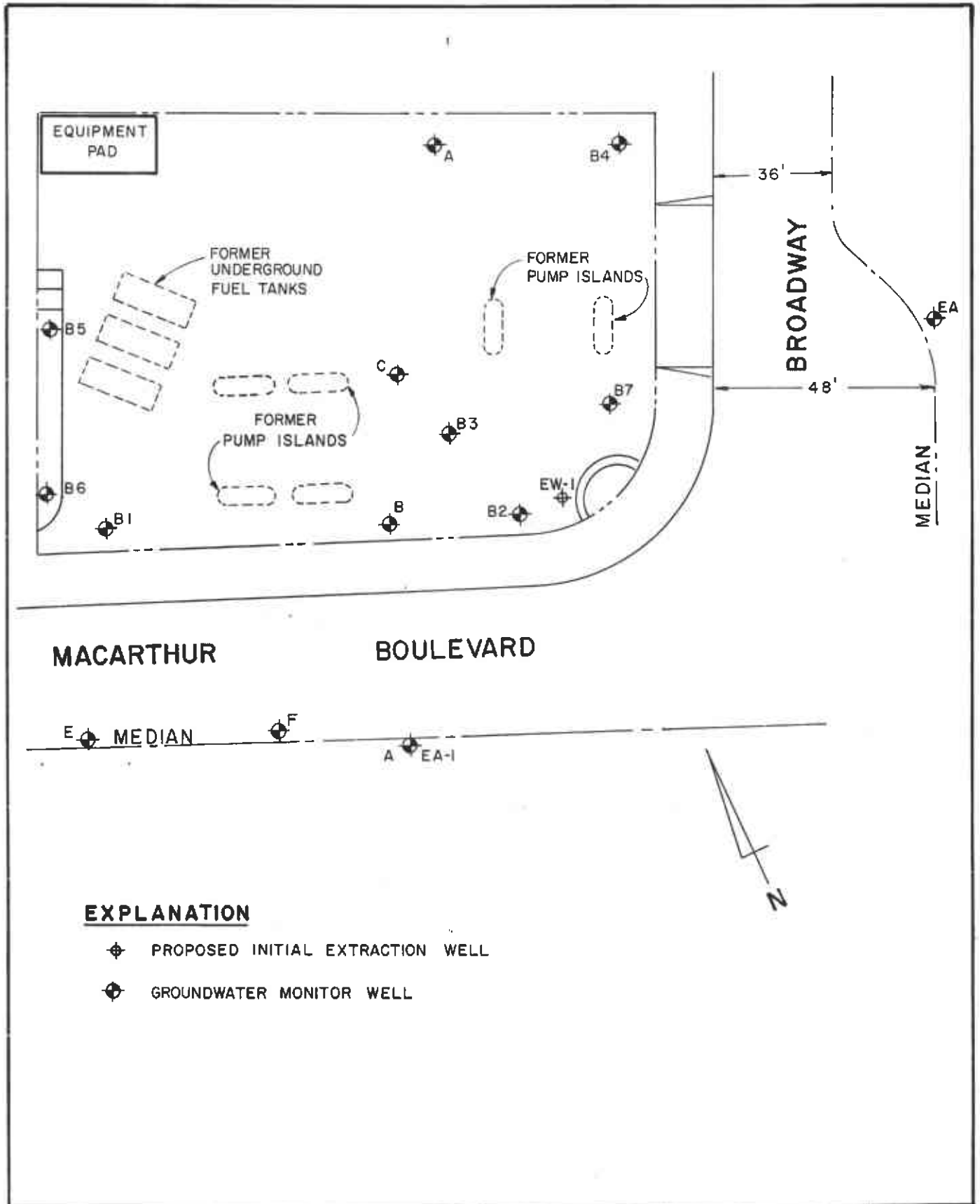
Duration of the project is estimated as follows:	Week:
Formal landowner approval, agreement on equipment pad location:	0
Apply for a sewer discharge permit, air discharge permit, begin application process for TTU permit from DHS:	1
Install one groundwater extraction well, develop well, perform aquifer test:	3
If soil landfilling option is desired, excavate and dispose of contaminated soil:	4
Report results of aquifer test, install additional extraction wells if necessary:	8
Receive "Authority To Construct" and "Permit To Operate" from BAAQMD and Sewer Use Permit from EBMUD, submit TTU notification to DHS:	10
Install well boxes, underground piping, equipment pad, treatment equipment, complete 30 day notification period for TTU to DHS:	12
Start-up and test equipment, begin full-time groundwater extraction and treatment:	14

This schedule assumes that all required permits can be obtained in a timely manner. Any delays imposed by the various regulatory agencies will effect the start-up date for the treatment system. The permit application process will be initiated promptly upon formal landowner approval and upon agreement of equipment pad location. All other work will be completed in accordance with the above schedule. Please feel free to contact us at (415) 524-9372 if we can provide any additional information.

Yours very truly,
CHEMICAL PROCESSORS, INC.



James R. Phillips
Staff Engineer



CHEMICAL PROCESSORS, INC.
 950-B GILMAN STREET
 BERKELEY, CALIFORNIA

SITE PLAN
 3201 BROADWAY
 OAKLAND, CALIFORNIA

FIGURE
 1

Appendix A

Aquifer Testing

INTRODUCTION

The general procedures for hydraulic testing of aquifers and water-bearing zones are contained in this appendix. The procedures provide for consistent and reproducible testing methods. They are designed to produce data necessary to define the hydraulic characteristics of the aquifer and a consistent analytical approach to quantification of aquifer characteristics.

PUMPING TESTS

In general, pumping tests consist of four parts: (1) baseline water-level measurements, (2) step-discharge pumping, (3) constant-discharge pumping, and (4) water-level recovery. The best results are obtained from a test in which the observation wells are located in the same water-bearing zone as the one being pumped. The pumping well should be of sufficient diameter to accommodate a constant-discharge pump and monitoring equipment. The monitoring equipment will consist of electric transducers and will be monitored by an In Situ Hermit^R Datalogger. To run the pump, a generator or permanent power source of at least 210 volts is required. All equipment is steam cleaned before and after testing. Discharge water that is pumped from the well will be contained in 55-gallon drums or a larger container, and disposed of by Chevron.

Baseline Water Level Survey

Before testing, baseline water levels in the pumping and observation wells are obtained. It is ideal to set up transducers in each well and obtain readings during a 24-hour period before testing. The baseline survey will record diurnal and other water-level trends which are used to compare with water level changes obtained during testing.

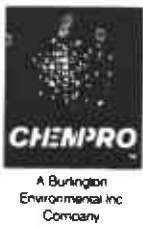
Step-Discharge Test

A step-discharge test is conducted to determine an appropriate sustainable pumping rate for the constant-discharge test and if possible, the well's efficiency. During a step-discharge test, water from the well is pumped at increasing discharge rates over several time periods. The water level in the pumping well is monitored and recorded in the field with a pressure transducer/datalogger system and an electric sounder. The depth to water data is plotted versus time to determine the optimum pumping rate for a constant-discharge pumping test. Each step is conducted until the drawdown within the well is relative stable.

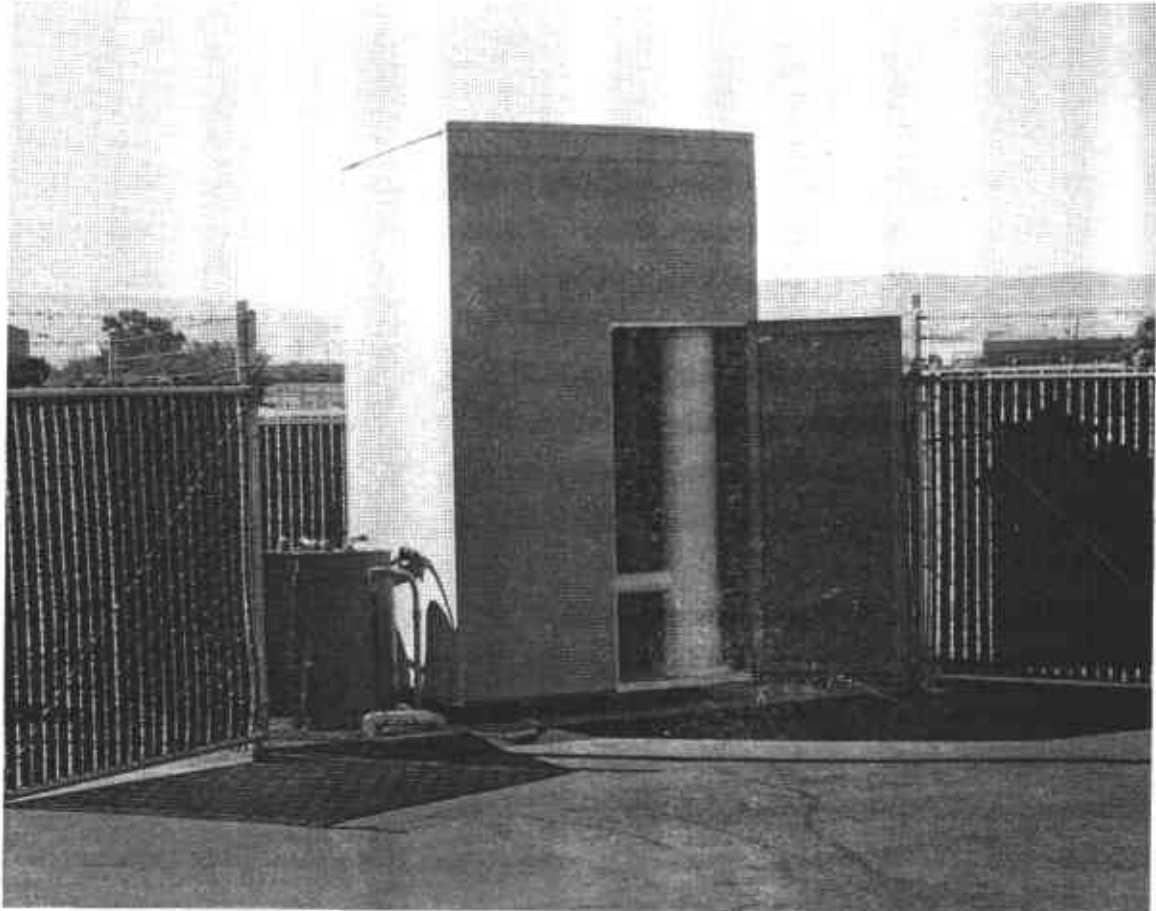
Constant-Discharge Test

During a constant-discharge test, ground water is pumped from the test well at a constant rate determined from the step-discharge test. The pumping rate is dependent on the hydraulic properties of the test zone and length of time the well will be pumped. The optimum test stresses the water-bearing zone without dewatering the well during testing. In most cases it is important to pump the well long enough to overcome borehole storage effects, and to observe drawdown in an adjacent observation well. Tests are generally run for 4 to 24 hours of pumping. After pumping has ceased, recovery is monitored while the water level in the well returns to a static level, or until the water level has returned to 90 percent of the static level. Drawdown and recovery are monitored during the test with a pressure transducer and electric well sounder.

There are many different methods used to analyze pumping test results (e.g. Jacob, 1963; Theis, 1935; Boulton, 1963). The method used is dependent on the type of aquifer being tested (confined, unconfined, or leaky). Depth-to-water information is plotted for all wells monitored during testing versus time. Drawdown and recovery data are used for the analysis. In general, several methods are used to get the best analysis of each test. Depending on the test design and results, it will be possible to calculate hydraulic parameters including transmissivity, storativity, hydraulic conductivity, and radius of influence.



CHEMPRO SB-10 AIR STRIPPER MODULE



The Chempro SB-10 Air Stripper is a modular design which provides minimal visual impact. The totally enclosed unit consists of four 1 foot diameter by 8 feet high columns, each containing approximately 4 cubic feet of polyethylene packing. The packing provides maximum surface area for efficient water/air contact. As the air contacts the water, the hydrocarbons volatilize into the air stream. The removal efficiency is typically 97%. The unit is equipped with safety shutoff switches and an automatic telephone dialer for process upsets. Options available for the unit are liquid phase carbon adsorption for water polishing, vapor treatment equipment and winterizing capabilities.

SPECIFICATIONS

Water Flow Rate: 0.5 - 20 gpm
throughput

Air Flow Rate: 300 CFM

Utilities: 230 volts/single phase/ 60 hertz
40 amperes

Pumps: 1/3 hp liquid feed and recycle
304 stainless steel wetted parts

Blower: 1 hp process air blower

Packing: 16 cu. ft. polyethylene

Construction: fiberglass and coated steel

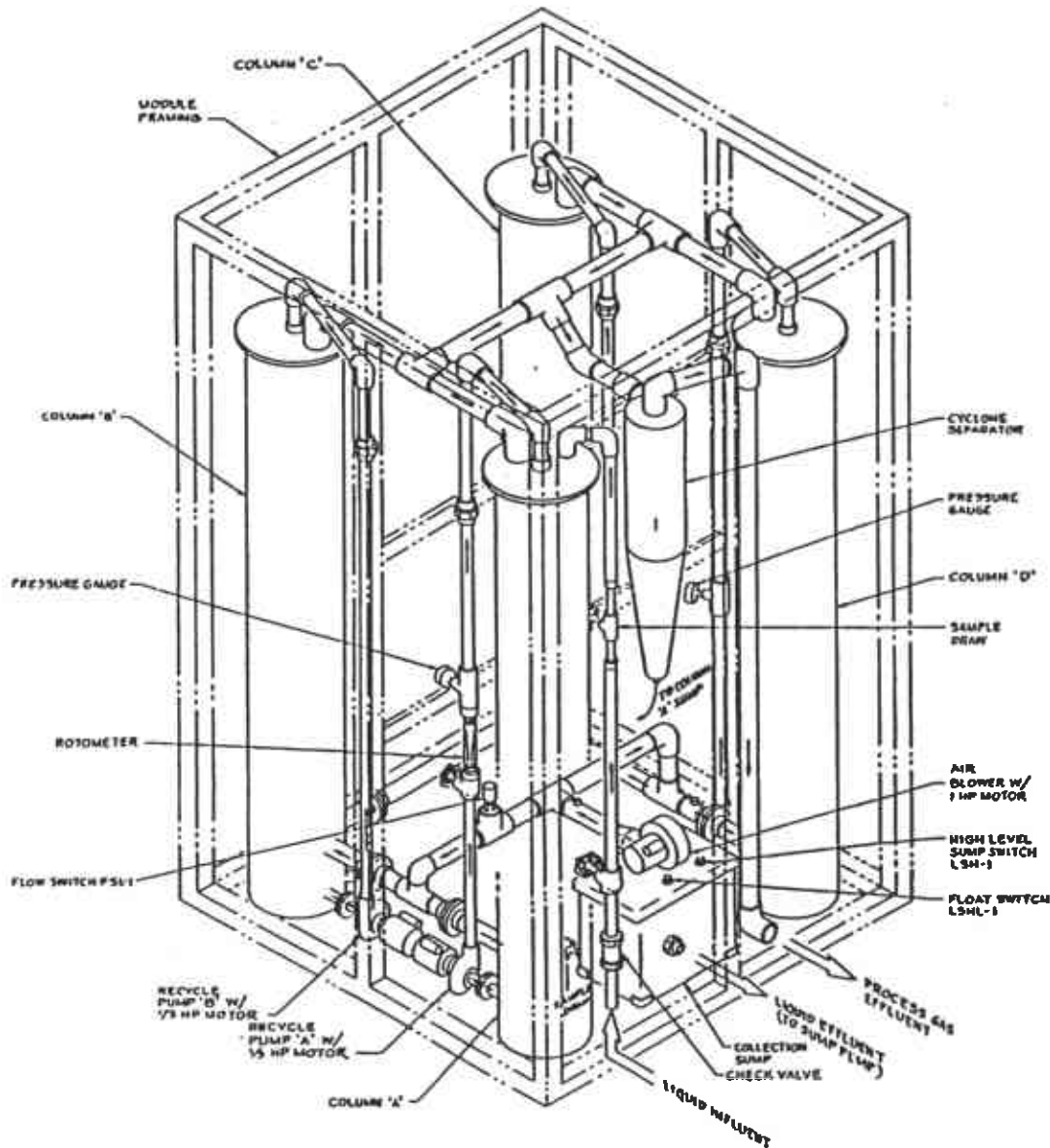
Plumbing: SCH-40 PVC

Dimensions: 6-ft. x 6-ft. x 10-ft high

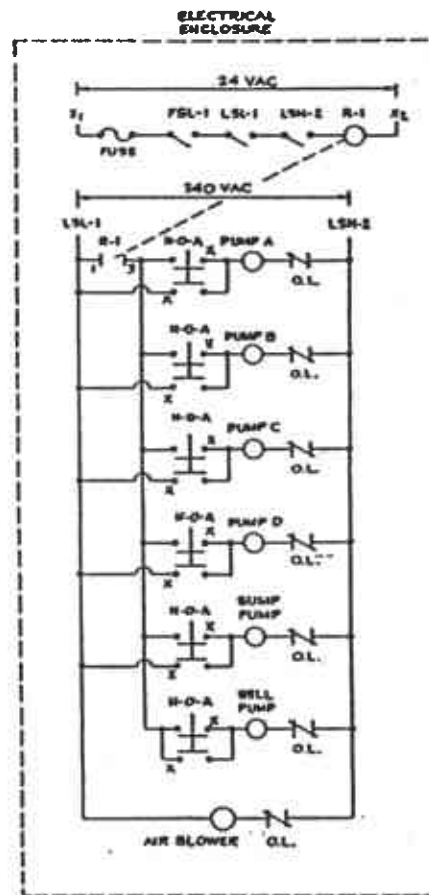
Shipping Weight: 2,000 pounds

Operating Weight: 2834 pounds

950 'B' Gilman Street, Berkeley, CA 94710 (415) 524-9372 Fax (415) 524-7439



ISOMETRIC



SCHEMATIC OF CONTROL SYSTEM

LEGEND:

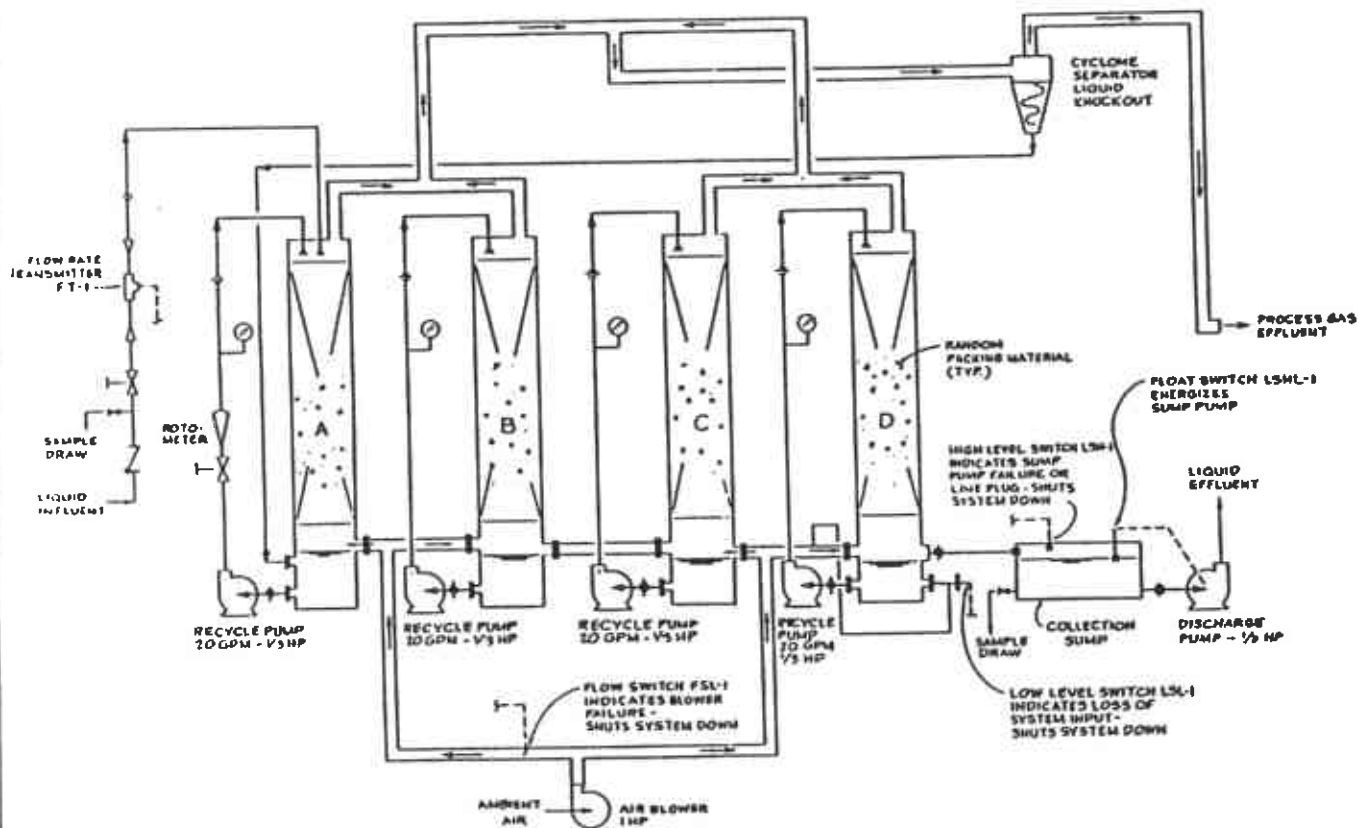
- N** OVERLOAD PROTECTION
- O.L.** OVERLOAD PROTECTION
- FSL-1** AIRFLOW SENSOR SWITCH
- LSL-1** LOW LEVEL INLET SWITCH
- LSH-1** HIGH LEVEL SUMP SWITCH
- N-O-A** MANUAL OPERATION
- OFF
- AUTOMATIC OPERATION

NOTE: IF SYSTEM SHUTS DOWN IN AUTO MODE DUE TO FSL, LSL, OR LSH BREAKING CREDIT TO R-1 (RELAY) TELEPHONE DIALER AUTOMATICALLY CALLS CHEMPRO OFFICE WITH VOICE MESSAGE.

CHEMPRO ENVIRONMENTAL SERVICE
 950 GILMAN ST., SUITE B
 BERKELEY, CALIFORNIA
 (415) 524-9372

SD-10 GAS-LIQUID CONTACTOR

DESIGNED BY R. GATTINGO
 CHECKED BY C. LAMMER
 SHEET 1 OF 1



CHEMPRO ENVIRONMENTAL SERVICE
 950 GILMAN ST., SUITE 8
 BERKELEY, CALIFORNIA
 (415) 524-9372

SB-10 GAS-LIQUID CONTACTOR

DESIGNED BY R. GIATINO
 CHECKED BY G. LAMMER

PROCESS FLOW DIAGRAM

DESIGNED BY R. GIATINO
 CHECKED BY G. LAMMER

SHEET NO.

1.0 SYSTEM DESCRIPTION

1.1 Introduction

The Chempro model SB-10 is an advanced air stripper designed to remove hydrocarbons from contaminated groundwater. Removal efficiency of volatile hydrocarbons has been estimated at 97%. This is accomplished by a unique design which cycles incoming water through four 12 inch diameter by 8 feet high columns arranged in series. The columns have been labeled A,B,C, and D, with A the first unit in the series and D the last. Each column is filled with approximately 4 cubic feet of random packed polyethylene packing material. The four columns, five pumps, discharge tank, blower, and control panel are placed on a painted steel skid and contained in a fiberglass enclosure. Besides allowing for improved design features, the enclosure deters vandals and prevents unwarranted attention. A few of the engineering features of the CES SB-10 include:

- Liquid throughput flow rates to 20 gpm
- Hydrocarbon resistant materials throughout
- Sample taps on the water influent and effluent
- Process upset controls with remote telephone dialer
- Thermostatically controlled heating equipment (optional)
- Central electrical control panel with manual or automatic motor operation
- Fiberglass enclosure for equipment protection and reduced visual impact

1.2 Liquid Flow Path

A brief description of the liquid flow path helps to understand SB-10 operations and will aid in troubleshooting operational problems. A process flow diagram has been included in Appendix A.

Process water from a well pump(s) enters the box and travels to the top of column A. The water is sprayed by a distributor from the top of the column which is filled with plastic packing material designed to break-up water droplets and release volatile components. After contacting with air as it falls by gravity through the column, the water collects in the lower section of the column (sump A). The water is then pumped to another distributor at the top of the column in the recycle stage. Once filling sump A, water spills off through four inch PVC pipe to column B. The process in column A is repeated in columns B,C, and D.

The four recycle pumps maintain a wetted packed bed in each of the four columns during intermittent groundwater delivery. Maintaining a wetted bed improves removal efficiency and prevents premature packed bed fouling.

Water from sump D spills off into a rectangular tank. A float switch in the tank activates the adjacent pump which discharges treated water out the side of the box. Water effluent is typically fed directly to the sanitary sewer (once permitted) or to aqueous carbon contactors for final polishing.

1.3 Air Flow Path

Once passing through two vents in the wall of the enclosure, ambient air enters a 1 hp pressure blower. Pressurized air from the blower is split four ways by four inch PVC

pipe and is fed in parallel to the lower section of each of the four columns. Air flows upward through the packing of each column, contacting with the water falling by gravity. The air then exits the top of each column and is piped together just before entering the cyclone separator. Process air is discharged out the top of the cyclone separator and then piped through 4 inch PVC out the side of the enclosure. Entrained water recovered by the separator is fed to sump A for recycling.

1.4 Equipment

- **Skid and enclosure:** A painted steel skid and fiberglass enclosure contains all the equipment and provides a modular, transportable unit with low visual impact.
- **Columns and packing:** Each of the four columns are 12 inches in diameter and 8 feet high. The lower section of each tower serves as a sump for the adjacent centrifugal pump. Each column contains approximately 5 feet of 1 inch spherical polyethylene packing material. These lightweight plastic rings have a very high surface area to volume ratio in order to maximize the liquid to air transfer efficiency of hydrocarbons in the water.
- **Recycle pumps:** Four-1/3 hp, 115/230 volt, single phase, Gould centrifugal pumps, model 3642, recycle water within each of the four columns. Each pump has a liquid filled pressure gauge on the pump discharge pipe to check for normal operation.
- **Discharge pump:** Treated water is discharged through a 1/3 hp, 115/230 volt, single phase, Gould centrifugal pump model 3642. The pump sits adjacent to a 30 gallon polyethylene tank and is controlled by a mercury float switch located inside the tank. Pump performance is 20 gpm at 30 feet of water total discharge head.
- **Blower:** A 1 hp, 230 volt, single phase, Peerless direct drive pressure blower, model PW-11, forces air through all four columns and then through the cyclone separator before being discharged out the box. The blower runs continuously when the main power switch is turned on.
- **Flowmeters:** A Signet paddlewheel flowmeter records both continuous and total liquid flow. The flow sensor is located on the inlet pipe and the meter is located adjacent to the control panel. A Blueline rotometer on the recycle piping of column "A" indicates the recycle flow rate. Once the incoming liquid flow rate has been set (not to exceed 20 gpm), the recycle flow rate should be adjusted so that the sum of the incoming and recycle flow rates equal 20 gpm.
- **Globe valves:** Two 1-1/2 inch PVC globe valves allow adjustment of the liquid flow. The valve on the inlet pipe (valve labeled PV) controls throughput process flow, while the valve on the column A recycle pipe (valve labeled RV) controls the recycle flow rate of all four columns.
- **Liquid sample taps:** Two sample taps are provided for influent and effluent water sampling. One 1/4 inch ball valve is located on the inlet pipe and the other ball valve is attached to the discharge tank.

- **Control switches:** Control switches include one vane type flow switch on the blower outlet, one infrared low level switch in the bottom of column D, and one high level float switch in the discharge tank. If any of these switches are tripped, the system shuts down and the telephone dialer is activated.
- **Electric control panels:** A 24"x40" NEMA-4 enclosure located inside the SB-10 contains all the pump motor controls, relays, and telephone dialer. A safety switch on the enclosure door is used to shut-off power before the panel can be opened. Well pumps have three position switches and indicator lights. Every motor has both short-circuit and overload protection.

Power requirements for the SB-10 are 120/240 volts, 100 amps, single phase.

- **Telephone dialer:** An automatic telephone dialer is located in the main electric enclosure. If a process upset switch shuts the system down, an adjustable time delay relay connected to the dialer is activated. If the system remains down for the set time period, the dialer becomes activated and calls three different numbers until a phone is answered. The recorded message indicates a system upset. The dialer can be deactivated by pressing the "abort call" switch on the control panel.

The adjustable time delay relay, located in the upper left hand corner of the enclosure, is set for 30 minutes. Once the dialer is activated, it will play through one complete tape. To reset the tape, it is necessary to short circuit the TC and CH1 or TC and CH2 terminals on the dialer. To change the message on the tape, contact CES in Berkeley, California, at (415) 524-9372.

- **Miscellaneous:** A fire extinguisher is located just inside the SB-10 enclosure. It should be checked periodically to make sure it remains charged. A 120 volt light provides illumination inside the box, the switch is located on the side of the main electric control panel.

2.0 START-UP PROCEDURES

Start-up procedures should be followed to avoid damaging equipment. The SB-10 has been fully tested in our shop to assure that all equipment functions properly.

Materials needed for system startup consist of the following:

- 1) A clean water source with normal pressure (approx. 10 to 20 psig)
- 2) A garden hose or similar
- 3) A hose thread by 1-1/2 inch socket adapter or compression fitting

SB-10 start-up steps to follow:

- 1) Connect discharge piping to the 1-1/2 inch PVC SB-10 outlet pipe (labeled OP).
- 2) Place the hose adapter on the 1-1/2 inch SB-10 inlet pipe (labeled IP).
- 3) Connect garden hose to the hose adapter.
- 4) Turn on water to the garden hose.* This process puts water into the four tower sumps.
- 5) Turn the main power switch on the electric panel to the "on" position.
- 6) Listen for blower operation.

- 7) Allow the discharge pump to cycle at least once.
- 8) Switch on the four recycle pumps to the "auto" position.
- 9) Turn off water to the garden hose and remove garden hose and hose adapter. Some of the water from the inlet pipe will drain out when the hose is removed.
- 10) Connect well pump(s) piping to the SB-10 inlet pipe (IP).
- 11) Turn on the well pump(s) and closely monitor the throughput process flow rate (indicated by the Signet meter) to make sure it does not exceed 20 gpm. Adjust the globe valve on the inlet pipe (PV) if needed.
- 12) Adjust the globe valve on the recycle pipe (RV) line so that the sum of the inlet flow and recycle flow is 20 gpm. The recycle flow rate is indicated by a clear PVC rotometer.
- 13) Check all pipe and fittings for leaks. Any leak should be repaired without delay. See Section 3.0 for leak patching recommendations.

*Approximately 10 to 20 psig is required to push water up the inlet pipe and into the first tower. Municipal water supplies are usually sufficient to deliver this required pressure.

3.0 ROUTINE MAINTENANCE

The following maintenance should be performed *weekly*:

- 1) Open the SB-10 and check for water leaks. If a leak is observed, shut-down the SB-10 and repair without delay. Any type of leak can be repaired with a fiberglass repair kit (for fiberglass components), PVC glue (for PVC components), and/or silicone caulking. Affected areas should be completely dry before attempting to patch. Contact Chempro if leak persists.
- 2) Check for the normal operation of all five centrifugal pumps. The liquid filled pressure gauges on the discharge of each recycle pump should indicate approximately 20 psig.
- 3) Check the blower for normal operation. Listen for any restrictions in the air flow. Place a manometer (pressure indicator) on the 1/4 inch fitting at the blower outlet to check blower discharge pressure. A reading between 1 and 7.5 inches of water indicates normal conditions. A reading higher than 8 inches of water indicates a restriction that should be corrected. Examine piping and check for any abnormalities.
- 4) Check the Signet flowmeter and verify that the process flow rate does not exceed 20 gpm. Adjust the globe valve (PV) if needed.
- 5) Check the rotometer to verify that the recycle rate, when added to the inlet flow rate does not exceed 20 gpm. Adjust the globe valve (RV) if needed.

4.0 SHUT-DOWN PROCEDURES

Shut-down procedures are simple:

- 1) Turn the main power (safety switch) to "off".
- 2) Steps should be taken to prevent water in the sumps and in the pumps from freezing. If shut-down in cold weather is expected, the sumps and pumps should be drained of water. A tapping screw on each pump (5) may be used to drain.

If you have any problems, complaints, suggestions, or questions, please contact Chempro operations in Berkeley, California at (415) 524-9372.

DISCLAIMER

Chempro reserves the right to make any equipment changes as needed. Chempro will not be liable for any incidental or consequential damages, loses, or expenses arising from installation, use, or any other causes.

STRIPPER DESIGN

LIQUID VISCOSITY (T), cp	0.85
LIQUID SURFACE TENSION, (T,P) dyne/cm	72
CRITICAL SURFACE TENSION, (material) dyne/cm	33
GAS DENSITY, (T,P) lbm/ft ³	0.074
LIQUID DENSITY, (T) lbm/ft ³	62.4
GRAVITATIONAL CONSTANT, ft ² /min	115826.57
SPECIFIC SURFACE AREA, (packing) ft ² /ft ³	55.5
EQUIVILANT UNIT SURFACE AREA, ft	0.0162
HENRY CONSTANT, (solute) atm/mole fraction	240
TEMPERATURE, K	298.15
VOLUMETRIC FLOW RATE, gallons/min	10
STRIPPING FACTOR, R	5
TOTAL PRESSURE, atm	1
PACKING FACTOR, (packing) Fp	30
PREDICTED LIQUID DIFFUSIVITY, ft ² /min	2.2585E-06

COLUMN DIAMETER @ 50% FLOODING

G(L)/G(g)*(GAS DENSITY/LIQUID DENSITY) ^{0.5}	1.02598098
G(L)/G(g)	29.7931034
FROM FIG. 18.39 PERRY'S Y VALUE @FLOODING	0.04

MASS FLUX (gas), lbm/min*ft ² @ flooding	27.1528123
MASS FLUX (gas) @ 50% flooding, lbm/min*ft ²	13.5764061
MASS FLUX (liquid), lbm/min*ft ²	404.483272
MASS FLOW RATE (liquid), lbm/min	83.4113086

DIAMETER OF COLUMN WITH 30% DESIGN FACTOR, ft	0.66613245
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PREDICTION OF WETTED PACKING AREA

REYNOLDS #	212.581047
FROUDE #	0.02013338
WEBER #	0.08267137
WETTED PACKING AREA, ft ² /ft ³	35.4720129

PREDICTION OF LIQUID PHASE MASS TRANSFER COEFFICIENT

k (liquid), 1/min	0.06005851
k(liquid)*WETTED AREA reduced by 50% design factor, 1/min	1.06519804

HEIGHT OF TRANSFER UNIT, (HTU) ft	6.08535076
PERCENT REMOVAL OF SOLUTE	0.97

STRIPPER DESIGN

NUMBER OF TRANSFER UNITS, (NTU)	4.11360795
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HEIGHT OF PACKED BED, ft	25.0327473
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SIZING STRIPPER BLOWER*

SUPERFICIAL VELOCITY, ft/s	3.05774913
LOADING, gpm/ft ²	28.6938568
C-FACTOR	0.10536178

dP, in. liquid/ft bed height from Fig. 11 for #1A cascade mini-rings	0.5
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TOTAL PRESSURE DROP, gage inches of water	52.2552857
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REQUIRED CFM	63.938755
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POWER : DRIVE FAN, hp with 30% design factor	1.14002081
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SIZING RECIRCULATION PUMP*

TOTAL HEAD, ft of water	15
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POWER: DRIVE PUMP, hp with 30% design factor	0.06565657
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* NOTE: THESE ITEMS SHOULD BE SIZED WITH PUMP CURVES

Design of aeration towers to strip volatile contaminants from drinking water

Michael C. Kavanaugh and R. Rhodes Trussell

Chlorohydrocarbon solvents in concentrations up to 1 mg/L are being found with disturbing frequency in ground and surface water supplies across the US. In addition, trihalomethane levels in many water systems exceed the federal standard of 0.1 mg/L. Preliminary analyses suggest that aeration may be a cost-effective process for removal of these trace organic contaminants. The authors have developed a procedure for the process design of air stripping in packed towers for the removal of volatile organic contaminants, which follow Henry's law at low concentrations. The design methodology incorporates the effects on system design of water and air temperature, volatility of the contaminant, and type and size of packing. It provides an analytical method for estimating the relative cost of air stripping for removal of volatile organic compounds, as well as a quantitative framework for design and evaluation of pilot plant studies.

Aeration has a long tradition in water treatment,¹⁻⁴ including such applications as the addition of oxygen or carbon dioxide gases to water or the removal of dissolved hydrogen sulfide gas. In the first application aeration leads to absorption of a gas by water, a process known as gas absorption. In the second example a sparingly soluble gas, H₂S, is released or stripped from the water by air, a process known as air stripping. Thus as it is used in the water treatment industry, the term aeration encompasses two distinct but analogous processes, gas absorption and air stripping.

drinking water supplies.⁵ Preliminary cost analyses⁶ of the air stripping process for removal of several toxic volatile organic contaminants suggest that this process may be considerably cheaper than such alternative processes as granular activated carbon (GAC) or adsorbent resins. Thus this process merits a detailed analysis of its technical and economic feasibility for control of volatile organics in drinking water.

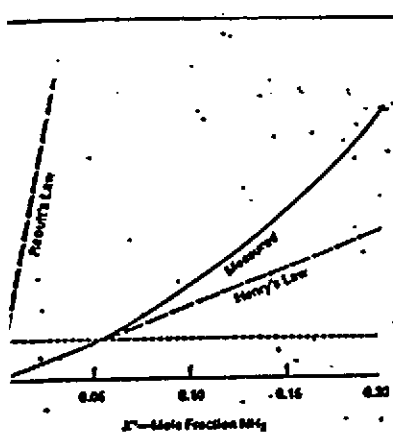
The design principles for gas absorption and air stripping have been extensively developed in the field of chemical engineering.^{7,10,15} Chemical engineers

Consequently, the procedures developed for the design of absorption or stripping systems can be simplified and applied to water treatment applications.

This paper presents a discussion of the basic principles of the design of air stripping systems as applied to the removal of volatile trace organics from dilute solutions. Although air stripping can be conducted in a number of alternative equipment designs, this discussion is limited to countercurrent packed towers, which offer several process advantages.

Physical chemistry of aeration

The kinetic theory of gases states that molecules of dissolved gases can readily move between the gas and liquid phases. Consequently, if water contains a volatile contaminant in excess of its equilibrium level, the contaminant will move from the liquid phase (water) to the gas phase (air) until equilibrium is reached. If the air in contact with the water is continuously replenished with fresh, contaminant-free air, eventually all of the contaminant will be removed from the solution. This is the basic operating principle of the air stripping process. The objective of the design of air stripping



1. Partial pressure vs concentration: Raoult's law, Henry's law

measured equilibrium partial pressure in the gas phase (P_A) versus a fraction of ammonia in the liquid in the NH_3-H_2O system at $10^\circ C$. As this is an ideal solution, Raoult's law predicts very high partial pressures. Henry's law closely models the system for the conditions encountered in most domestic systems (for $X = 0.05$, $NH_3 = 2780$ mg/L).

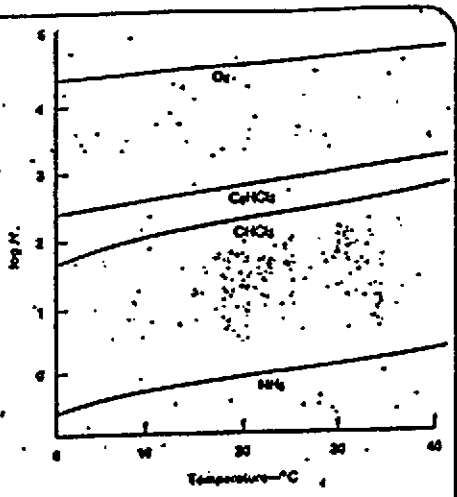


Figure 2. Influence of temperature on Henry's constants

Henry's constants vary with temperature in a manner consistent with the van't Hoff relation. For hydrocarbons, H values change about threefold for every $10^\circ C$ temperature rise. Shown are values for oxygen, a slightly soluble gas; two hydrocarbons, chloroform and TCE; and ammonia, a very soluble gas which reacts with water.

TABLE 1
Henry's constants for selected compounds*

Compound	Formula	Henry's Constant atm	Reference
chloride	CH_2Cl_2	3.55×10^4	11
on	O_2	4.3×10^4	12
gas	N_2	8.6×10^4	12
and	CH_4	3.8×10^4	12
	O_2	3.8×10^4	9
phenol	C_6H_5Cl	3.5×10^4	11
on dioxide	CO_2	1.51×10^4	12
on tetrachloride	CCl_4	1.29×10^4	12
chloroethylene	C_2Cl_4	1.1×10^4	12
chloroethylene	$C_2H_2Cl_2$	3.5×10^4	12
hydroethylene	H_2S	5.18×10^4	12
rogen sulfide	CH_2Cl_2	4.8×10^4	11
romethane	CH_2Cl_2	4.0×10^4	12
Trichloroethane	OCH_2Cl	3.4×10^4 ($25^\circ C$)	13
ene	CH_2Cl_2	3.53×10^4 ($25^\circ C$)	13
Trimethylbenzene	C_6H_5Cl	2.4×10^4	12
ene	CH_2Cl_2	1.8×10^4	13
chlorobenzene	CH_2Cl_2	1.7×10^4	11
ene	CH_2Cl_2	41	11
chloroethane	CH_2Cl_2	41	11
Trichloroethane	CH_2Cl_2	41	11
de dioxide	SO_2	36	11
ene	$CHBr_3$	25	11
ene	NH_3	0.76	12
ene	C_6H_5Cl	0.12	11
chlorobenzene	C_6H_5Cl	0.0094	11

*Pure $20^\circ C$ except where noted otherwise
 † from water solubility data and partial pressure of pure liquid at specified temperature
 ‡ approximate chemical formula

According to Dalton's law the total pressure of an ideal gas mixture is the sum of the partial pressures of all of its components. From this it may be shown that the partial pressure of a given contaminant in the air is the product of the total pressure and the fractional volume or gas phase mole fraction of the contaminant in the air

$$P_A = Y_A P_T \quad (3)$$

where Y_A = mole fraction of contaminant A in gas phase and P_T = total pressure.

Unfortunately, most solutions of importance in potable water treatment do not show ideal behavior. For example, Figure 1 shows the partial pressure of ammonia in air above an air-water mixture as a function of the mole fraction of the ammonia in the water. A line corresponding to the predictions of Raoult's law is shown in Figure 1, and it can be seen that the deviations are substantial. When nonideal solutions are very dilute, however, it is generally observed that the equilibrium partial pressure of the contaminant in the air above a solution is still proportional to the solution concentration of the contaminant. This phenomenon is known as Henry's law and may be mathematically represented as

$$P_A = H_A X_A \quad (4)$$

where H_A = Henry's constant of contaminant A (atm).

Thus at equilibrium the concentrations or mole fractions of contaminant A in the liquid and gas phases are related by Eq (3) and (4) to give

$$Y_A = X_A \frac{H}{P_T} \quad (5)$$

The larger the Henry's constant, the greater will be the equilibrium concentration of A in the air. Thus contaminants with large Henry's constants are more easily removed by air stripping.

Most gases and vapors of interest follow Henry's law quite satisfactorily in the range of concentrations experienced in domestic water treatment. Table 1 shows Henry's constants for 25 selected compounds at $20^\circ C$. For those compounds that are liquids at $20^\circ C$, the Henry's constant was computed from solubility data and the partial pressure of the pure liquid at the system temperatures and 1 atm total pressure [Eq (5)]. For very water-soluble volatile compounds, such as chloroform (approximately 7000 mg/L or $X \cong 1.0 \times 10^{-2}$ at $20^\circ C$), the Henry's constant has thus been computed at concentrations much higher than those normally encountered in water treatment (< 1 mg/L $CHCl_3$ or

... of gas-liquid equilibrium be outlined before suitable rate ons can be developed. For an ideal m, the concentration of any onant A in the liquid phase and in the ase can be related to each other by 's law'

$$P_A = P_A^* X_A \quad (1)$$

The mole fraction is defined as the concentration of the contaminant in the solution (kmol/m³) divided by the sum of the concentrations of all the components in the solution. Water is the dominant component in any solution of interest in potable water treatment. Thus, because water contains 55.6 kmol/m³, mole fractions may be approximated as

Table 1 may be high, which would exaggerate their potential for removal by air stripping. However, since it is not anticipated that the values of Henry's constants in the low-concentration region will differ by more than a factor of two, values in Table 1 can be used for feasibility calculations. Research is urgently needed to obtain values of Henry's constants for low contaminant concentrations typical of trace organic levels found in water supplies.

Like all equilibrium constants, Henry's constants are strongly influenced by temperature. Figure 2 shows this effect for several constants of interest. The relationship of the Henry's constant to temperature can be modeled by a van't Hoff-type relation. If the enthalpy change caused by dissolution of the contaminant in water is considered independent of temperature, the relation takes the form

$$\log H = \frac{-\Delta H^\circ}{RT} + K \quad (6)$$

where R = universal gas constant, 1.987 kcal/kmol °K; T = absolute temperature (°K); ΔH° = change in enthalpy due to dissolution of component A in water (kcal/kmol); and K = constant.

Table 2 shows values of ΔH° and K for twenty compounds of interest in water treatment that were developed from least squares fitting of data from reference 12. In all cases correlation coefficients were greater than 0.99. The values show that Henry's constant for most volatile hydrocarbons increases about threefold for every 10°C temperature rise.

Choice of aeration methods

The wide variety of devices that may be employed to accomplish gas transfer in water treatment include diffused aeration, the coke tray aerator, the counter-current packed tower, and the cross-flow tower (Figures 3A-3D). Selection of the appropriate equipment configuration for solving an aeration problem depends primarily on process feasibility and cost. The device must provide satisfactory mass transfer with minimum energy losses. Ease of operation, noise control, and the esthetic appearance of the equipment may also be important for treatment plants located in residential areas.

Diffused aeration. In diffused aeration, air is bubbled into a contact chamber through a diffuser. Diffused aeration is ideally conducted counterflow, with the untreated water entering at the top, the treated water exiting through the bottom, the fresh air entering at the bottom, and the exhausted air leaving through

vide for oxygenation, particularly in wastewater treatment.

Coke tray aerator. A coke tray aerator is a simple, low maintenance design without air blowers. The water being treated trickles through several layers of trays, producing a large amount of surface area for gas transfer. Coke tray aerators are fairly popular for removal of such contaminants as hydrogen sulfide and iron and manganese. It is likely that the effectiveness of these applications of coke tray aerators is due largely to the fact that the surface area of the coke serves as a support medium for biological slimes that mediate the oxidation reaction. It is difficult to model the gas transfer efficiency of coke tray aerators because the air-to-water ratio is not controlled.

Countercurrent packed towers. In countercurrent packed towers, packing materials are used which provide high void volumes and high surface area. The water flows downward by gravity and air is forced upward. The untreated

TABLE 2
Henry's constant temperature dependence

Compound	Formula	ΔH° (kcal/kmol) $\times 10^{-4}$	K
Benzene	C ₆ H ₆	3.84	8.06
Chloroform	CHCl ₃	4.03	8.16
Carbon tetrachloride	CCl ₄	4.06	10.08
Methane	CH ₄	1.54	7.22
Ammonia	NH ₃	3.764	6.31
Chloromethane	CH ₃ Cl	2.44	6.53
1,2-Dichloroethane	C ₂ H ₄ Cl ₂	3.82	7.82
1,1,1-Trichloroethane	C ₂ H ₃ Cl ₃	3.96	8.30
1,1-Dichloroethane	C ₂ H ₄ Cl ₂	3.78	8.87
Trichloroethylene	C ₂ HCl ₃	3.41	8.59
Tetrachloroethylene	C ₂ Cl ₄	4.58	10.38
Carbon dioxide	CO ₂	2.07	6.78
Hydrogen sulfide	H ₂ S	1.90	8.94
Chlorine	Cl ₂	1.74	8.76
Chlorine dioxide	ClO ₂	2.83	8.84
Sulfur dioxide	SO ₂	2.40	6.16
Diffuorochloromethane	CHF ₂ Cl	2.82	7.11
Oxygen	O ₂	1.43	6.85
Nitrogen	N ₂	1.12	6.06
Ozone	O ₃	2.12	

TABLE 3
Equipment characteristics:
diffused aeration versus packed column*

Method	Interfacial Volume	Volume H ₂ O
	H ₂ O Volume	Volume Liquid Film
Diffused aeration	20	4000-10 000
Packed column	1200	10-100

*After Levenspiel**

the gas and minimizes the thickness of the water layer on the packing, promoting efficient mass transfer. The counter-current packed tower is used for the removal of ammonia, hydrogen sulfide, and carbon dioxide.

Cross-flow tower. In a cross-flow tower, the water flows down through the packing as in other packed towers, but the air is pulled horizontally across the packing. Cross-flow towers are widely used as cooling towers but are not commonly used for air stripping. On the other hand, such towers can be and have been designed for stripping applications. They generally have a lower profile than countercurrent towers and are sometimes less costly to build and operate. Consequently, cross-flow towers should also be considered for air stripping applications. Analytical methods for design of these towers are still under development."

From a mass transfer perspective the two extremes are probably diffused aeration and the countercurrent packed tower. It is important to compare the

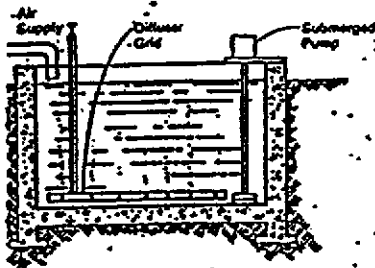


Figure 3A. Diffused aeration
 bubbled into contact chamber; counter-current. Deep basins, smaller bubbles, mechanical stirring improve transfer; very good for oxygenation and ozonation.

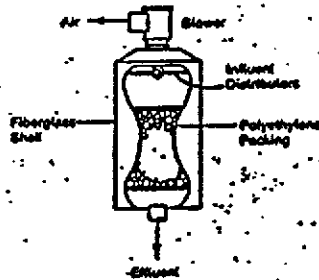


Figure 3B. Packed tower
 High surface area packing and forced or induced air draft; subject to systematic engineering analysis. Effective in removing most volatile contaminants. After McCarty.⁶

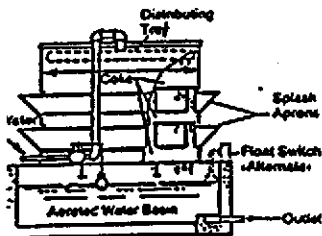


Figure 3C. Coke tray aerator
 low maintenance design. Difficult to retrofit popular for removal of H₂S, Fe, Mn. Coke may serve as support for biological mediation. Figure courtesy of Permutit.

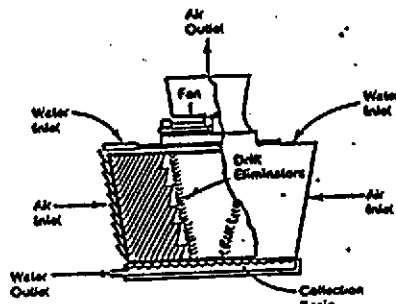


Figure 3D. Cross-flow tower
 Air is pulled horizontally through the packing; lower height and capital cost than counter-current towers; commonly used for cooling. Figure courtesy of Marley Co.

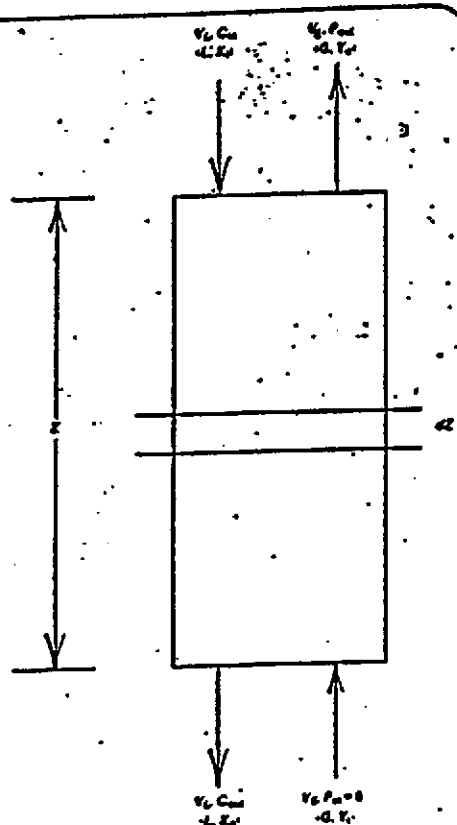


Figure 4. Process schematic for countercurrent packed tower
 Water flows down with high concentration of contaminant at top (C_{in}, X_{in}) and low concentration at bottom (C_{out}, X_{out}). Forced air travels upward and contains little or no contaminant at the bottom (P_{in}, Y_{in}) and a higher level of contaminant at the top (P_{out}, Y_{out}).

eration provides much less interarea for mass transfer but much liquid contact. Conversely, towers provide a great deal more area but much lower liquid volume compared to the volume of liquid. In addition, much greater air volumes are practical with a tower design because of lower air drops. These data indicate that diffused aeration should be used when the principal objective is to maximize the solution of a valuable gas in the liquid (e.g., oxygenation or ozonation). For tower aeration should be used when the objective is to maximize the removal of a volatile contaminant in the liquid (e.g., stripping of ammonia, hydrogen sulfide, or trace organics).

Choice of packed tower design

The principal choices must be made in designing a packed tower for removing volatile dissolved contaminants from water. They are (1) air-to-water

stripping of the contaminant, and the mass transfer characteristics of the packing. Liquid versus gas-controlled mass transfer. The rate of mass transfer in a packed column varies with packing depth and depends on the resistances to mass transfer in both the liquid and gas phases. At any point in the column the rate of mass transfer between phases is proportional to the difference between the equilibrium concentration and the actual solute (contaminant) concentration in either phase. For transfer from the liquid (water) to the gas (air) phase (air stripping), the steady-state mass transfer rate per unit volume of packing is defined by the relation¹⁰

$$J_A = K_L a (C_A^* - C_A) \quad (7)$$

where J_A = the rate of mass transfer of A (kmole/s), C_A^* = the equilibrium aqueous concentration of A (kmol/m³) at the system temperature and pressure (Henry's law), C_A = the aqueous concentration of A at any point in the column,

and is related to the local gas and liquid phase mass transfer coefficients k_G and k_L by the expression¹⁰

$$\frac{1}{K_L} = \frac{1}{k_L} + \frac{C_o}{k_G H_A} \quad (8)$$

Similarly, the overall gas phase mass transfer coefficient K_G can be related to the local mass transfer coefficients by the relation

$$\frac{1}{K_G} = \frac{1}{k_G} + \frac{H_A}{k_L C_o} \quad (9)$$

where K_G = overall gas phase mass transfer coefficient (kmol/s · atm · m²), H_A is Henry's coefficient for the solute A, and C_o is the molar density of water (55.6 kmol/m³). When a solute has a large Henry's constant, as do slightly soluble gases (e.g., O₂) or volatile liquids (e.g., trichloroethylene), the overall transfer coefficients K_L and K_G depend primarily on the local liquid phase resistance to mass transfer. From Eq (8) and (9) it is easily seen that

(02-11-16) 185

TABLE 4
Relating mass transfer coefficients:
Relative K_{Ga} values for several common packings*

Packing Type	K_{Ga} for Nominal Packing Size ($\text{kmol/s} \cdot \text{m}^2 \cdot \text{atm}) \times 10^3$				
	1 in.	1.5 in.	2 in.	3 in.	3.5 in.
Super Intalox	1.43		0.94		0.62
Pall rings	1.10	0.96	0.85		
Tellerettes			0.85		
Marspak			0.76	0.80	
Hell-Pak			1.25	0.53	
Raschig rings (ceramic)	1.03	0.85	0.74		0.42
Bed saddles (ceramic)	1.11	0.80	0.65		

*After Eckert¹¹; $\text{mol/hr} \cdot \text{cu ft (atm)} = 22.4 \cdot (\text{kmol/s} \cdot \text{m}^2 \cdot \text{atm})$. Values for CO₂ absorption by NaOH at $L' = 6.7 \text{ kg/m}^2 \cdot \text{s}$.

NH₃) or liquids of lower volatility (e.g., pentachlorophenol), mass transfer resistances in the gas phase may control the overall coefficients.

As can be seen from Eq (7), the rate of mass transfer per unit volume of packing can be increased by increasing the magnitude of either K_L or the gas-liquid interfacial area a . When the value of K_L is controlled by liquid phase resistance ($K_L = k_L$), the value of K_L is relatively insensitive to changes in gas flow rate. As a result, the efficiency of mass transfer can only be improved by increasing the liquid loading rate or by selecting a packing that increases a .

When the gas phase resistance controls mass transfer, $K_L \cong k_G H_A / C_G$. Under these circumstances, the rate of mass transfer can be improved by increasing the air flow rate (increasing air turbulence), which increases k_G , as well as by increasing the air-water interfacial area. For most stripping applications in water treatment, the bulk of the resistances to mass transfer reside in the liquid phase, with the exception of ammonia stripping where diffusional resistance in both phases may be important. Consequently, the design of tower packings should maximize the liquid mass transfer coefficient k_L and the interfacial area a .

Development of removal efficiency equation. Figure 4 shows schematically a column of cross-sectional area S that contains packing materials of depth Z . Water containing an undesirable contaminant or solute flows downward at a superficial velocity of $V_L = Q_L/S$ ($Q_L = \text{volumetric flow rate}$), countercurrent to the upward air flow at a superficial velocity of $V_G = Q_G/S$. The dissolved contaminant will be stripped from the water to the gas phase depending on the column design and the relative volatility of the solute. The aqueous concentration decreases from C_1 to C_2 .

size of packing, and the necessary air flow rate to achieve a specified degree of removal must be known.

In the differential depth of packing, dZ , the steady-state rate of mass transfer of A per unit volume of packing from water to air is given by

$$J_A = \frac{(\text{moles } A \text{ stripped})}{(\text{time})(\text{volume of packing})} \quad (11)$$

$$= \frac{d(Q_L C_A)}{S dZ}$$

Only 0.1 to 0.2 percent of the water is evaporated and the quantity of solute leaving the water is small; therefore, Q_L is unchanged as it passes through the tower. Combining with Eq (7), Eq (11) becomes

$$J_A = \frac{Q_L dC_A}{S dZ} = K_L a (C_A^* - C_A) \quad (12)$$

The mass transfer literature reports that it is convenient to use mole fractions instead of mass or molar concentrations and to replace volumetric flow rates with molar or mass flux rates. Defining the molar flux of A in the liquid (water) and gas (air) phases as L ($\text{kmol/m}^2 \cdot \text{s}$) and G ($\text{kmol/m}^2 \cdot \text{s}$), respectively, and introducing mole fraction ($X_A = C_A/C_G$ for dilute solutions), Eq (12) in integral form becomes

$$\int_0^Z dZ = \frac{L}{K_L a C_G} \int_{X_{La}}^{X_{La}^{\text{out}}} \frac{dX_A}{X_A^* - X_A} \quad (13)$$

where the limits of integration refer to the influent and effluent solute mole fractions. The height of packing Z required to achieve the desired removal of solute is thus the product of two quantities— $L/K_L a C_G$, termed the height of a transfer unit (HTU), and an integral, defined as the number of transfer units (NTU). That is, $Z = (\text{HTU})(\text{NTU})$.

faculty of removing solute A from the liquid phase. When the difference between the equilibrium and actual concentration of solute A is large, the mass transfer driving force and the rate of removal will be large. As the actual concentration approaches the equilibrium value, however, the integral term approaches infinity and separation becomes exceedingly difficult, requiring a large number of transfer units and an unreasonably tall packed column.

For dilute solutions ($X_A < 10^{-3}$) and solutes obeying Henry's law, the expression for NTU can be solved analytically. At any point in the packed column, X_A and Y_A are related by a material balance around either the upper or lower section of the column. A material balance around the bottom part of the column (Figure 4) gives

$$Y = \frac{L}{G} (X - X_1) + Y_1 \quad (14)$$

In addition, the mole fraction of A in the air is related to the equilibrium mole fraction of A in the water through Henry's law [Eq (5)] given as

$$Y_A = \frac{H_A}{P_T} X_A$$

Substituting Eq (5) and (14) in the integral expression for NTU with $Y_1 = 0$, the number of transfer units becomes¹⁴

$$\text{NTU} = \left(\frac{R}{R-1} \right) \ln \left[\frac{X_{La}/X_{out}(R-1) + 1}{R} \right] \quad (15)$$

with $R = (H_A/P_T)(G/L) \cong \text{stripping factor}$.

Equations (5) and (14) are illustrated in Figure 5 for trichloroethylene (TCE) in water at 20°C and 1 atm. The difference between Eq (14), the so-called operating line, and Eq (5), the equilibrium line, is a measure of the mass transfer driving force. At the column liquid inlet (top), $(X^* - X_1)$ is large, signifying high rates of mass transfer. As stripping proceeds, the difference decreases and becomes quite small at the column liquid outlet.

For the operating line shown, the hypothetical conditions were TCE influent and effluent concentrations of 500 $\mu\text{g/L}$ ($X_1 = 6.85 \times 10^{-4}$) and 5 $\mu\text{g/L}$ ($X_2 = 6.85 \times 10^{-6}$), respectively; no TCE in the stripping air ($Y_1 = 0$); and a stripping factor of $R = 2$. For TCE ($H = 550 \text{ atm}$ at 20°C), this gives $L/G = 275$ and $Y_2 = 1.88 \times 10^{-4}$.

Equation (15) is the basic removal efficiency design relation. It has been plotted by Treybal¹⁵ and is shown in slightly modified form in Figure 6. Thus the

es (G/L). Similar plots have been developed for cross-flow tower

l on Eq (13) and (15) there are factors which must be considered design of packed columns for any problem: (1) the height of a unit, (2) the number of transfer and (3) the air-to-water ratio. The drop characteristics of the column must also be evaluated. Factors depend on the characteristics of the packing material, the relative viscosity or solubility of the contaminant system temperature, and the liquid flow rates. The height of a unit for a particular packing can be calculated as a function of liquid mass rate using the expression from

$$HTU = \frac{L}{K_L a C_O}$$

If this expression requires data on a system under consideration some cases packing manufacturer supply this information for other systems, giving $K_L a$ values as a function of temperature and liquid flow rate. Mass transfer correlations can be used for design estimates when other data are unavailable. Preferably, studies for determination of mass transfer coefficients should precede design because mass transfer coefficients depend so strongly on packing characteristics, temperature, and liquid and gas flow rates, among other factors. Once $K_L a$ values have been determined for a particular packing, values for another system can be estimated from the values shown in Table 4. When liquid resistance controls the rate of mass transfer from Eq (10)

$$K_L a = \frac{K_G a H_A}{C_s} \quad (16)$$

A typical empirical correlation used for liquid-phase mass transfer coefficient in towers containing randomly packed materials is given by Perry:

$$\frac{K_L a}{D_A} = \alpha \left(\frac{L'}{\mu_L} \right)^{1-n} \left(\frac{\mu_L}{\rho_L D_A} \right)^{0.5} \quad (17)$$

D_A is the molecular diffusion coefficient of A in water (sq ft/hr), μ_L and ρ_L are liquid viscosity and density, L' is liquid mass flux rate (lb/sq ft·hr) and n are empirical constants that depend on the type and size of packing. For 1.5-in. Berl saddles $\alpha = 140$ and $n = 0.28$, with British units for all sizes and $K_L a$ with units of hr⁻¹.

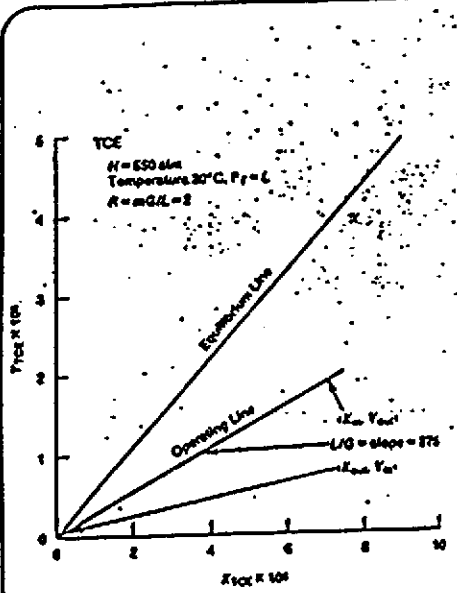


Figure 5. Equilibrium and operating lines for trichloroethylene (TCE)

The equilibrium line shows the equilibrium relationship between the mole fraction in the gas phase (Y_{TCE}) and in the aqueous phase (X_{TCE}) as described by Henry's law. The operating line shows the dynamic relationship between X and Y in the column for a stripping factor of 2. For TCE this gives an L/G of 275 at 20°C and 1 atm.

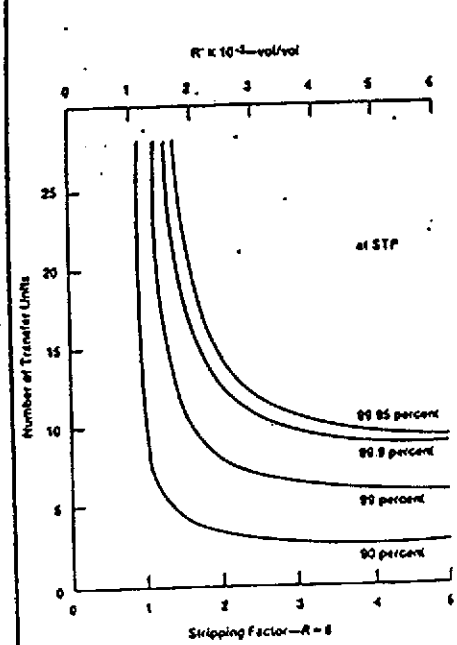


Figure 7. Relationship between stripping factor and NTU

Shows influence of stripping factor (R) and percent removal on number of transfer units (NTUs) required. Note R must be greater than 1 to get much removal, but increasing R ceases to yield improved results above values of 4 to 5.

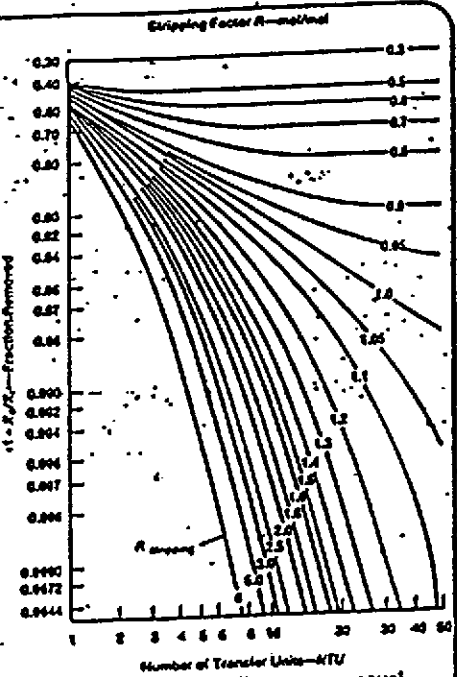


Figure 6. Design diagram—removal efficiency

This plot shows the relationship between the stripping factor, the fraction of contaminant to be removed, and the number of transfer units (NTUs) necessary. Knowing any two of these parameters permits the other to be predicted. The plot is based on Eq (15) and adapted from a plot by Treybal.¹⁰

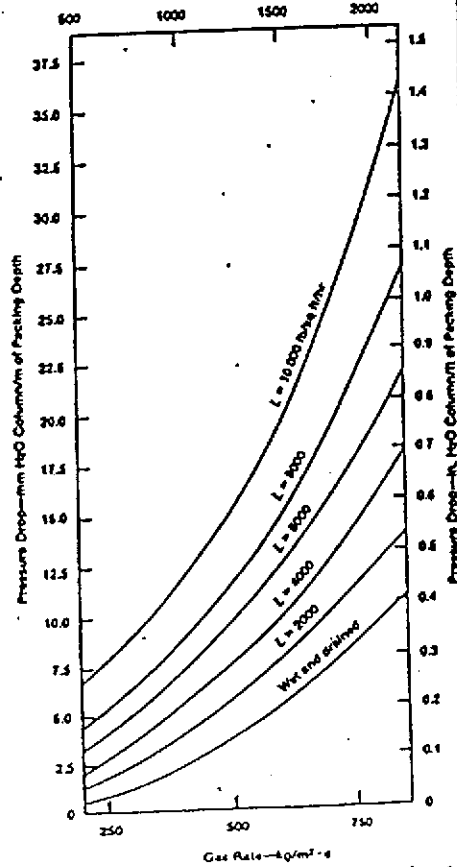


Figure 8. Influence of liquid and gas rates on

available in handbooks.⁹ For dilute solutions the empirical correlation of Wilke and Chang¹¹ (see Treybal¹⁰) is recommended. Using this correlation, D_A for chloroform is approximately 1.44×10^{-5} m²/s at 20°C.

For 50-mm Berl saddles and a liquid flux rate of $L' = 5$ kg/m²·s (3700 lb/sq ft/hr) the value of $k_L a$ at 20°C for stripping of CHCl₃ is about 0.7 min⁻¹, computed using Eq (17). This compares with $k_L a$ values for diffused air systems of from 0.03–0.2 min⁻¹. In general, $k_L a$ values in packed towers are larger than those in diffused air systems.

Number of transfer units. Drinking water contaminants that are volatile enough to be removed by air stripping are usually present at concentration levels less than 1 mg/L. Therefore, the analytical solution to the steady-state equation for mass transfer in packed columns, Eq (15), is applicable. Optimum column designs are typically based on stripping factors (R) between 1.2 and 5. The effect of varying R on the number of transfer units is illustrated in Figure 7 for several levels of contaminant removal. For 90 percent removal, the NTUs increase rapidly for $R < 1$. Diminishing returns set in quickly, however, as R is increased beyond 2. For very high removals (> 90 percent), which may be typical of water treatment applications, R s between 2 and 5 may provide the most economical design.

Air-to-water ratio. For removal of a specific contaminant, the gas-to-liquid ratio is determined when the stripping factor is selected. For the air-water system at $p_T = 1$ atm, the ratio of dry air volume V_A to water volume V_W may be determined from R by

$$\begin{aligned} V_A/V_W &= \frac{R}{H_A} \frac{\text{mol wt air}}{\text{mol wt H}_2\text{O}} \frac{\rho_{\text{H}_2\text{O}}}{\rho_{\text{air}}} \\ &= 1325 \frac{R}{H_A} \text{ (at } 20^\circ\text{C)} \end{aligned}$$

Examination of Figure 6 and 7 will reveal that the depth of packing, as represented by NTU, is affected only by a relatively narrow range of stripping factors for a given fraction removed. For R values greater than 3, increasing R has little effect on the NTUs required. Hence the principal factor influencing the air-to-water ratio is the value of R required to achieve a desired removal efficiency. Table 5 shows the air-to-water ratios required to achieve an R value of 3 for a number of contaminants that may be found in water supplies.

Pressure drop. The pressure drop of a gas rising countercurrent to liquid flowing through a packed tower typically follows the pattern illustrated in Figure 8, adopted from commercial literature

given liquid loading rate, gas pressure drop increases approximately in proportion to the square of the gas velocity. At very high gas rates, entrainment of the liquid by the rising gas may occur, characterized by a sudden rapid increase in the gas pressure drop. Similarly, when the liquid rate is increased at a fixed gas flow, the tower may fill with liquid. Under these conditions the tower is flooded, and either the liquid or the gas flow rates must be reduced.

Packed towers are usually designed to operate with a gas pressure drop well below flooding conditions. According to Treybal,¹⁰ most stripping towers are designed for gas pressure drops of 200 to 400 N/m² per metre of packing depth (0.25 to 0.5 in. H₂O/ft). For any given gas loading rate and a selected design gas pressure drop, the allowable liquid loading can be obtained from data similar to those shown in Figure 8.

A generalized pressure drop correlation commonly used for design of towers with random packing is shown in Figure 9.¹⁶ At a specified gas pressure drop, the allowable gas loading rate is specified by the gas and liquid density, the liquid viscosity, and a packing factor C_f characteristic of the type and size of the packing selected. Packing factors for several commonly used packings are shown in Table 6. Once the stripping factor R and the design gas pressure drop are selected, the gas loading rate is obtained from the ordinate axis in Figure 9.

When the value of the abscissa is greater than 4, very high liquid loading rates produce backcycling of the gas and unstable hydrodynamic behavior. This tends to reduce the stripping efficiency of the tower. Similarly, high gas flow rates in the region of abscissa values less than 0.02 cause liquid entrainment, which also reduces the overall efficiency of the tower. For values of the abscissa beyond these boundaries, pilot studies are recommended to determine the effect of high or low gas flow rates on removal efficiencies.^{10,16} Towers operating in these regions may require additional packing depth to compensate for the efficiency reductions.

For the air-water system at 20°C and 1 atm, the abscissa in Figure 9 is approximately 0.0347 (L'/G'). Substituting the stripping factor R , this becomes 0.0555 (H/R). Thus for values of $R \leq 5$, use of Figure 9 for stripping tower design is restricted to dissolved compounds with Henry's constants ranging from about 1.8 to 360 atm. Pilot studies are strongly recommended for tower design when the contaminant exhibits Henry's constants outside this range, although Figure 9 can still be used for preliminary estimates of the cost of stripping towers.

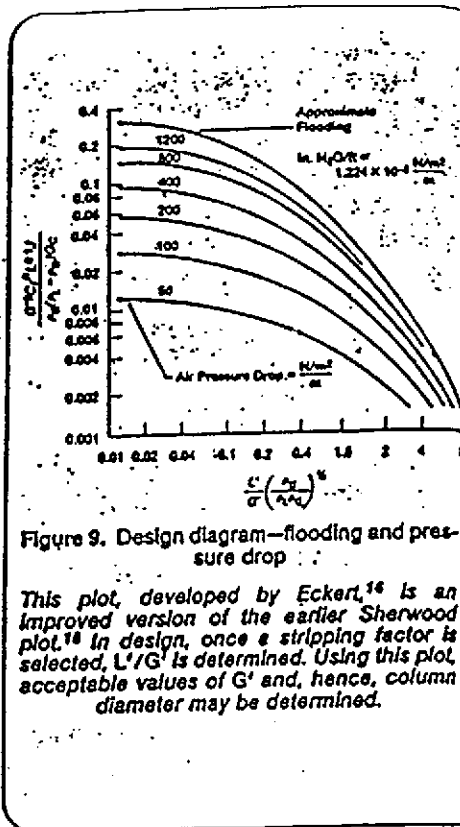


Figure 9. Design diagram—flooding and pressure drop.

This plot, developed by Eckert,¹⁶ is an improved version of the earlier Sherwood plot.¹⁸ In design, once a stripping factor is selected, L'/G' is determined. Using this plot, acceptable values of G' and, hence, column diameter may be determined.

confronted with two design problems—evaluation of the feasibility of using an existing packed tower and development of design criteria for a new tower. The type of design problem dictates the appropriate design procedure. For the design of a new stripping tower, the preceding design concepts can be used to estimate the process and determine the economic feasibility of air stripping for trace contaminant removal compared to alternative treatment systems. Application of these concepts requires phase equilibria data for the contaminants of concern (Henry's constants for the range of design temperatures, Table 2), and mass transfer and gas pressure drop data for tower packings with desirable material characteristics such as resistance to corrosion and ease of handling. These data either are supplied by the manufacturer, are available in the literature, or must be determined by pilot studies. For most contaminants of interest in domestic water supply, pilot studies are necessary.

A suggested design procedure for packed column design to remove a single contaminant from water is

- Select a packing that is made from a satisfactory material and has a low packing factor and an acceptable relative mass transfer coefficient (Table 4).
- For several values of the stripping factor R between 1 and 5, compute NTU for the desired degree of removal at the

TABLE 5
Influence of Henry's constant on air-to-water ratio*

Compound	Henry's Constant atm	Volume Air Volume Water
butyl chloride	3.55 × 10 ⁴	0.011
hexane	3.5 × 10 ⁴	0.11
carbon dioxide	1.81 × 10 ⁴	2.8
carbon tetrachloride	1.20 × 10 ⁴	3.1
tetrachloroethylene	1.1 × 10 ⁴	3.8
trichloroethylene	850	7.2
hydrogen sulfide	815	7.7
1,1-Trichloroethane	400	1.9
chloroform	170	23
2-Dichloroethane	61	65
1,2-Trichloroethane	43	81
monochloroamine	35	110
ammonia	0.78	8300

TABLE 6
Packing factor C_f for common plastic packings and Raschig rings*

Packing Type	C_f for Nominal Packing Size Shown				
	1 in.	1.5 in.	2 in.	3 in.	2.5 in.
Super Intalox	21		21	34	34
Pall rings	31	32	25		
Tellerettes	40		30	30	
Maspak			32	15	
Heil-Pak	45		46	37	
Raschig rings	155	95			
Bert saddles	110	64	45		

*From commercial literature and reference 14

g the generalized gas pressure relation, determine allowable rates for each R value at specified temperatures (Figure 9). Determine the required column diameter for the specified water loading

pute the liquid-phase mass coefficient $K_L a$ and the height of transfer unit for each value of L using literature correlations.

pute the capital costs for packing Z, column diameter ϕ , volume V , and air flow rate for each R.

several trace volatile contaminants present in a water supply, the procedure should be carried out. Final design criteria will be the compound whose effluent concentration is most difficult to achieve.

on of tower packings. Selecting an appropriate packing includes selection of packing shape (e.g., Super Intalox, Pall rings, Maspak, Heil-Pak), materials of construction (e.g., PVC, polypropylene, ceramic, plastic), and a nominal size (e.g., 1 in., 2 in., 3 in.). Choice of size and shape involves a trade-off between low packing factors, minimum head loss (minimum column diameter), and maximum overall mass transfer. Selection of materials of construction is influenced by the cost of material, its weight, and the

and high durability. Generally, plastic packings are limited to bed depths of less than 6 m (20 ft), since greater depths will require multiple support plates.

Larger packings are less expensive on a unit volume basis and allow higher water application rates and correspondingly smaller tower diameters for a given water flow. On the other hand, packings of smaller nominal size provide larger mass transfer coefficients and thus smaller HTUs (shorter depth of packing required). Consequently, when a modest degree of removal is required, larger packings are appropriate. If a high degree of removal is required, smaller packings may be more economical. To avoid poor liquid distribution due to wall effects, the ratio of column diameter to nominal packing size should be greater than twelve.

Design example. The design procedure may be illustrated by considering the removal of chloroform (CHCl_3) from water by air stripping in a packed column. After chlorination, a 65.7-L/s (1.5-mgd) surface supply contains 200 $\mu\text{g/L}$ CHCl_3 . The effluent concentration must be reduced to 50 $\mu\text{g/L}$ CHCl_3 . For a design water and air temperature of 20°C, determine the dimensions of the packed tower for a stripping factor of $R = 3$.

1. Select the packing material. In most water treatment applications, light, low-

exhibiting good mass transfer characteristics (compare $K_G a$ values in Table 4). For illustration, 50-mm (2-in.) Super Intalox will be used (packing factor $C_f = 21$), a packing size that should eliminate wall effects.

2. Compute the number of transfer units (NTU) for $R = 3$. Desired removal efficiency is $(1 - 50/200) \times 100 = 75$ percent. From Eq (15), $\text{NTU} = 1.65$. (Note that the NTU is independent of temperature.)

3. Determine the allowable gas flow at 20°C and $p_T = 1$ atm at selected gas pressure drop.

For CHCl_3 , $H = 170$ atm, thus $H/p_T = 170$; $\rho_w = 1.205$ kg/m^3 ; $\rho_{\text{H}_2\text{O}} = 998$ kg/m^3 ; $\text{MW}_{\text{CHCl}_3} = 28.8$ kg/k mole (dry); thus $R = 170$ $\text{G/L} = 272$ G/L .

For $R = 3$, $G'/L' = 1.1 \times 10^{-3}$ (kg/kg) or $G''/L'' = 8.15$ (vol/vol). Because $H_{\text{CHCl}_3} < 360$, Figure 9 can be used. Allowable gas flow for gas pressure drop of 200 $\text{N/m}^2/\text{m}$ (0.25 in. $\text{H}_2\text{O}/\text{ft}$) is then obtained from Figure 9. The abscissa is

$$\frac{L'}{G'} \left(\frac{\rho_G}{\rho_L - \rho_G} \right)^{1/2} = 3.15$$

From the ordinate,

$$G' = \left[\frac{\rho_G(\rho_L - \rho_G)(0.037)}{C_f \mu_L^{0.1}} \right]^{1/2}$$

$= 0.65$ $\text{kg/m}^2 \cdot \text{s}$ (478 $\text{lb/hr} \cdot \text{sq ft}$)

determine column diameter ϕ .

$$L' = \frac{Q_L \rho_L}{S}$$

$$L' = \left[\frac{4}{\pi} \frac{Q_L \rho_L}{L'} \right]^{1/4} = 1.19 \text{ m (3.9 ft)}$$

compute $K_L a$ and height of transfer (TU). Mass transfer correlations in Handbook* do not include data for Intalox saddles. However, we use general correlation for 50-mm Berl saddles [Eq (17)]. For CHCl_3 , $D_{\text{CHCl}_3} = 1.44 \times 10^{-5} \text{ m}^2/\text{s}$ (10^{-5} sq ft/hr), and the following data and Eq (17),

$$k_L = 0.001 \text{ kg/m} \cdot \text{s} \text{ (2.41 lb/ft} \cdot \text{hr)}$$

$$\rho_L = 998 \text{ kg/m}^3$$

$$a_{\text{Berl}} = 238.8 \text{ hr}^{-1} = 4.0 \text{ min}^{-1}$$

Super Intalox, use relative $K_L a$ (2-in. packing) from Table 4 to get $k_L a$.

$$\frac{\text{Super Intalox}}{K_L a (\text{Berl})} = \frac{0.94 \times 10^{-2}}{0.65 \times 10^{-2}} = 1.45$$

$$a (\text{Super Intalox}) = 5.8 \text{ min}^{-1}$$

$$\text{and } HTU = \frac{L}{k_L a C_a} = 0.61 \text{ m}$$

compute height of packing Z.

$$TU(NTU) = (0.61 \text{ m})(1.65) = 1.01 \text{ m}$$

tower dimensions. Assume safety factor of 1.5 (50 percent greater design specifications).

$$Z \approx 1.5 \text{ m (5.0 ft)}$$

$$\phi = 1.2 \text{ m (3.9 ft)}$$

data available from handbooks and mass transfer literature, as well as published design procedures for solutions discussed previously, it is possible to determine the dimensions of stripping tower and the air flow required to achieve a specified stripping efficiency. For an actual stripping problem, the designer would follow the procedure for several values of stripping factor R and then compute actual costs for each design. This would determine the optimum design.

Analytical design procedures are only approximate as the input data, however. The data on $k_L a$ and Henry's constant for volatile organics in very dilute solutions are lacking, caution must be exercised in using the methodology described. The procedure does, however, represent a powerful tool for estimating relative cost of aeration for removal of volatile organic compounds from drinking water supplies. Further, it provides a quantitative framework for comparing and evaluating the results of

contaminants in various waters and in different climates, the accuracy of the analytical design procedures should improve.

Temperature effects. Stripping tower efficiency and tower hydraulic characteristics are strongly dependent on the water and air design temperatures. As the water temperature drops, both Henry's constants (Table 2) and mass transfer coefficients [Eq (17)] decrease, making removal by stripping more difficult. In the design example, both the tower diameter and packing depth would increase as the design water temperature decreased. For example, at a water temperature of 5°C and an air temperature of -12°C, which is typical of winter conditions in some regions of the US, the HTU for the above example would increase nearly fivefold to 3 m and the required column diameter to 1.6 m (5.25 ft). Therefore, careful analysis of each case is required to ensure selection of the most cost-effective treatment system.

In the design procedure described, isothermal operation was assumed. A temperature gradient in the tower will develop, however, because of differences between the entering wet bulb air temperature and the inlet water temperature. The effects of nonisothermal operation on design are discussed elsewhere for design of ammonia stripping towers.¹¹ For stripping of volatile organics, the gas-liquid ratios are much lower than in ammonia stripping applications, so that isothermal operation is often a good assumption. However, the final design of a stripping tower should include a heat balance analysis to ensure that excessive cooling, and consequently excessive water evaporation, will not occur.

Conclusions

The following basic conclusions can be drawn from this discussion.

- Packed towers are an effective method for removing many volatile contaminants from drinking waters.

- A systematic procedure is available for designing packed towers for this purpose.

- At present any design should be preceded by pilot studies, although the data and methodology presented in this paper should be helpful in establishing preliminary design criteria and bases for cost estimates.

- Before effective designs can be accomplished without pilot studies, investigations must be conducted to determine Henry's constants of most likely contaminants at low solute concentrations and over a range of temperatures and $K_L a$ values for various packings.

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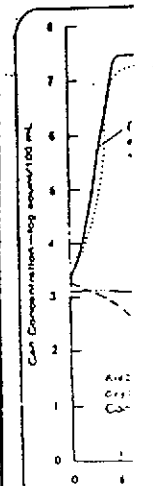
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Rese bacte

William M.

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The East (EBMUD) b elevation fr heights th reservoir v ft) or more, ft). To mini there are m individual (1000 gal) t total operat system is 3 More the determined in 1969 wa high bacter interior of steel cylind on the botte (24 ft) on enamel. Th had been c Small fra coating wa testing. Af water, the placed in a



\$ 13.75/ft³
 \$ 18.75/ft³

CORRELATION EQUATIONS FOR PREDICTING THE
 PRESSURE DROP AND HTU VALUES OF 3.5"
 LANPAC™ IN VOC/AIR STRIPPING APPLICATIONS

$$HTU = A \times \left(\frac{L}{M_L}\right)^{0.33} \times \left(\frac{M_L}{\rho_L D_L}\right)^{0.5} \times \left(\frac{T}{286}\right)^{-4.255}$$

Where: A = 0.006 for Halogenated Hydrocarbons (TCE, PCE, 1, 1, 1-TCA, 1,1-DCE, etc.)

A = 0.0042 for Aromatics (BTX's, etc.)

HTU = Height of Transfer Unit in ft.

L = Liquid Loading Rate in lbs/hr/ft²

M_L = Viscosity of Water in lbs/hr. ft.

(M_L = 4.3231 x (T/273)⁻⁷ lbs/hr. ft.)

ρ_L : Density of Water in lbs/cu. ft.

T : Water Temperature in °K

D_L : Diffusivity of VOC Species in Water in ft²/hr.

(D_L = 6.3635 x 10⁻⁴ x (T/273)⁸ x $\frac{1}{0.6288 (V_c)}$ ft²/hr.)

$$\log_{10} \left(\frac{\Delta P}{\rho_g U_G^2}\right) = -1.25 + 2.14 \times 10^{-5} \times L$$

Where: ΔP = Pressure Drop in "W.C./ft of Packing

L = Liquid Loading Rate in lbs/hr/ft²

ρ_G = Gas Density in lbs/cu. ft

U_G = Superficial Gas Velocity in ft/sec

V_o VALUES FOR SOME VOLATILE ORGANIC COMPOUNDS*

<u>Compound</u>	<u>V_o</u>
Trifluorobromomethane	200
Chlorotrifluoromethane	180
Dichlorodifluoromethane	217
Trichlorofluoromethane	243
Carbon Tetrachloride	276
Carbon Tetrafluoride	140
Chlorodifluoromane	165
Dichloromonofluoromethane	197
Chloroform	239
Dibromomethane	-
Dichloromethane	193
Tetrachloroethylene	290
TCE	256
Vinyl Chloride	169
1-Chloro,1-Difluoroethylene	231
1,1,2-Trichloroethane	294
Ethylene	129
1,1-Dichloroethane	240
1,2-Dichloroethane	220
1,1-Difluoroethane	181
MEK	267
Bromobenzene	324
Chlorobenzene	308
Fluorobenzene	271
Benzene	259
Toluene	316
Xylene	375
Ethylbenzene	374

*Available in Appendix A, "The Properties of Gases and Liquids", 3rd Edition, By Reid, Prausnitz and Sherwood.

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Table 1

ANALYTICAL RESULTS

Purgeable Aromatics and Total Petroleum Hydrocarbons
 as Gasoline in Water
 EPA Method 8020/8015¹

GTEL Sample Number		01	02	03	
Client Identification		2	3	4	
Date Sampled		04/16/90	04/16/90	04/16/90	
Date Analyzed		04/17/90	04/17/90	04/17/90	
Analyte	Detection Limit, ug/L	Concentration, ug/L			
Benzene	0.3	6800	3	<0.3	
Toluene	0.3	3500	2	<0.3	
Ethylbenzene	0.3	1500	1	<0.3	
Xylene (total)	0.6	4700	2	<0.6	
TPH as Gasoline	50	46000	380	<50	

1 = Extraction by EPA Method 5030

↑
 AIR STRIPPED INFLUENT

↑
 AIR STRIPPED EFFLUENT

↑
 1ST CARBON UNIT EFFLUENT