

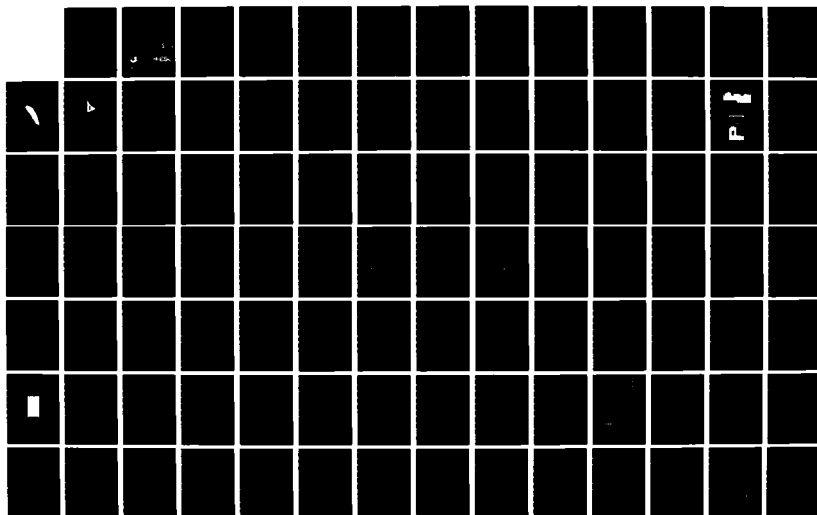
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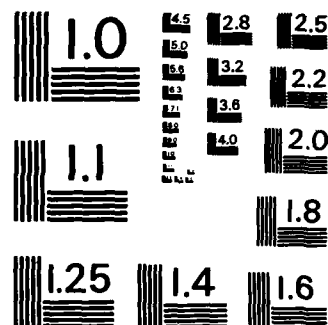
DEVELOPMENT OF PACKED-TOWER AIR STRIPPERS FOR
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**Development of Packed-Tower Air Strippers
for Trichloroethylene Removal at
Wurtsmith Air Force Base, Michigan**

R. L. GROSS

AUGUST 1985

FINAL REPORT

DECEMBER 1979 - MARCH 1985

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Packed-tower air stripping was researched and developed to treat trichloroethylene (TCE)-contaminated groundwater at Wurtsmith Air Force Base (Oscoda), Michigan. A leaking underground storage tank had caused a 1000 meters (3200 feet) long, 500 meters (1600 feet) wide, and 18 meters (60 feet) deep plume, with a maximum concentration approaching 10,000 ppb. While activated carbon could have produced treated water with an effluent TCE concentration below Michigan's 1.5 ppb discharge standard, the projected \$1.5 million capital cost and the annual \$400,000 operating and maintenance costs were prohibitive. At the request of HQ Strategic Air Command, the Engineering and Services Center investigated alternate groundwater treatment techniques. (Continued)					
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BLK 11. Trichloroethylene Removal at Wurtsmith Air Force Base, Michigan.

BLK 19. Laboratory studies were performed to determine removal efficiencies and mass transfer coefficients for TCE on 16 mm (5/8-inch) (and 25 mm (1-inch)) polypropylene Pall rings at various liquid and air flows, and at temperatures ranging from 10-30°C (50-86°F). The liquid-phase mass transfer coefficient relationship for 16 mm rings and TCE was found to be: $K_L a = \exp(8.52 - 2515/T(^{\circ}K))$. The Henry's Law constant for trichloroethylene was determined over the same temperature range, and was found to be: $H = \exp(9.7 - 4308/T(^{\circ}K))$. Performance equations and removal efficiencies were combined to provide relationships for determining the required packing volume.

Based on these studies, twin packed-tower air strippers were built onsite at Wurtsmith AFB. The towers are 9 meters (30 feet) high, 1.5 meters (5 feet) in diameter, and have a 5.5-meter (18-foot) packed bed. Originally, 16 mm rings were used; in May 83, these were replaced by 25 mm rings. The strippers are designed to treat 4540 L/min (1200 gal/min) in parallel, 2270 L/min (600 gal/min) in series (overall 6.6 ML/day (1.75 MGD)), at 90 and 99 percent TCE removal, respectively. Carbon was used as a polishing step to ensure the 1.5 ppb discharge limit was met. The strippers were performance-tested from May 1982 to May 1983, with removal efficiencies averaging better than 99.9 percent. No seasonal effects were seen. In a special test, the towers were operated for 120 days with no carbon polishing: the influent TCE level of 600 ppb was reduced to below the detection limit (1.5 ppb) by stripping alone. During the summer of 1983, an unexpected biological growth appeared on the packing, which was controlled with constant chlorination. The growth was cultured and showed some ability to degrade TCE.

Originator Supplied Keywords include)

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PREFACE

This report was prepared by the Air Force Engineering and Services Center (AFESC), Engineering and Services Laboratory, Tyndall Air Force Base, Florida under Job Order Number 21037020, Prototype Packed-Tower Air-Stripping System Development. It also incorporates an earlier laboratory investigation performed under Job Order Number 19002025, Groundwater Transport and Removal Techniques For Organic Solvents. Data from these efforts resulted in the design, construction and successful operation of a packed-tower aeration system for removing trichloroethylene from groundwater at Wurtsmith Air Force Base, Michigan.

This report summarizes the prototype air stripper work done between October 1981 and March 1985 and the laboratory research effort done between December 1979 and December 1981. Captain Randy L. Gross was the AFESC/RDWW Project Officer for the air-stripping work and Captain Daniel D. Berlinrut was the AFESC/RDVS Project Officer for the laboratory studies.

The project's success was due to the dedication and hard work of the following individuals: MSgt Dan Stork and MSgt Stacy Brown who assembled the hardware and performed the onsite analyses; Captain Jack Jeter for the biological analyses; Captain Pat Johnson and the Wurtsmith Bioenvironmental Engineering personnel for providing office space, extra hands and logistics; and Mr Mike Drewett, Mr Jim Suhanic and MSgt Brad Hitt of Civil Engineering for providing crucial base support and liaison activities. Special thanks go to Lt Col Steven TerMaath, the former Project Officer, for his guidance and technical expertise.

The trademarks and trade names of material appearing in this report do not constitute endorsement or rejection of any specific piece of equipment for Air Force use, nor can it be used for advertising a product.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

A. OBJECTIVES

This report summarizes the supporting research, equipment and process specifications, and the performance evaluation data for the packed-tower air stripping of trichloroethylene at Wurtsmith Air Force Base, Michigan. Specifically, the following program objectives were set:

1. Determine scale-up factors from laboratory data for full-scale packed-tower air-stripping units.
2. Determine effects of temperature on removal efficiency in the laboratory, then observe them in the field.
3. Evaluate operational and maintenance requirements for a 6.6-million-liter/day (1.75-million-gallon/day) air-stripping facility.

B. BACKGROUND

In late 1977, trichloroethylene (TCE), a degreasing agent, was discovered in the drinking water at Wurtsmith Air Force Base, Michigan. Subsequent analysis of the seven primary drinking water wells showed three had significant levels of TCE as high as 6700 micrograms/liter (ppb). The source of the TCE was traced to an 1890-liter (500-gallon) underground tank that was used to temporarily store spent TCE from a degreasing operation. When the tank was dug up, the connection between the filler pipe and the tank was determined to be the leak's source. Thus, the TCE leakage into the groundwater was probably intermittent, occurring only when the tank was filled or emptied. Since no one knows when the tank first started leaking, the quantity of TCE leaked can only be estimated. (Reference 1).

In March 1978, initial attempts were made to purge the trichloroethylene from the aquifer by pumping nearby wells (former drinking water supply wells) and drilling several new purge wells. The water was pumped to an aeration basin where sparging was used to remove as much TCE as possible. The water was then piped to the sewage treatment plant. In the fall of 1979, activated carbon was used to treat the effluent water from the aeration basin (Reference 1).

The United States Geological Survey (USGS) began an ongoing investigation into the extent of the TCE contamination in September 1979. Their main tasks included rate and direction of groundwater movement and selection of suitable sites for purge well installation. Since then, over 375 wells ranging from 3 to 10 centimeters (1.25 to 4 inches) in diameter were drilled on the base and surrounding area for pumping tests, collecting water samples for analysis and measuring water levels. The USGS found the TCE contamination plume (Figure 1) to be about 1000 meters (3200 feet) long and about 500 meters (1600 feet) wide. Also shown are the locations of the five purge wells (Wells 1, 2, 3, R7D and AF3) used to contain the TCE plume and supply water to the air-stripping system discussed in this report. The purge wells were located on the northwest side of Arrow Street, where the TCE contamination was highest (Figure 2). The total purge rate recommended by the USGS was 4540 L/min (1200 gal/min).

Because of the contamination level, the State of Michigan won a Federal Court mandate for plume containment and aquifer cleanup, setting the discharge criteria for TCE at 1.5 ppb maximum. When the Air Force began interim cleanup operations in 1979, activated carbon was the only accepted treatment method that could meet the discharge limit. However, a typical 3.8-million-liter/day (1-million-gallon/day) activated carbon system would have a \$1.5 million capital cost and \$400,000 annual operating cost (Section VII). The Strategic Air Command (SAC), which operates Wurtsmith, realized these costs would have a major impact on its mission capability, especially if cleanup operations were required for up to 20 years as expected. In 1979, SAC asked the Air Force Engineering and Services Center (AFESC) to investigate other treatment options (References 2,3).

C. AIR STRIPPING

After an initial literature review of treatment technologies, air stripping appeared to be a viable alternative. Air stripping involves bringing the contaminated water in contact with the air so that the contaminant leaves the water. There are primarily two types of air stripping, diffused aeration and countercurrent contacting of air and water.

at the bottom of the tower provides a water seal to prevent the air from blowing out the drain. The water leaves the tower through an inverted U-shaped overflow box with a siphon break that maintains the water seal in the tower. The air is blown into the tower just below the support plate.

C. EQUIPMENT AND INSTRUMENTATION

The 6-meter by 6-meter by 3.7-meter (20- by 20- by 12-foot) building was constructed to house the air strippers' pumps, blowers and electrical controls. Overall, the building was designed to be weathertight, withstand 113 km/h (70 mph) winds, support a 1676-pascals (35 lb_f/ft²) live load on the roof, and have an insulation U-value of at least 0.15. The towers are bolted to a reinforced concrete slab pedestal that forms part of the floor. The wooden frame structure has exterior cedar weatherboards and is insulated with 9 centimeters (3.5 inches) of batt insulation. A propane heater keeps the building at 4°C (40 °F) during the winter. Three banks of fluorescent lights provide at least 5.4 lumens/m² (50 foot candles). A wooden deck and railing is located on the roof to provide access to the tops of the towers. A metal deck spans the towers just below the upper manways, and also the lower manways inside the building. A removable wooden ladder is used to climb up on the roof.

The purge well water is delivered to the top of air strippers by the purge wells' pumps. A sample tap and temperature gauge (Figure 6) are located on the influent water line. Flow to the towers is controlled by pull-chain operated Gate Valves 1,2 and 3, depending on series or parallel flow configuration. The two 1135 L/minute (300 gal/min) pumps (P-1 and P-2) are used during series operation to move the water from the bottom of Tower 1 to the top of Tower 2. Sight glasses on the sides of the towers allow monitoring of the water level in the wet well. Sample taps are located at the bottom of the towers. Each tower has a dedicated air blower, controlled manually by a damper. The blowers, originally rated at 58 m³/min (2000 ft³/min) at 41 centimeters (16 inches) of water static pressure, were also changed in May 1993 to 107 m³/min (3700 ft³/minute) at 38 centimeters (11 inches) of water static pressure by changing the 7.46-kilowatt (10-horsepower) motors to 11.19 kilowatt (15 horsepower) (Section V). A temperature gauge is located on the inlet air line after the damper. Each tower has a well-type manometer containing oil of unity specific gravity to measure the pressure drop between

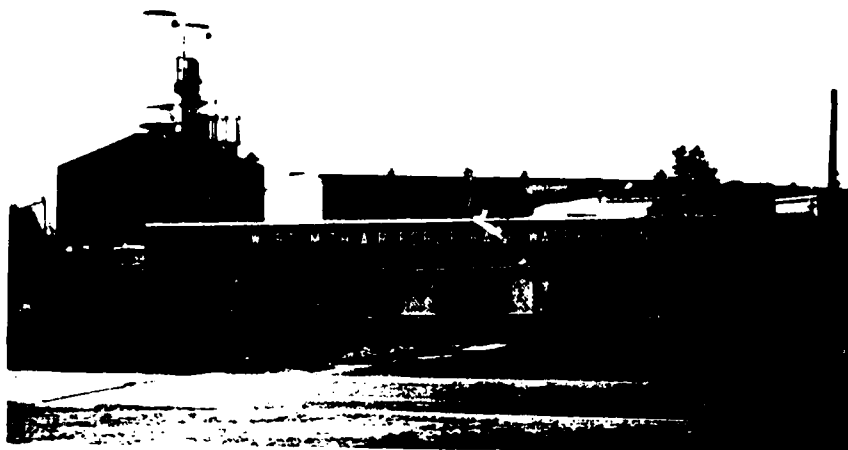


Figure 7. Wurtsmith AFB Packed-Tower Air Strippers and Water Treatment Facility.

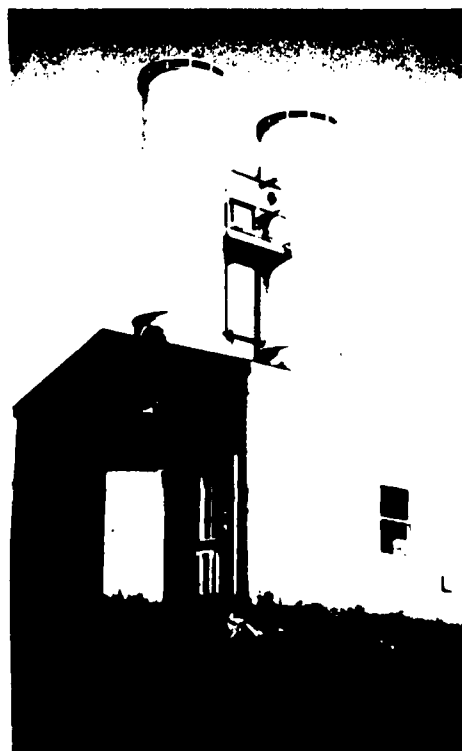


Figure 8. Wurtsmith AFB Packed-Tower Air Strippers.

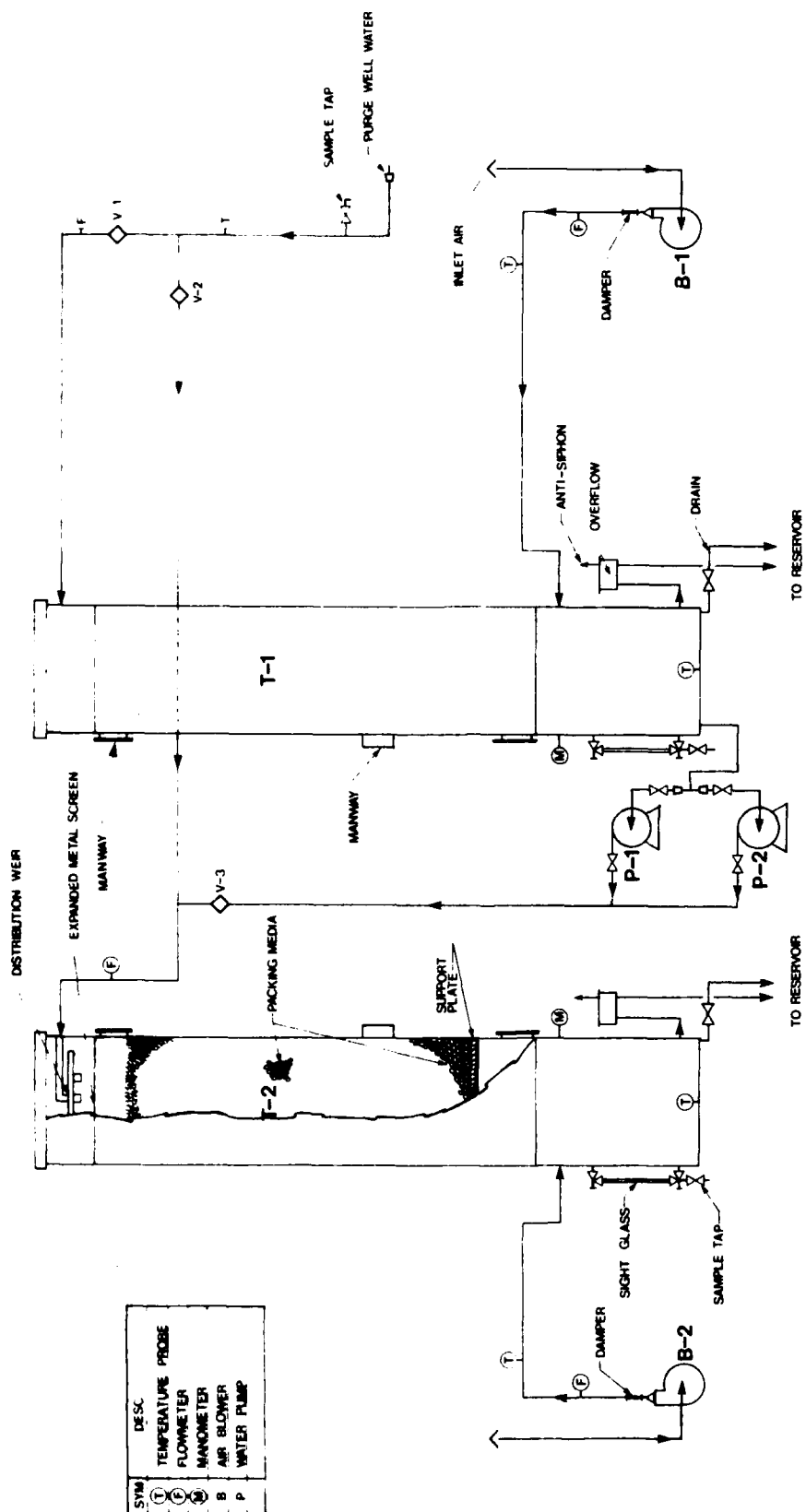


Figure 6. Prototype Packed-Tower Process Flow Schematic.

SECTION III

AIR-STRIPPER SYSTEM DESCRIPTION

A. SITING AND WATER FLOW SCHEME

The Air Force contracted CKS Engineers Inc., Warrington, PA, to design and build the air strippers onsite. Two packed towers were built to give the flexibility of either parallel or series operation. The process flow schematic is shown in Figure 6. The air strippers are located next to the existing water treatment plant to take advantage of a power supply and a 757,000-liter (200,000-gallon) underground reservoir. The five purge wells (Figure 1) were tied into a single pipeline to supply about 4540 L/min (1200 gal/min) of water to the strippers. A pressure-proportioning valve diverts any water that is not going to the air strippers into the reservoir. This allows continuous operation of the purge wells when the air strippers are shut off. The effluent water from the air strippers drains into the reservoir, which also contains spargers for additional TCE removal. The effluent water from the reservoirs passes through a series of carbon adsorption units before being discharged to nearby Van Etten Creek. The carbon is used to ensure the 1.5 ppb discharge level is met.

B. PACKED TOWER DESCRIPTION

Figures 7 and 8 show the packed-tower air strippers (Figure 6 also shows a cutaway view of one packed tower). The towers are structural carbon steel about 9 meters (30 feet) high and 1.5 meters (5 feet) in diameter, coated inside and out with a durable polyurethane paint. The design specifications call for corrosion and rust protection for a minimum lifetime of 25 years. Originally, they were packed with 0.3 meters (1 foot) of 25-millimeter (1-inch) polypropylene Pall rings on top of the support plate, followed by 5.2 meters (17 feet) of 16-millimeter (5/8-inch) Pall rings. In May 1983, the small rings were replaced with 25-millimeter (1-inch) Pall rings (Section V). An expanded metal grid lies between the top of the packing and the water distribution weir to prevent birds from nesting on the packing during shutdown periods. A manway at the top of the tower allows access to the top of the packing, while another manway is located just above the support plate. Both have glass viewports. A small access port is located below the support plate for viewing the underside of the plate. An 1890-liter (500-gallon) wet well

TABLE 1. ORIGINAL FULL-SCALE DESIGN SPECIFICATIONS

WATER FLOW:	<u>PARALLEL</u>	2270-4540 L/min (600-1200 gal/min)
	<u>SERIES</u>	1135-2270 L/min (300-600 gal/min)
AIR FLOW:	Nominal volumetric air/water ratio of 10 to 25; 11-58 m ³ /min (300-2000 ft ³ /min) throughout water flow range	
EFFICIENCY	<u>PARALLEL</u>	>90% removal at 10°C
	<u>SERIES</u>	>99% removal at 10°C
OPERATING TEMPERATURES:	<u>WATER</u>	10°C (50°F)
	<u>AIR</u>	-25 TO 25°C (-13° TO 77°F)
INSTRUMENTATION:	<u>WATER</u>	
	FLOW SENSITIVITY	± 95 L/min (25 gal/min)
	TEMPERATURE	0 to 50 $\pm 1^\circ\text{C}$ (32 to 122 $\pm 2^\circ\text{F}$)
	<u>AIR</u>	
	FLOW SENSITIVITY	± 1.01 m ³ /min (35 ft ³ /min)
	TEMPERATURE	-50 to 50 $\pm 1^\circ\text{C}$ (-58 to 122 $\pm 2^\circ\text{F}$)
	<u>TOWER PRESSURE DROP</u>	
	MANOMETERS	0 to 41 ± 0.3 cm of water (0 to 16 ± 0.1 inches)

volumetric flow rate of the water to be treated yields the required volume of packing. Selection of packed-bed depth and tower diameter depends on standard tower sizes and allowable hydraulic loads on the packing. Some additional laboratory experiments are described in Appendix A.

B. FULL-SCALE DESIGN SPECIFICATIONS

The decision to proceed with a full-scale packed-tower air stripper was based on these laboratory studies which demonstrated the feasibility of high-efficiency removal of TCE. The design specifications for the full-scale unit are given in Table 1. However, several uncertainties remained. Large-scale air-stripper operations had not been documented in the literature. The scale-up from 38 to over 4540 L/min (10 to over 1200 gal/min) was unconfirmed. Since temperature effected removal efficiencies, it was uncertain how the towers would operate during the Michigan winters. To fully evaluate air-stripping technology and identify any operational anomalies, the following objectives were set: determine scale-up factors for the full-scale unit, determine temperature effects on operation during subzero weather, and evaluate operational and maintenance needs. Although the air stripper was designed full-scale, the instrumentation and flow controls were kept simple so a research evaluation of the stripper's performance could be made.

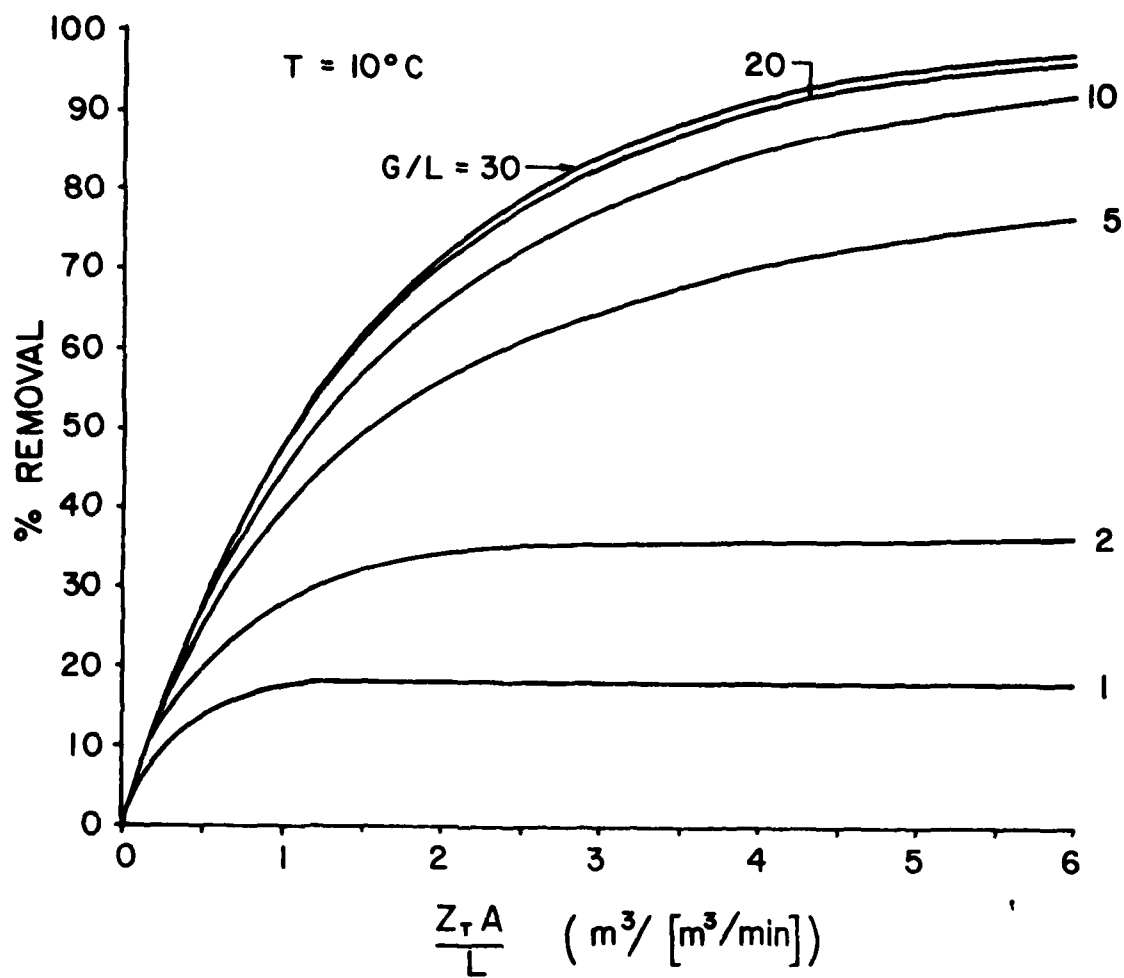


Figure 5. Predicted Percent Removal of Trichloroethylene for 16-Millimeter Pall Rings (Reference 7).

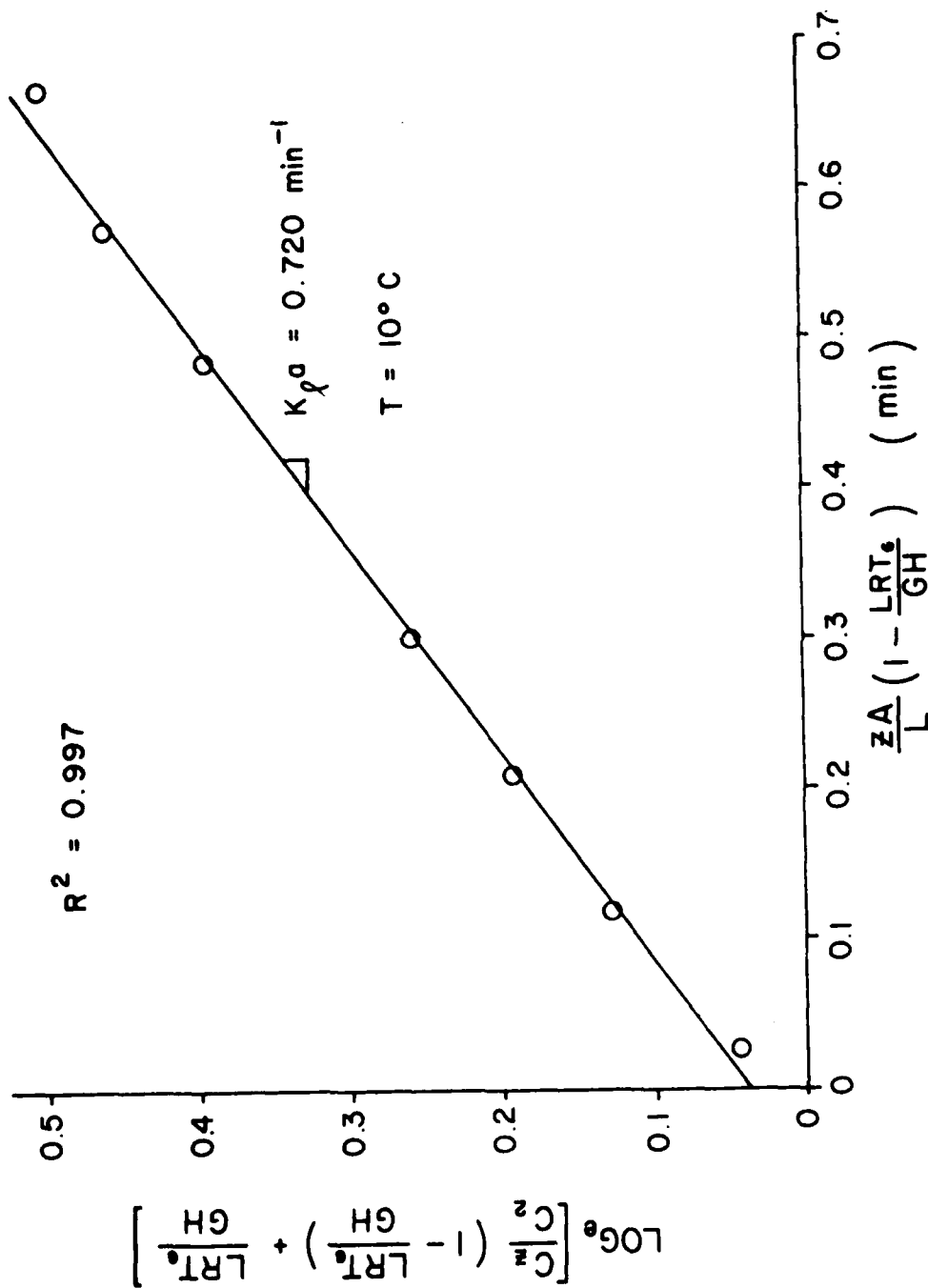


Figure 4. Typical Mass Transfer Coefficient Determination Plot (Reference 7).

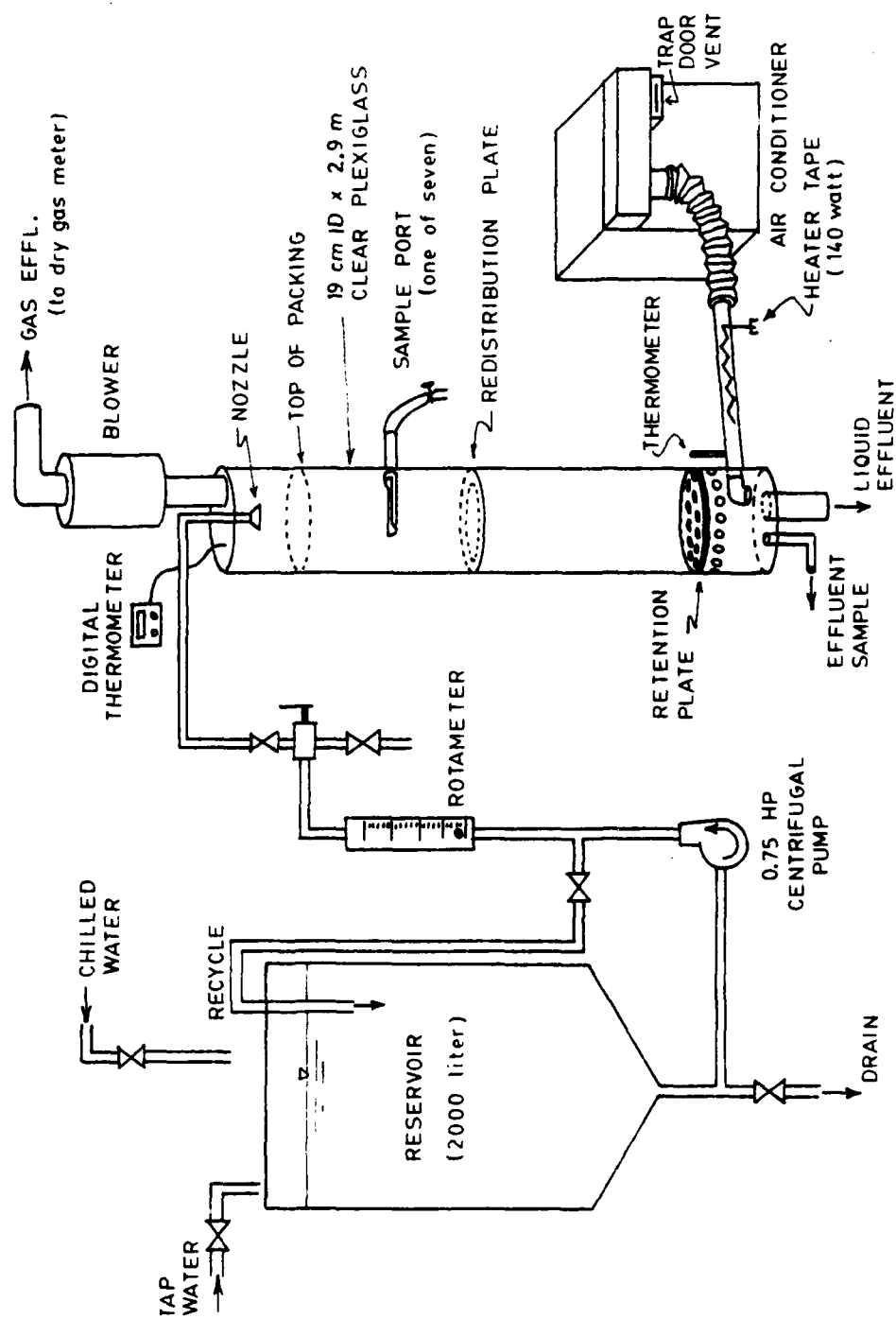


Figure 3. Laboratory Packed-Tower Air Stripper (Reference 7).

SECTION II

PACKED TOWER DESIGN

A. LABORATORY ANALYSES

Before the packed towers could be properly designed and built, laboratory studies were needed to investigate the removal efficiencies for trichloroethylene and determine mass transfer coefficients. A 19-centimeter (8-inch) inside diameter, 2.9-meter (10-foot) high, Plexiglas® column was constructed (Figure 3). The column was randomly packed with 2.5 meters (8 feet) of 16-millimeter (5/8-inch) polypropylene Pall rings. Known concentrations of TCE in water were made up in a 2000-liter (530-gallon) storage tank and pumped to the column at flow rates of up to 38 L/min (10 gal/min). Sample ports at about 0.3-meter (1-foot) intervals on the column allowed collection of water samples for TCE analysis. Gossett (Reference 7) showed that the concentration profile over the length of the column, when plotted with other parameters (Appendix A and Figure 4), gave the mass transfer coefficients. Liquid and air temperatures were varied from 10-30 °C (50-86 °F).

Combining removal efficiencies and equations for packed column performance, Gossett developed graphs for determining the necessary volume of packing. An example graph is shown in Figure 5 where G/L is the volume-to-volume ratio of the air and water flows, L is the volumetric water flow rate, Z_T is the depth of packing, and A is the cross-sectional area of the packed column. The temperature dependence of both Henry's Law Constant and mass transfer coefficient makes graphs at various temperatures necessary. The family of curves shows removal efficiency depends on the air-to-water ratios up to a point where maximum rate of transfer is reached. This point corresponds to the plateau region of the curve. Selection of air-to-water ratio is usually a trade-off between operational costs for high air flows and capital costs for larger columns (more packing) or multiple columns at low air-to-water ratios.

The data in Figure 5 can be used as the first step in designing a packed column. Using the desired removal efficiency at the proper water temperature, a value of $Z_T A/L$ is obtained from the graph. Multiplying this value by the

to achieve parts per billion effluent concentrations. Both Henry's Constants and mass transfer rates were unverified at these low concentrations. This information was necessary to design efficient packed towers and evaluate their performance.

1. Diffused aeration consists of sparging compressed air through a body of water. The contaminant is transferred to the air bubbles and exhausted to the atmosphere. The EPA and other civilian groups had investigated the process and recommended its application (Reference 4) where concentrations were very low and only 50-85 percent removal was needed. Diffused aeration is usually not very efficient because the small interfacial area between the air bubbles and bulk liquid and short contact times limits the transfer of the organic to the air.

2. Countercurrent contacting consists of flowing water down through a packed column while forcing air upward. The packing material, typically an open-structured plastic, increases the transfer of the contaminant to the air by increasing the interfacial area and contact times. The operating ranges of packed columns generally require less energy to move the air and water and have more operational flexibility than diffused aeration. Cocurrent contacting of the air and water can also be done, but this process is less efficient than countercurrent (Appendix A).

Air stripping is not a new technology and has been widely used in chemical engineering for both absorption and desorption of gases in liquids. Although some successes were reported in the literature (References 5,6), the air-stripping process was essentially unproven for full-scale operation for volatile chlorinated solvents like TCE.

The potential for an organic to be air-stripped can be determined from its Henry's Law Constant. This parameter is a ratio of the organic concentration in the air above the liquid to the concentration in the liquid phase at equilibrium. The greater the Henry's Constant, the easier to transfer the organic from the liquid to the gas. Generally, the Henry's Constant increases as the organic solubility in water decreases and increases as the temperature increases.

Countercurrent packed columns were chosen for further study because of their efficiency and similar costs compared to diffused aeration. However, packed-column air stripping had not been demonstrated on a groundwater supply

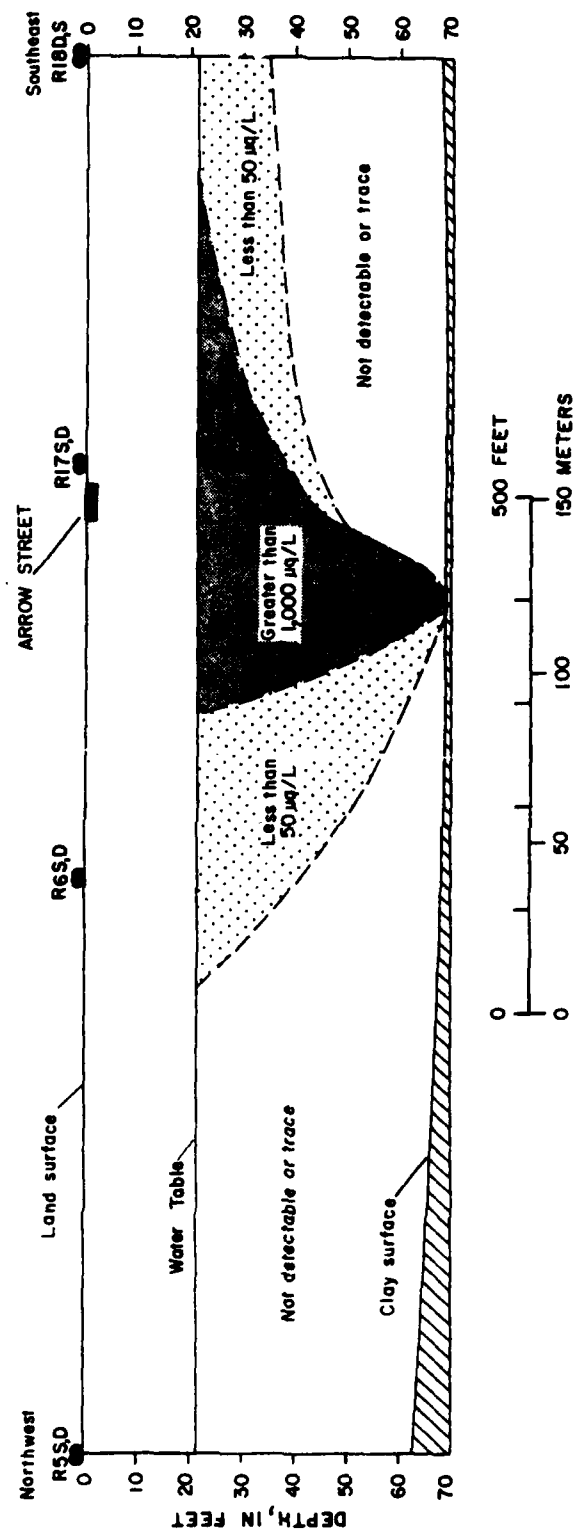


Figure 2. Cross Section of the Wurtsmith AFB Trichloroethylene Contamination Plume (Reference 1).

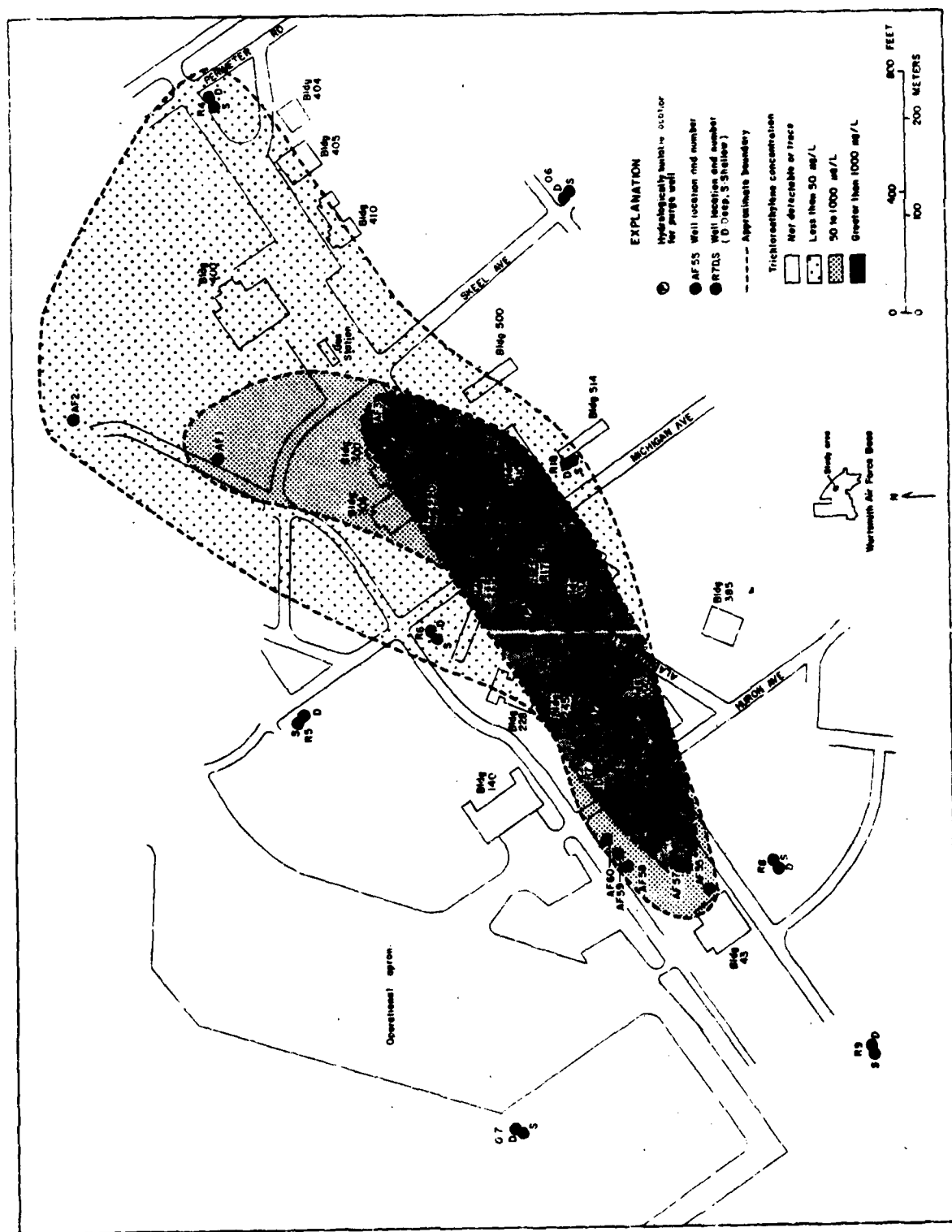


Figure 1. Wurtsmith AFB Trichloroethylene Contamination Plume (Reference 1).

the wet well and the top of the tower across the packed bed. Before the blower motors were changed, air flow rates were measured with Eagle Eye Airbar® flow meters. These meters sense a pressure differential caused by the air flowing past a sensor element. A reading was taken from the meter and converted to a volumetric flow rate with a conversion table supplied by the manufacturer. After the motors were changed, the flow rates were out of range for the meters. A well-type manometer was used to measure the pressure drop, and the manufacturer's pressure drop vs flow rate calibrations used to calculate the air flow rate. The manufacturer confirmed that the new flow rates were still within the range of calibration curves. To get the accuracy over the air-flow range of interest (Table 1), both 20- and 38-centimeter (8- and 11-inch) diameter air intake stacks were made. Each stack contained an Airbar® sensing element and had its own calibration curve. The stacks were manually lifted into place on a pedestal on the outside of the building using a block and tackle.

Similarly, the water flow rates were measured with Eagle Eye Annubar® flow meters. Meter readings were converted to flow rates using the manufacturer's calibration curves. The meters gave readings from 1135 to 2365 L/min (300 to 625 gal/min).

D. OPERATION

The air strippers can be operated in either parallel or series. In parallel operation, 4540 L/min (1200 gal/min) of water can be processed by dividing the flow evenly between the two columns (on Figure 6, Valves 1 and 2 open, 3 closed). In series operation, only 2270 L/min (600 gal/min) can be treated (Valve 2 closed, 1 and 3 open). As the water in the wet well of Tower 1 reaches the top of the overflow, the two intertower pumps (P-1 and P-2) automatically start. The water is moved from the bottom of Tower 1 to the top of Tower 2. By adjusting Valve 3, the water level in the wet well can be balanced. During series operation, the drain valves are closed, while in parallel operation they are opened slightly. Too much water flowing through the overflow box blocks the antisiphon tube, causing siphoning and draining of the wet well. The air flow can then escape through the drains instead of being forced up the tower.

Higher trichloroethylene removal can be accomplished through series operation than with parallel operation. In series, the same volume of water is "double-stripped" since it passes through twice as much packing material and has more contact with air than in parallel flow. Parallel operation only provides a "once-through" flow of the water.

SECTION IV

ONSITE LABORATORY SETUP AND SAMPLING PROCEDURES

A. LABORATORY SETUP

To evaluate the performance of the air stripper, analyses of the TCE concentrations were needed with a short turnaround time. Due to the location of Wurtsmith, local laboratory analyses were not available. Therefore, onsite analytical procedures and sampling techniques were developed to give accurate concentration levels. The analytical method chosen was direct headspace analysis on a gas chromatograph (GC) using a flame ionization detector after the method of Dietz and Singley (Reference 8), as modified by Gossett (Reference 7). Standards were prepared by saturating organic-free water with trichloroethylene (literature value of 1100 ppm at 25 °C: Reference 9). This stock solution was successively diluted to give various concentrations. The headspaces above these solutions were analyzed on the GC and the resulting peak heights correlated to the concentrations. Thus, the linearity and sensitivity of the GC were verified. Typically, this method allowed detection of TCE concentrations in the water as low as 1 ppb. A more detailed discussion of the standard preparation technique is given in Appendix B.

B. SAMPLING PROCEDURES

Obtaining accurate and repeatable samples was a critical factor for a successful performance evaluation of the air strippers. Since the method developed during the laboratory studies proved reliable, the same technique was employed in the field. Two hundred and forty milliliter, amber-colored sample bottles with Teflon®-lined silicone septa in screw caps were used. A 100 mL graduated cylinder was filled with 120 mL of water and marked. A small hole was drilled at this level to ensure the same amount of liquid would be placed in the bottles for each sample. As the samples were taken, the bottles were immediately capped and labeled.

Back in the laboratory, the bottles were shaken on a shaker table for at least 5 minutes to allow temperature equilibrium. Once shaken, the bottles were allowed to rest for about 1 minute, to allow the headspace to equilibrate. One mL of headspace was withdrawn in a gas-tight syringe through the

bottle's septum and injected into the GC. Each bottle was sampled at least twice, and the peak heights averaged. Using the calibration curves from the standards, the TCE concentration was determined. A more detailed discussion is given in Appendix B.

SECTION V

PERFORMANCE EVALUATION

A. INTRODUCTION

The air-stripping system was completed in May 1982, and evaluation continued until May 1983. Although the strippers performed better than expected, the decision was made to return exclusively to the activated carbon to treat the purge well water to comply fully with the court mandate. Since the carbon usage estimates were based on the existing trichloroethylene levels and the carbon equipment rental contracts were set for 1 year, it was not cost-effective to operate the strippers to reduce the TCE concentration entering the carbon units. Litigation is underway to have the air strippers accepted as the sole cleanup process for the aquifer. The following discussion is given chronologically to document the performance evaluation and changes made to the system.

B. INITIAL TESTING

The initial check-out testing and performance evaluations of the air strippers were done on 5 and 6 May 1982. The test provided preliminary data on removal efficiencies and familiarized Wurtsmith personnel with the system. The data summary in Table 2 shows the excellent performance of the strippers. Trichloroethylene removal of 97 to 99.4 percent was achieved in parallel operation (2270 L/min (600 gal/min) each tower) and greater than 99.9 percent in series. The TCE levels entering the air strippers varied from 8900 to 6750 ppb, (an average concentration of 7770 ppb) which was nearly four times the expected levels. The inlet air temperatures for the low air-to-water ratios were generally higher than those for the high ratios. Closing down the blowers' dampers to throttle back the air flow caused the air to heat up.

Figure 9 shows the percent of TCE removed as a function of hydraulic loading rate and volumetric air/water ratios (G/L). A loading rate of 1.34 m³/min/m² corresponds to a water flow rate of 2270 L/min (600 gal/min). As expected, the higher the G/L, the greater the removal, although the advantages of increasing the G/L beyond 25:1 begin to diminish. The higher the water loading rate the shorter the air/water contact time and, hence, reduced removal.

TABLE 2. MAY 1982 AIR STRIPPER PERFORMANCE DATA

<u>Water Flow</u> <u>(L/min)</u>	<u>Vol Air-to-</u> <u>Water Ratio</u>	<u>Percent Removed</u> <u>(Parallel)</u>	<u>Percent Removed</u> <u>(Series)</u>
1135	10	95	99.8
1700	10	94	99.8
2270	10	86	96.0
1135	18	98	99.9
1700	18	97	99.9
2270	18	90	99.7
1135	25	98	99.9
1700	25	98	99.9
2270	25	98	99.9

Average influent concentration 7770 ppb
 Water temperature 11°C (52°F)
 Air temperature range 20-35°C (68-95°F)

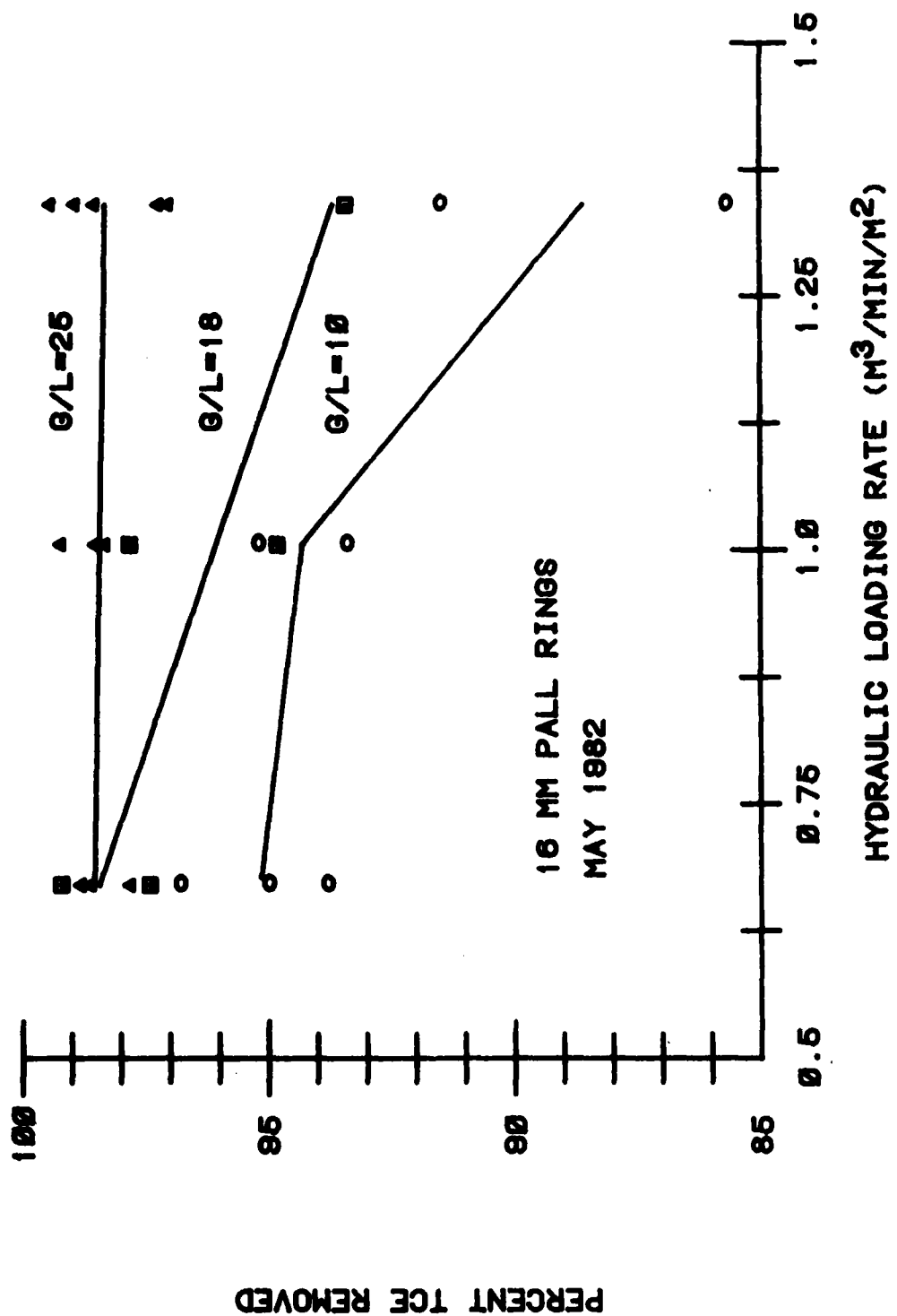


Figure 9. Packed Tower Performance (May 1982).

Upon completion of these tests, the air stripper units were left operating in parallel and were monitored by Wurtsmith water treatment plant personnel. The water flow of 3780 L/min (1000 gal/min) was evenly divided between the two towers with an air-to-water ratio of 25:1.

C. WARM WEATHER TEST

Warm weather operational data, obtained from 6 to 27 August 1982, verified the May performance results. A summary of this data, Table 3 and Figure 10, shows the percent of TCE removed versus hydraulic loading rate and air-to-water ratios. As in May, removal was excellent, despite the unusual problem of biological growth in the towers. This problem and subsequent cleaning of the packing is discussed in Section VI. A comparison of the August performance to that of May (Figure 9) and January (Figure 11) shows that the August performance is lower. Apparently removing the packing disturbed the bed enough to cause the noticeable differences in removal efficiency. However, the effects are short-lived because May and January performance is similar. Because of the drawdown around the wells and the reclassification of sand around their casings, total purge well output was down to 3600 L/min (950 gal/min) by August.

D. WINTER TEST

The winter tests were performed between 18 January and 1 February 1983 to confirm the performance of the air strippers in subzero weather. The coldest temperature recorded during the test was -15°C (5°F) but the blowers warmed the air to -5°C (23°F). Still, there was no evidence of icing and, as shown in Table 4 and Figure 11, no noticeable effect on performance.

Figure 11 shows the percent TCE removed versus the hydraulic loading rate and volumetric air-to-water ratios. The same removal trends seen in May and August are evident. To compare the laboratory predictions (Figure 5) with the actual tower performance, the percentage of TCE removed in the towers was plotted against various values of $Z_T A/L$. Figure 12 shows these results with data from all three test periods. The prediction for G/L of 10 is very good, while the laboratory data underestimated the actual performance for G/Ls of 18 and 25. At the higher G/L ratios, the actual mass transfer coefficient in the towers is higher than predicted in the laboratory, giving more removal than expected. Figure 13 shows the estimated mass transfer coefficients, calculated

TABLE 3. AUGUST 1982 AIR STRIPPER PERFORMANCE DATA

<u>Water Flow</u> <u>(L/min)</u>	<u>Vol Air-to -</u> <u>Water Ratio</u>	<u>Percent Removed</u> <u>(Parallel)</u>	<u>Percent Removed</u> <u>(Series)</u>
1135	10	96	>99.99
1700	10	88	98.6
2270	10	82	97.0
1135	18	99	>99.99
1700	18	96	>99.99
2270	18	92	99.8
1135	25	99.9	>99.99
1700	25	98	>99.99
2270	25	94	99.9

Average influent concentration 1500 ppb
 Water temperature 11°C (52°F)
 Air temperature range 20-32°C (68-90°F)

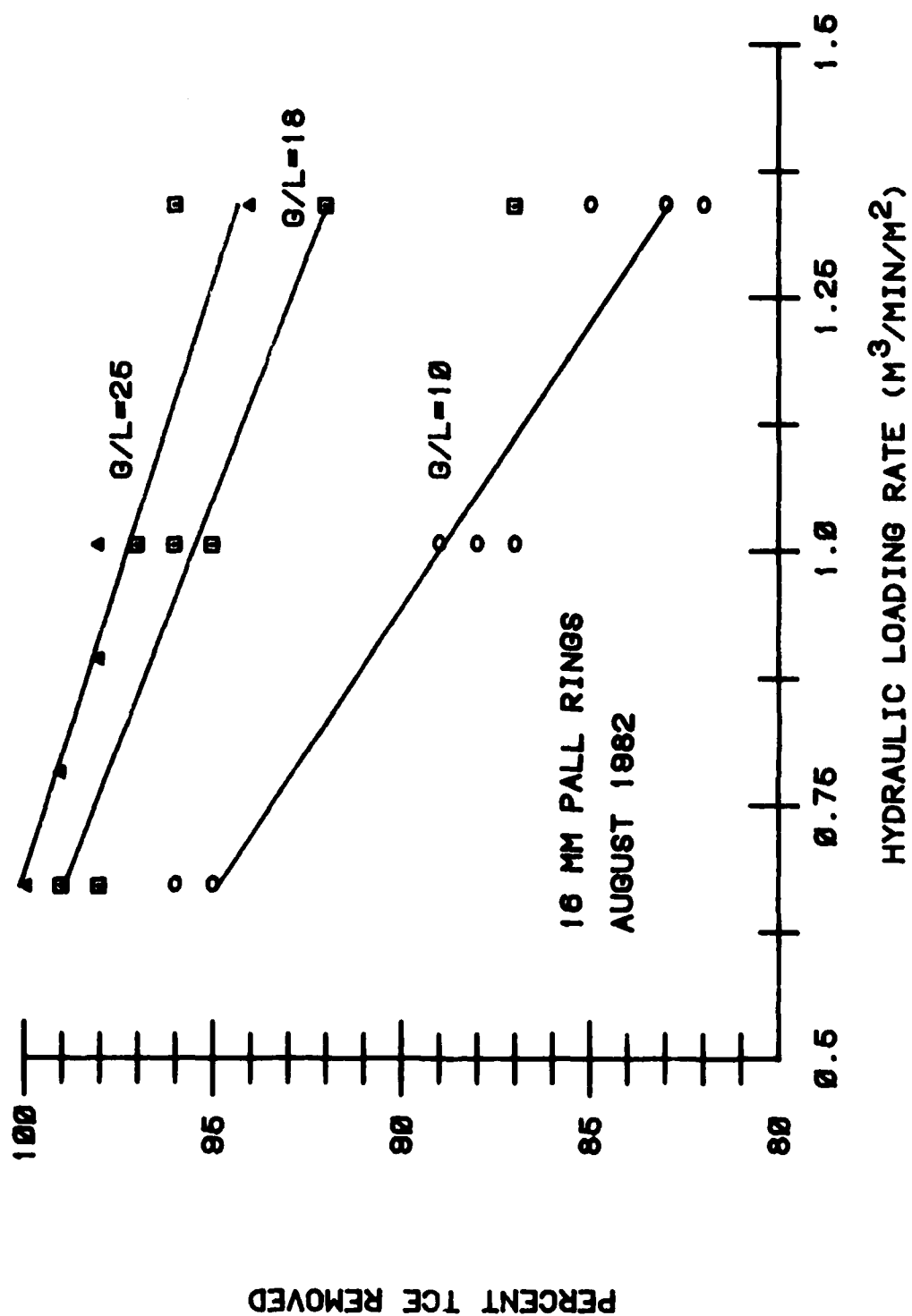


Figure 10. Packed Tower Performance (August 1982).

TABLE 4. JANUARY 1983 AIR STRIPPER PERFORMANCE DATA

<u>Water Flow (L/min)</u>	<u>Vol Air-to- Water Ratio</u>	<u>Percent Removed (Parallel)</u>	<u>Percent Removed (Series)</u>
1135	10	94	-
1700	10	95	-
2270	10	94	99.2
2575	10	91	99.2
1135	18	98	-
2270	18	99	>99.99
1135	25	99	>99.99
1700	25 ^a	99	>99.99

^a 28:1 first tower, 24:1 second tower

Average influent concentration 700 ppb

Water temperature 10°C (50°F)

Air Temperature range -5 to 12°C (23-54°F)

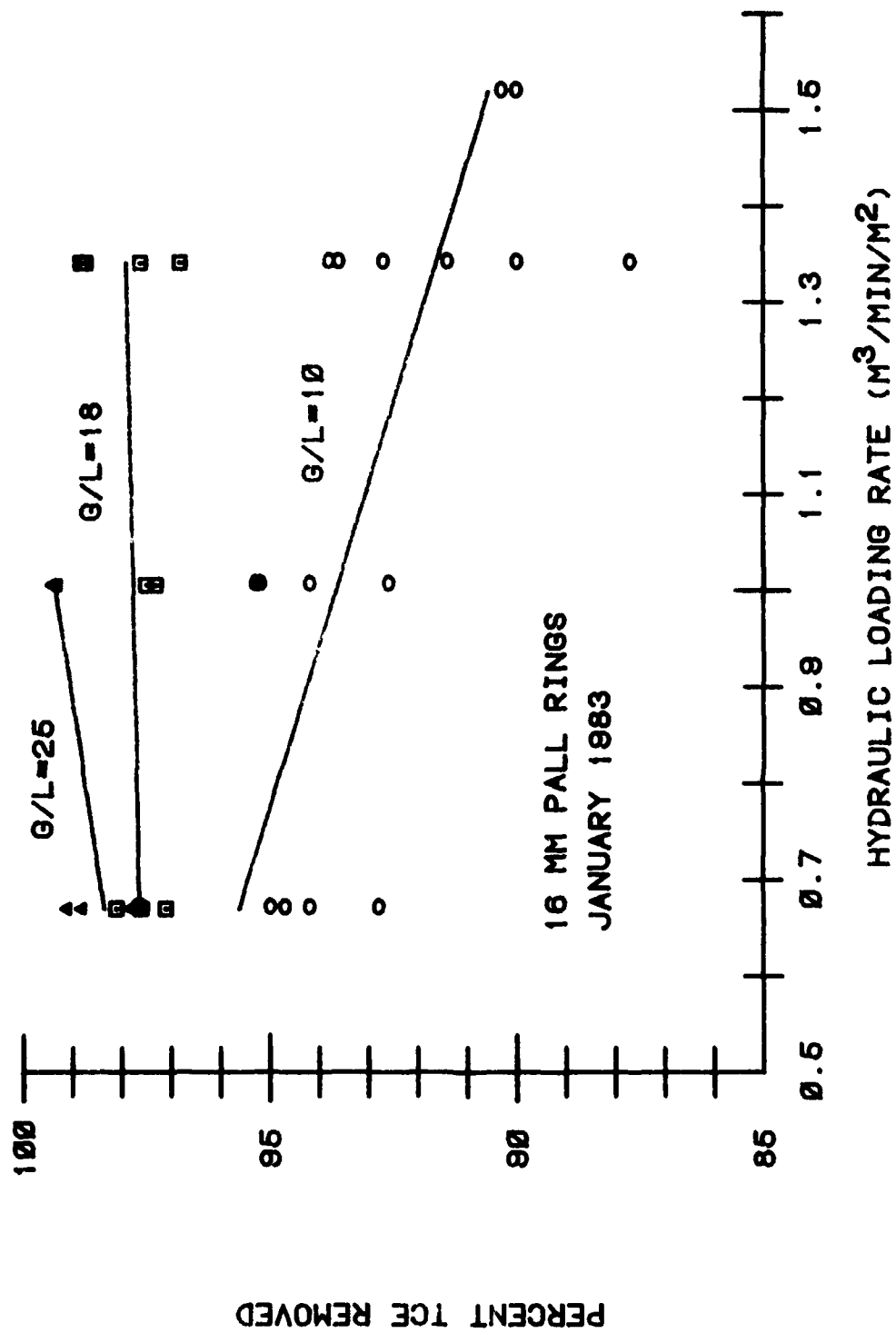


Figure 11. Packed Tower Performance (January 1983).

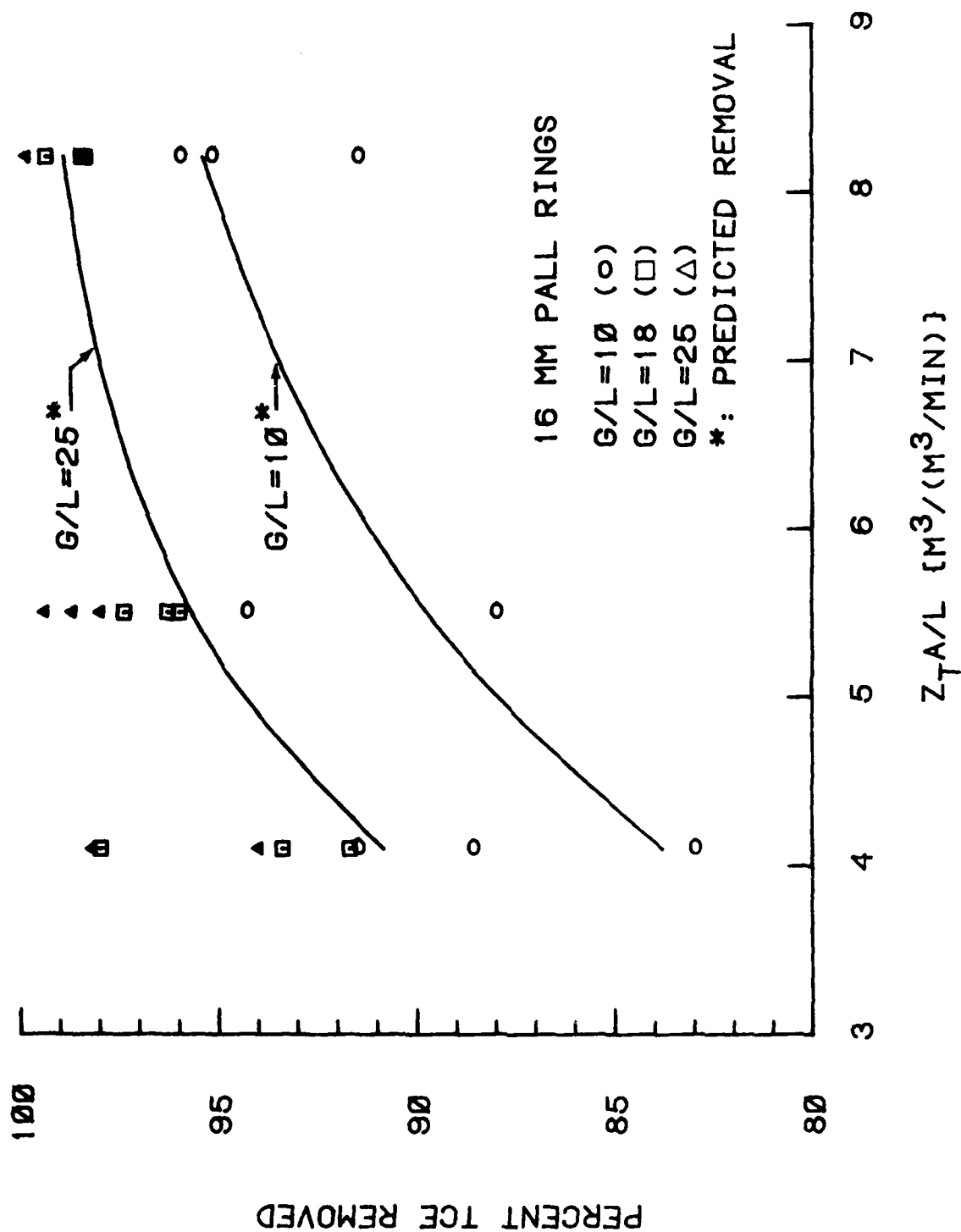


Figure 12. Actual Percentage of Trichloroethylene Removed Compared to Predicted Removal.

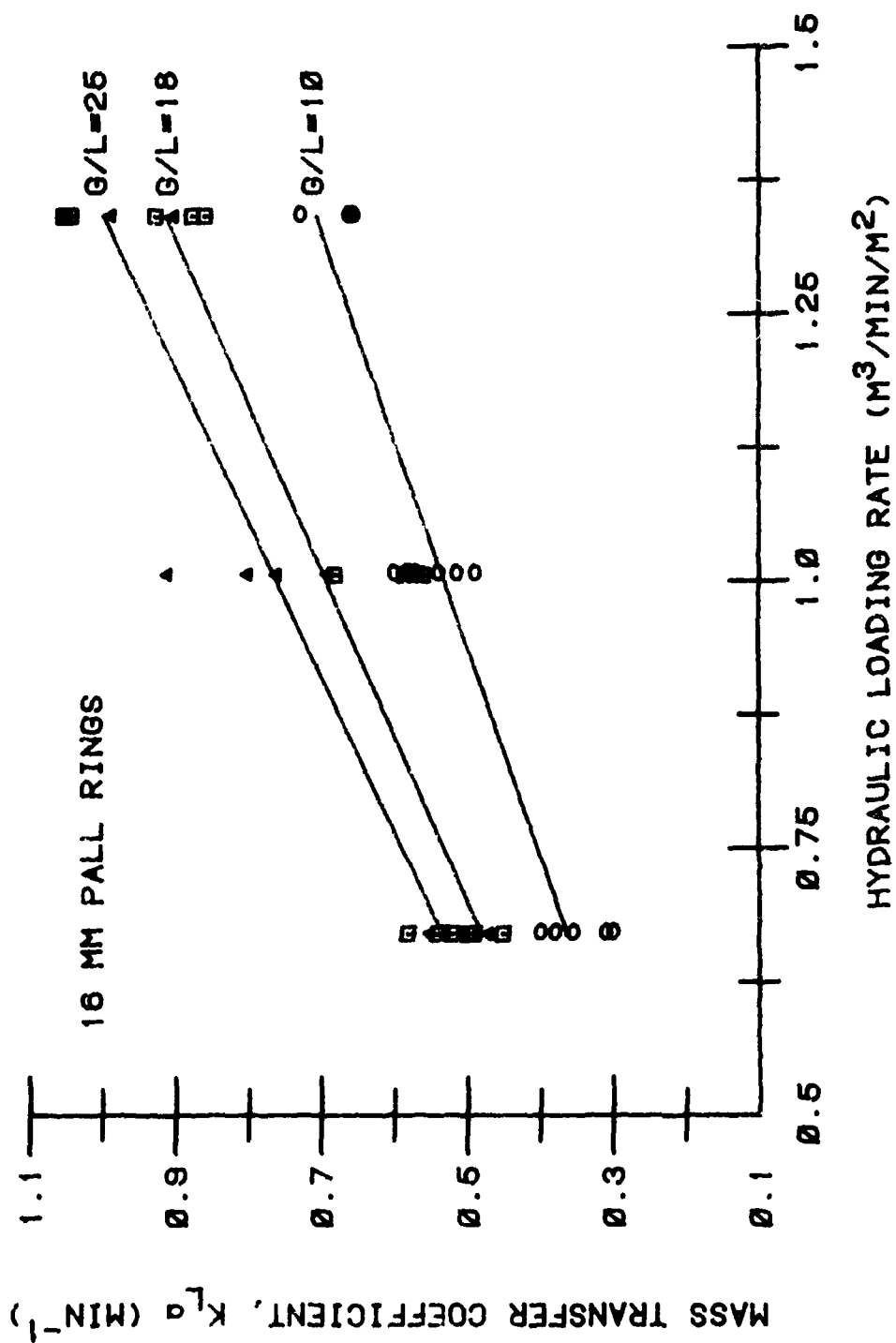


Figure 13. Estimated Mass Transfer Coefficients in the Packed Towers with 16-Millimeter Pall Rings.

SECTION VI

PACKING CLEANING AND MICROBIOLOGICAL STUDIES

A. PACKING CLEANING

After the initial testing on 5 and 6 May 1982, the air strippers were operated continuously by Wurtsmith water treatment plant personnel, who maintained a volumetric air-to-water ratio of 25:1 in each tower. Because of fluctuation in the water flow, some periodic adjustment of the air blowers' dampers were necessary. However, by July, the plant personnel found they could not achieve the desired air-to-water ratio, even with the dampers fully open. They then noticed that the pressure drop through the towers had reached 41 centimeters (16 inches) of water, the operational limits of the blowers. Inspection of the packing showed a dark brown biological growth in the tops of the towers. Plant personnel remarked that similar growth could be found in the well casings, and apparently it migrated into the packed towers. Chlorination with a solution of HTH® swimming pool chlorine introduced into the influent water line had little effect on the growth. The towers were operated at reduced flow rates until the August warm-weather tests.

In August, attempts were made to kill the growth and have it sluff off the packing. High concentrations of chlorine (from HTH®) were added to the influent water to the towers so at least 0.5 ppm residual was detected in the bottom of the towers. (The chlorine residual in the reservoirs was chemically removed with sodium thiosulphate before the water was released to the carbon adsorption system.) After 2 days, the packing was inspected again. Although it looked clean on top, after digging down about 1 meter (3 feet), the heavy growth was encountered. Since the towers could not be filled with superchlorinated water, the only alternative was to remove the packing and clean it.

The packing was removed with a compressed air eductor normally used for cleaning out leaves and debris from catch basins. The eductor is a venturi tube with compressed air causing a vacuum across its mouth. Working at the

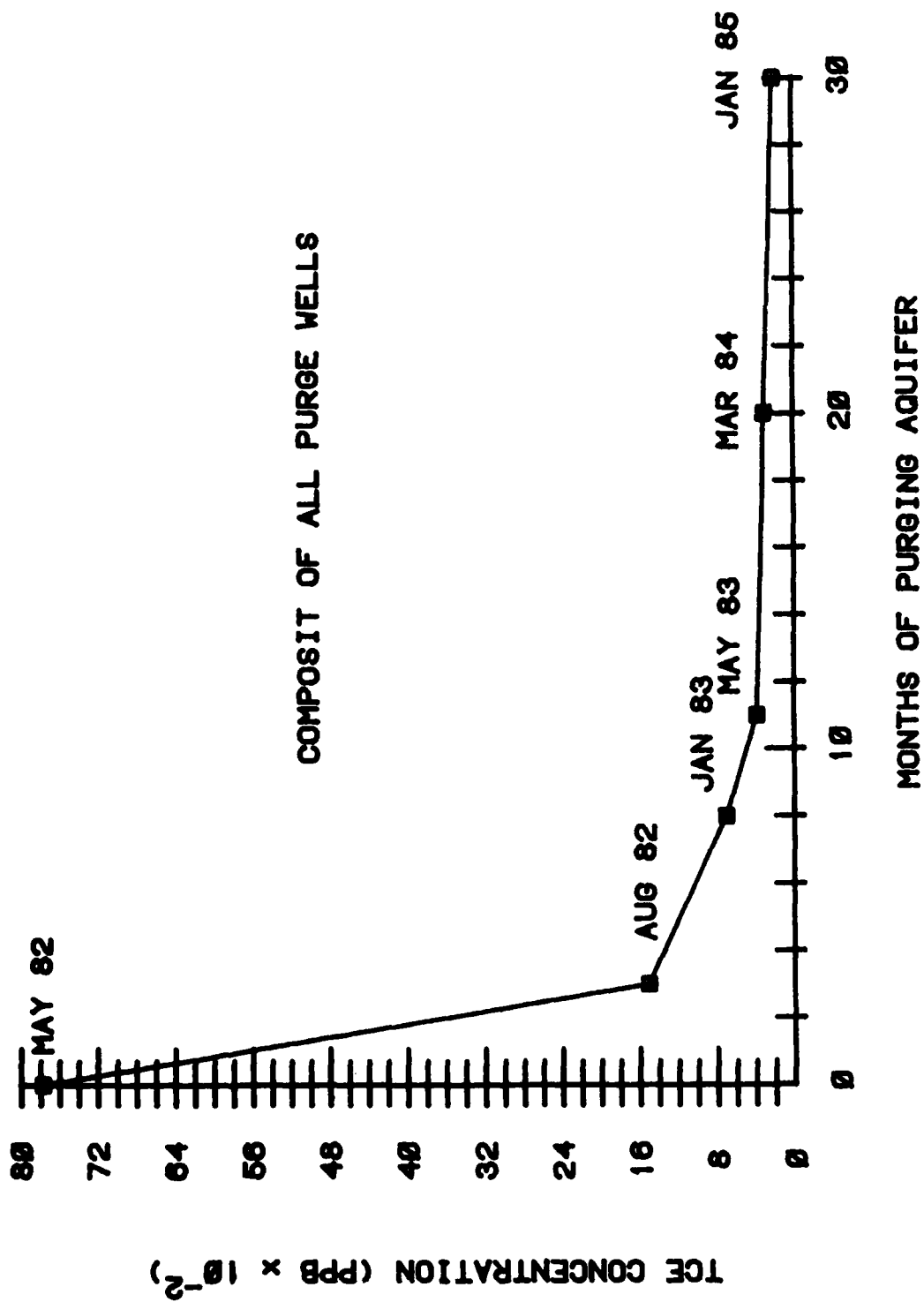


Figure 16. Purge Wells' Concentration Versus Pumping Time.

As of January 1985, the Michigan Department of Natural Resources had given approval to operate the air strippers, provided maximum discharge of TCE into the air did not exceed 63.5 g/h (0.14 lb/hour) or 562.5 kg/yr (1240 lb/year). To increase dispersion, the effective tower height will be increased by 3.1 meters (10 feet) by adding the length to the top of the existing towers.

I. PURGE WELLS' CONCENTRATION HISTORY

Figure 16 shows the TCE concentration found in the purge wells over time. As expected, the concentration decrease is rapid at first, then begins to slowly tail off. From May 1982 to January 1985, about 4.3 billion liters (1.14 billion gallons) of water were removed from the aquifer, with an average trichloroethylene concentration of 950 ppb. At these levels, about 2840 liters (750 gallons) of TCE has been removed. This amount, plus the estimated 2190 liters (580 gallons) purged by the U.S. Geological Survey between 1977 and 1981 (Reference 1), indicate that about 5000 liters (1300 gallons) had leaked into the aquifer.

TABLE 8. PACKED TOWER PRESSURE DROPS FOR 16- AND 25-MILLIMETER
FALL RINGS

Hydraulic Loading Rate ($\text{m}^3/\text{min}/\text{m}^2$)	G/L	Pressure Drop (Inches Water)		
		16mm (May 82)	16mm (Aug 82) ^a	25 mm (May 83)
0.67	10	-	0.5	0.3
	12	0.3	-	-
	18	0.7	0.7	0.5
	22	-	1.5	-
	25	1.4	1.7	-
	30	1.7	-	-
1.01	10	0.7	0.9	0.6
	14	-	1.8	-
	18	2.3	2.6	1.4
	22	-	2.9	-
	25	3.7	3.7	2.8
	30	5.2	-	-
1.34	10	2.0	1.6	-
	12	-	2.3	-
	14	-	3.6	-
	18	4.7	5.2	3.7
	22	-	8.5	-
	25	9.1	10.2	6.8
	33	-	-	15.5

^a After packing was cleaned

turbulence or air/water mixing). In this case, increasing the G/L above 25:1 may increase the removal efficiency enough to warrant the high air flow rates.

At the air-to-water ratios above 45:1, high pressure drops were again seen. The cause was finally found to be the expanded metal screen located between the top of the packing and the water distribution weir. This screen prevents birds from nesting in the towers during shutdown periods. As the water enters the distribution weir and overflows, it floods the screen. Under relatively low air flows (less than $60 \text{ m}^3/\text{min}$ ($2100 \text{ ft}^3/\text{min}$)), the air and water pass easily through the screen. Under high air flows (above $70 \text{ m}^3/\text{min}$ ($2450 \text{ ft}^3/\text{min}$)) and high water flow rates, the water restricts the air from passing through the screen. Spray could be felt and seen being blown out of the tops of the towers. Fortunately, the increased pressure drop does not effect the operational range of the blowers. Should the pressure drop become limiting, the grid could either be removed or its openings enlarged.

Table 8 shows the pressure drop in the packed towers for both the 16- and 25-millimeter (5/8- and 1-inch) Pall rings. The pressure drop for the 16-millimeter rings did not change significantly over time. As expected, the pressure drop for the 25-millimeter (1-inch) rings was less than the smaller rings at all water flow rates.

H. UNIT SHUTDOWN

The air-stripping system performance tests were concluded on 31 May 1983. This coincided with the end of the allowed 120-day test period without the carbon units. Since the original consent decree between the Air Force and the State of Michigan specified activated carbon as the treatment process, the carbon units were put back on-line. Since the Air Force had already negotiated a carbon rental agreement with fixed carbon replacement costs (Section VII), it was not economical to run the air strippers to reduce the TCE load on the carbon. The data from the year of performance testing was used by the Air Force to demonstrate the capability of packed-tower aeration to remove trichloroethylene to below 1.5 ppb. The ultimate goal is to replace the activated carbon with the air-stripping system. The towers were superchlorinated for several hours before being shutdown, and all purge well water diverted into the reservoir. The water lines were drained and the instrument lines purged. No other special procedures were done to "mothball" the system.

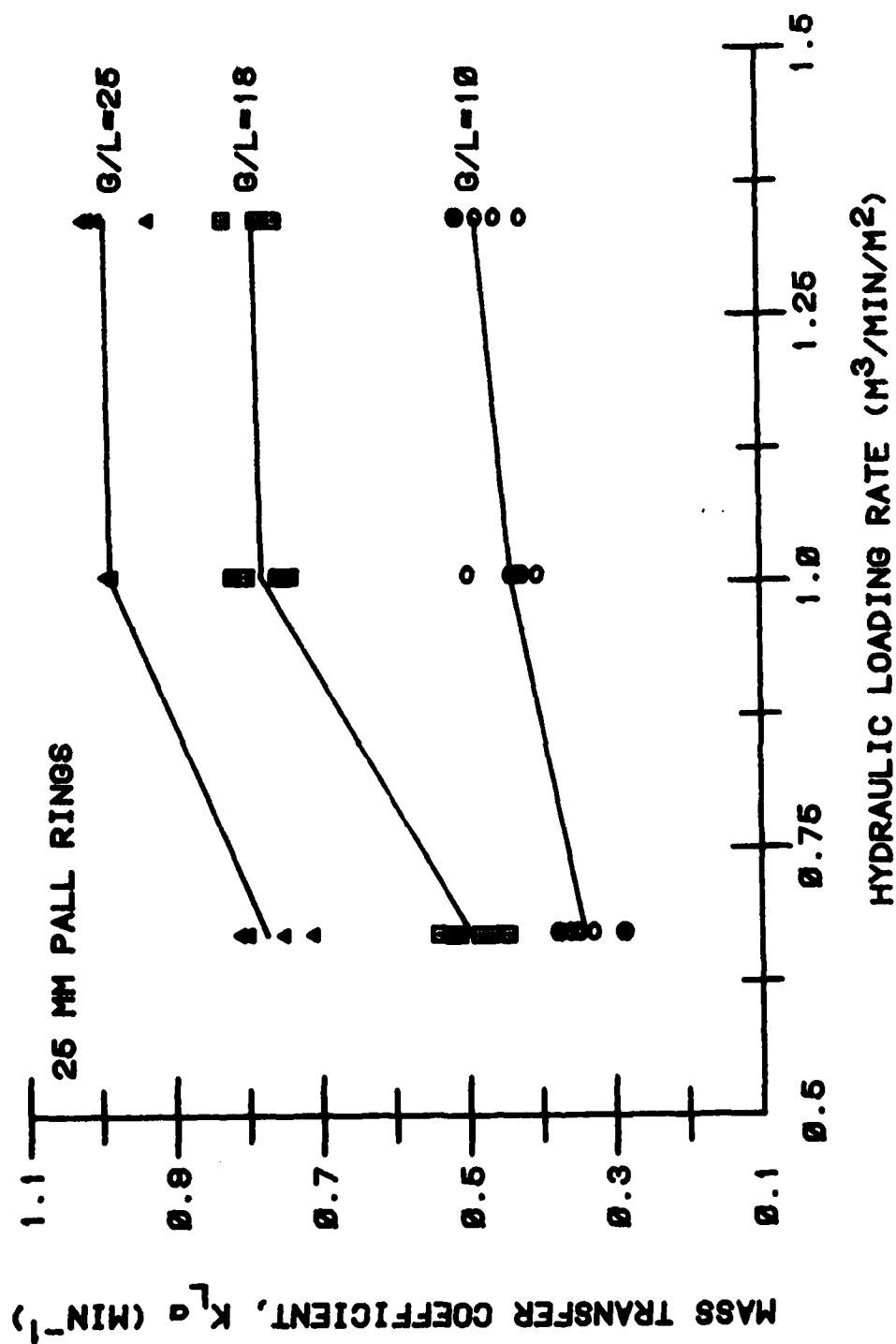


Figure 15. Estimated Mass Transfer Coefficients in the packed Towers with 25-Millimeter Pall Rings.

Table 7. May 1983 Air Stripper Performance Data

<u>Water Flow (L/min)</u>	<u>Vol Air-to- Water Ratio</u>	<u>Percent Removed (Parallel)</u>	<u>Percent Removed (Series)</u>
1135	10	94	99.6
1700	10	90	99.5
2270	10	92	99.3
1135	18	98	-
1700	18	99	>99.99
2270	18	99	>99.99
1700	25	99.5	-
2270	25	99.0	>99.99
1135	45	99.9	-
1700	45	99.8	>99.99

Average influent concentration 380 ppb
 Water temperature 11°C (52°F)
 Air temperature range 9-22°C (48-72°F)

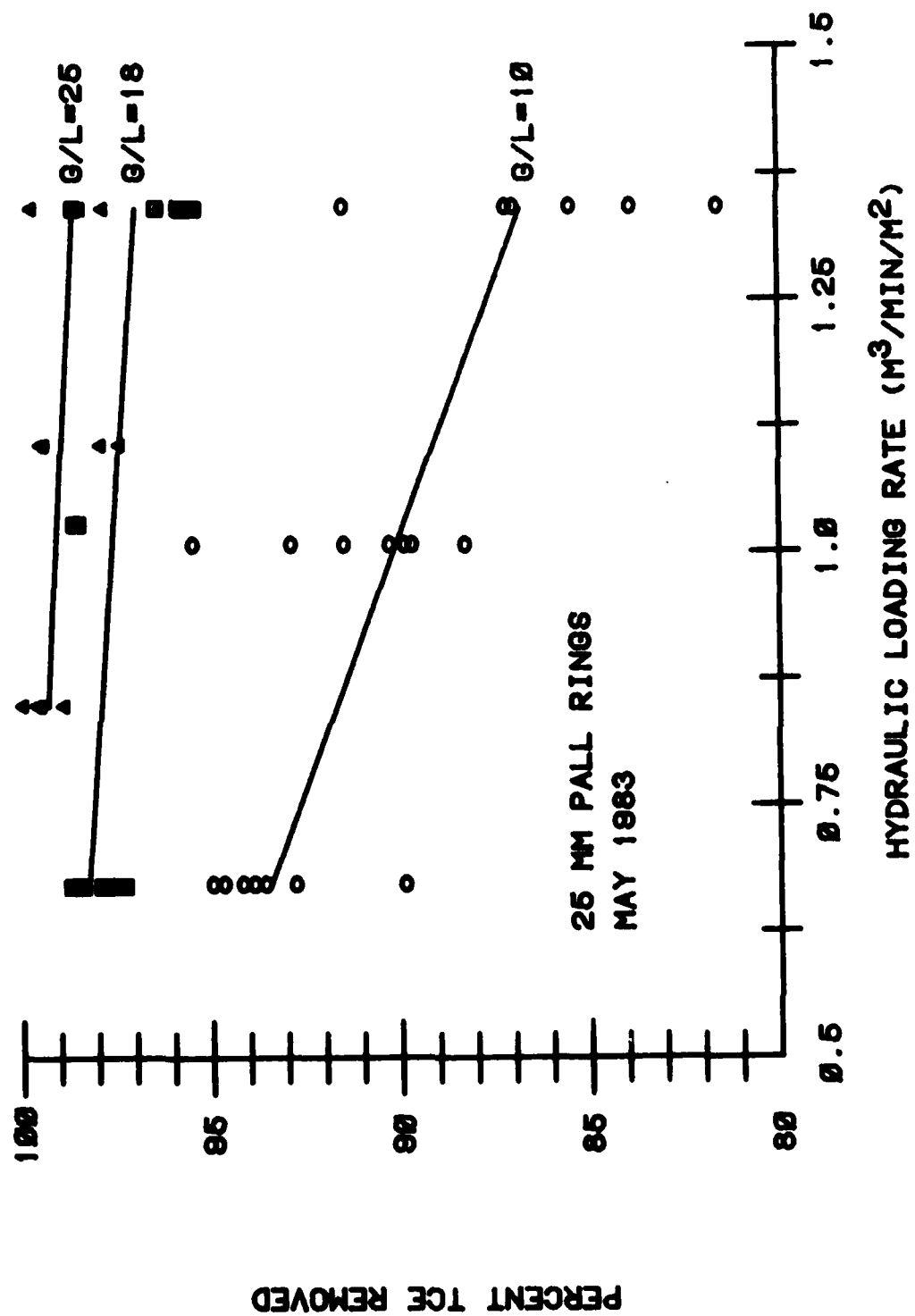


Figure 14. Packed Tower Performance (May 1983).

The first performance tests were an attempt to duplicate the flow conditions of August 1982 to compare the removal efficiencies between the two sizes of Pall rings. However, problems arose with both the air and water Annubars® (flow-measuring devices). The air Airbar® flow-sensing units had dirt in them, probably from a combination of airborne dust and physically changing the air intake stacks. Attempts to blow the dirt out of the sensors with compressed air, purge the instruments lines to the meters, and zero the meters were not totally successful. Since the larger motors produced more air flow than the meters were originally designed to register, the meters were eventually replaced with well-type manometers. The pressure differential readings were converted to flow rates using the manufacturer's calibration curves. The water Annubars'® flow sensors in the influent water lines were clogged with biological growth. Although the lines were purged, the meters themselves were sealed and some growth could still have been inside them. Even periodic cleaning of the sensor did not guarantee correct water flow readings at all times. This problem became particularly apparent during series flow operation, when the meter reading on Tower 1 would sometimes differ from that of Tower 2 by almost 40 percent, yet the water flows between the towers were balanced. Because of these problems, the data relating volumetric air-to-water ratios, water flow rates and removal efficiencies (Figure 14) are generally more scattered than the earlier tests.

The overall removal efficiencies show the air-stripping system is capable of meeting the 1.5 ppb level (Table 7). With the towers operating in parallel, the total purge well output of 3220 L/min (850 gal/min) could be treated. The influent trichloroethylene concentration averaged 380 ppb, and at a 45:1 volumetric air-to-water ratio, less than 1.0 ppb remained in the tower's effluent water. The same removal efficiency could be obtained by series operation and a water flow rate of 2270 L/min (600 gal/min) and a volumetric air-to-water ratio of 18:1.

As with the 16-millimeter (5/8-inch) packing, the estimated mass transfer coefficients were calculated (Figure 15). The data show the liquid-phase resistance limit was reached as the hydraulic loading increased, but the gas-phase resistance was appreciable. This could be due to the increase in the effective area of the packing with increased airflow (i.e., increased

TABLE 6. MODIFIED FULL-SCALE DESIGN SPECIFICATIONS

WATER FLOW:	<u>PARALLEL</u>	2270-4540 L/min (600-1200 gal/min)
	<u>SERIES</u>	1135-2270 L/min (300-600 gal/min)
AIR FLOW:	Nominal volumetric air/water ratio of 10 to 45; 11-107 m ³ /min (300-3700 ft ³ /min) throughout water flow range	
EFFICIENCY	<u>PARALLEL</u>	>90% removal at 10°C
	<u>SERIES</u>	>99% removal at 10°C
OPERATING TEMPERATURES:	<u>WATER</u>	10°C (50°F)
	<u>AIR</u>	-25 to 25°C (13° TO 77°F)
INSTRUMENTATION:	<u>WATER</u>	
	FLOW SENSITIVITY	± 100 L/min (25 gal/min)
	TEMPERATURE	0 to 50 $\pm 1^\circ\text{C}$ (32 to 122 $\pm 2^\circ\text{F}$)
	<u>AIR</u>	
	FLOW SENSITIVITY	± 1.01 m ³ /min (35 ft ³ /min)
	TEMPERATURE	-50 to 50 $\pm 1^\circ\text{C}$ (-58 to 122 $\pm 2^\circ\text{F}$)
	<u>TOWER PRESSURE DROP</u>	
	MANOMETERS	0 to 41 ± 0.3 cm of water (0 to 16 ± 0.1 inches)

TABLE 5. TCE REMOVAL FOR 25-MILLIMETER PALL RINGS (LABORATORY STUDIES)

<u>Hydraulic Loading Rate</u> <u>(m³/min/m²)</u>	<u>Air-To-Water</u> <u>Ratio (Vol:Vol)</u>	<u>AVG % TCE</u> <u>REMOVED</u>
0.86	27	92.3
	54	97.3
	75	98.5
	97	99.0
1.14	17	88.2
	23	91.2
	45	97.1
	50	98.4
1.35	18	86.6
	26	95.3
	35	97.0
	45	98.6
1.71	15	89.5
	18	95.5
	25	96.4
	45	97.2
	47	97.8

effect on removal efficiency was a concern. During February and March 1983, laboratory studies were done at the Engineering and Services Laboratory on the 25-millimeter (1-inch) rings, using a 30-centimeter (12-inch) diameter column. Overall TCE removal efficiencies were studied at hydraulic loading rates similar to those seen at Wurtsmith (Table 5). Although the water temperatures were warmer (16-20°C), the data confirmed that the same removal efficiencies could be obtained using the larger rings, but a higher volumetric air-to-water ratio (45:1) was needed than previously used (25:1). Changing the blowers was considered, but this would have involved a costly retrofit of the system. Fortunately, a simple blower motor change provided the needed extra air flow from the existing blower housing and damper system.

G. TOWER MODIFICATIONS AND PERFORMANCE

The air-stripping system was modified and performance tested from 9 to 27 May 1983. The 16-millimeter (5/8-inch) Pall rings were removed using the same method as cleaning (Section VI). The rings were dark brown to black at the top of the tower, changing to a lighter brown at the bottom. The tower walls were also a similar color. Analysis showed the color to be mainly oxides of iron and manganese. Apparently the chlorination promoted the oxidation of these minerals since the color was not seen prior to chlorination. The precipitates did not seem to effect the operation of the towers, although some blockage of the packing may occur over a very long time. Small clumps of biological growth were found in the top few feet of the packing, but not throughout, as before. Continuous chlorination controlled the growth. The support plate was severely clogged with pieces of broken packing and sand. The small pieces of packing, lodged in the weave of the support plate, prevented the small amounts of sand from the purge wells from passing through. With the water holes clogged, the water had to exit the plate through the air holes, causing the high pressure drop. The 16-millimeter (5/8-inch) packing was badly broken and, having no practical salvage value, was disposed of. The original 7.46-kilowatt (10-horsepower) blower motors were replaced by 11.19-kilowatt (15-horsepower) motors, which increased the maximum operational range (at maximum hydraulic loading rate) from 25:1 volumetric air-to-water ratio to 45:1 (Table 6).

polypropylene plastic becomes brittle below 4°C (40°F), and removing it from the towers caused the packing to break. The 25-millimeter (1-inch) packing apparently had more resilience and did not damage easily. More broken packing was found in Tower 1 because the packing was handled twice as much. The broken pieces of packing could have partially clogged the support plate or blocked the air passages through the packing, causing the high pressure drop. More importantly, the broken pieces may trap the biological mass, promoting its growth and replugging the towers. Thus, the decision was made to change the packing to 25-millimeter (1-inch) Pall rings because (a) they are sturdier than the smaller rings and could be cleaned again, if necessary, with little damage, (b) as a more open packing, any biological clumps may tend to pass through it more easily, and (c) the larger packing could handle higher water and air loading rates than the smaller rings.

E. EXTENDED 120-DAY TEST

Despite the pressure drop problem, the towers' ability to remove TCE to the 1.5 ppb discharge level set by Michigan was investigated. At the end of the regular performance evaluations in January 1983, the towers were operated in parallel at a 1630 L/min (430 gal/min) flow rate, each at a volumetric air-to-water ratio of 32:1. The trichloroethylene concentration was reduced from about 650 ppb to below 4 ppb in the towers (99.4 percent removal). By using the sparging system in the reservoir, the TCE levels were kept under 1.5 ppb. The onsite analysis was done for about 30 hours, and permission was obtained from the Michigan Department of Natural Resources to operate the system for an additional 30 days without the carbon. Wurtsmith's Bioenvironmental Engineering personnel conducted the sampling and sent split samples to the Engineering and Services Laboratory at Tyndall AFB, Florida, and the Occupational and Environmental Health Laboratory at Brooks AFB, Texas, for analysis. Since the air strippers and reservoir system showed consistent removal to below the 1.5 ppb limit, the test period was extended for a total of 120 days. The TCE concentration leaving the reservoir remained below 1.5 ppb throughout the entire test.

F. LABORATORY STUDY ON 25-MILLIMETER (1-INCH) PALL RINGS

Since the 25-millimeter (1-inch) rings have less surface area for mass transfer per volume of packing than the 16-millimeter (5/8-inch) rings, the

from the influent and effluent TCE concentration data, for all the 16-millimeter (5/8-inch) packing tests versus hydraulic loading. The trend of increasing K_{La} with increasing loading rate is expected, as is the slight increase in mass transfer with increased air rate (G/L). Thus, it appears that all the resistance to mass transfer is not exclusively in the liquid phase but some does occur in the gaseous phase as well (Appendix A).

The only significant problem was an unexpected 41 centimeters (16 inches) of water pressure drop through the towers. The maximum volumetric air-to-water ratio was 14:1 at 2270 L/min (600 gal/min) instead of the desired 25:1. The 25:1 ratio was obtained for the 1135 and 1700 L/min (300 and 450 gal/min) flow rates. The packing was inspected and found to be clean with some minor debris from the purge wells. The bottom of the support plate looked clean but growth appeared to be within the metal weaves of the plate and on the adjacent packing. After considering that biological growth may be present in the center of the tower, heavy chlorination (over 3 ppm) was applied for 2 days. The pressure drop did not change, although the packing appeared cleaner. A long piece of copper tubing was inserted into the tower from the top of the packing to check the pressure drop along the length of the tower. The pressure drop appeared linear with depth over the accessible portions of the tower, indicating that no one layer of packing was causing the pressure drop. Thus, biological growth did not appear to be the cause of the high pressure drop.

Further observation of the packing revealed many pieces to be broken or chipped, with small pieces of plastic dispersed within the packing. About 0.03 m^3 (1 ft^3) of packing was removed from the towers and visually inspected. Towers 1 and 2 had 45 and 24 percent of the 16-millimeter (5/8-inch) packing broken, respectively, but none of the 25-millimeter (1-inch) packing was broken. A representative from the packing manufacturer (Norton Company) said that while no studies had been performed to relate broken packing to pressure drop, one of their observations showed 20-25 percent broken caused 20-25 percent decrease in bed depth and a 20 percent increase in pressure drop. Both towers showed at most a 5 to 10 percent decrease in bed depth and almost a doubling in pressure drop. While no firm conclusions were reached about the pressure drop's source, the cause of the broken packing was due to the handling during cleaning (Section VI). According to the manufacturer,

top of the first tower, the eductor was used to suck up the packing. It was conveyed to a large dump truck through a short length of flexible duct connected to about 12 meters (40 feet) of 10-centimeter (4-inch) diameter PVC pipe. A fire hose was used to wash the packing in the towers, and near the bottom of the towers, guide the packing to the eductor's mouth. The 16-millimeter (5/8-inch) Pall rings were removed until the 30.5-centimeter (1-foot) layers of 25-millimeter (1-inch) Pall rings were reached. The packing was hosed down thoroughly to remove any biological debris washed off the smaller rings. Then the access port at the bottom of the tower was removed and the support plate cleaned from underneath. The second tower's packing was cleaned in similar fashion, except the cleaned 16-millimeter (5/8-inch) rings were moved into the first tower instead of the dump truck. Once the second tower was emptied (down to the 25-millimeter (1-inch) rings), the eductor was used to fill the tower from the dump truck. During this operation, no broken packing was seen. The entire cleaning and refilling of the towers took a 5-man team about 40 hours over 3 days. After cleaning, the pressure drop returned to the levels seen in the initial tests of May.

Once the packing was cleaned, the towers were operated with intermittent chlorination. A 380-liter (100-gallon) plastic tank was installed in the air-stripper building to hold the HTH[®] chlorine solution. The solution was added to the influent water 3 days a week so that only a trace of chlorine residual was seen at the bottom of the towers. Because of the carbon units, large concentrations of chlorine could not be added.

By November 1982, the high pressure drop problem had returned. The packing again showed very heavy growth. During a 10-day period, the packing was again removed from the towers and cleaned. The weather at this time made the job much harder. The towers remained off after the cleaning operations in preparation for the January 1983 winter tests. During this time, the purge well water was directed into the aerated underground reservoir before being discharged to the carbon units.

Starting with the January tests, the towers were continuously chlorinated. The HTH[®] solution was used because of its simplicity and availability. No significant growth was found in the towers after they had run from January to May. The constant chlorination appeared to be the answer to controlling the

biological growth. For future, long-term operations, gaseous chlorinators could be installed near the purge wells. This would provide better disinfection as well as reduced cost.

B. MICROBIOLOGICAL STUDIES

Many conflicting theories exist concerning the microbiological character of the subsurface environment. For many years, groundwater was considered devoid of microorganisms. This theory has been disproved, along with the theory that groundwaters are protected by the overlying soils from contamination. While the existence of large numbers of organisms has been documented by many researchers, the activity of the organisms has not been determined. Naturally existing organisms in groundwater are probably stressed due to a variety of factors such as low levels of organic material for energy or for metabolism, limiting nitrogen and phosphorous sources, or low temperatures. There are some species of naturally occurring groundwater bacteria that have the ability to degrade hydrocarbon compounds. Trichloroethylene degradation has been reported by several researchers to proceed in anaerobic or nearly anaerobic conditions. The initial step in this degradation has been suggested as an anaerobic dechlorination. Other research has been directed at aerobic mechanisms for TCE degradation. If TCE degradation occurs in the air-stripping column, aerobic mechanisms would definitely predominate.

In August 1982, the air-stripping towers had considerable biological growth on the packing material. The presence of these organisms indicated an adequate utilizable food source in this contaminated aquifer. Samples of the packing material were taken to the USAF Hospital Clinic at Wurtsmith AFB for identification of microorganisms. The bacterial colonies identified were species of Vibrio, Serratia, Moraxella, Citrobacter, Enterobacter, Pasteurella, Klebsiella, and Pseudomonas, all typical soil bacteria. The identification of these organisms was accomplished with the API 20-E Diagnostic System®.

The accumulation of bacteria on the packing material caused a significant increase in pressure drop in the towers and, therefore, had to be controlled. Studies were conducted to determine the efficiency of chlorine disinfection for control of the organisms. A series of tests was run, using varying

chlorine concentrations and contact times. Five samples of 500 mL of the influent to the towers were placed in beakers and chlorine was added so that concentrations of 0.25, 0.5, 0.75, 1.0, and 1.5 mg/L were obtained in the beakers. A 100 mL sample from each of the beakers was taken at 15, 40, and 60 minutes, the chlorine quenched with sodium thiosulfate, and the sample filtered with a Millipore® filtration apparatus, using 0.45-micrometer Whatman® filter paper. The filter papers were aseptically placed onto sterile Bacto Plate Count Agar® plates. The plates were inverted and incubated for 34 hours at room temperature, 21-24°C (70°-75°F).

At the 34-hour incubation time, very little growth had occurred. The plates were inverted and incubated for an additional 8 hours at room temperature. At this time, all plates of the 15- and 40-minute contact time exhibited growth. Only the 1 and 1.5 mg/L chlorine samples with 60-minute contact time showed no growth. Results of the chlorination study are shown in Table 9.

A chlorination schedule of 1 hour/day, 3 days/week, was begun to control the biological growth. This mode of operation was continued until November 1982. The periodic addition of chlorine did not sufficiently prevent biological accumulation in the towers, possibly due to protection from polysaccharide secretions around aggregates of bacteria.

Overall TCE removal efficiency was not significantly reduced by the clogging in the towers, although reduced air flows should reduce the air stripping removal efficiency. Therefore, the possibility of a biological removal mechanism seemed feasible. To investigate this possibility, samples of the biomass were provided to two agencies, EG&G Idaho, Inc., and the Savannah River Laboratory (SAL), Savannah, Georgia. The SAL conducted an isolation on the biomass, and a *Pseudomonas* species was identified. All of the bacteria present in the sample were not isolated and identified. The SAL also conducted a controlled experiment to indicate biodegradation of TCE. Tests were set up in which trichlorethylene was used as the sole substrate in growth media. Samples inoculated with the organisms and samples without the organisms were used in the experiment. Growth occurred in the media with TCE and the TCE concentration decreased. Conversely, no decrease was observed in the experiment without microorganisms.

TABLE 9. CHLORINE DISINFECTION OF WURTSMITH GROUNDWATER
AT 34-HOUR AND 42-HOUR INCUBATION

Chlorine (mg/L) Concentration	Volume Sample (mL)	Contact Time (min)	Colonies/100mL Incubation	
			34 Hr/42 Hr	
	1.0	15	100	1100
0.25				
	10	15	0	0
0.25				
	1.0	15	0	0
0.5				
	10	15	0	120
0.5				
	1.0	15	0	80
0.75				
	10	15	0	80
0.75				
	1.0	15	0	0
1.0				
	10	15	0	130
1.0				
	1.0	15	0	300
1.5				
	1.0	40	100	100
0.25				
	10	40	0	0
0.25				
	1.0	40	0	10
0.5				
	50	40	0	16
0.75				
	10	40	0	0
0.75				
	50	40	0	6
1.0				
	50	40	0	<10
1.5				
	92	60	0	45
0.25				
	50	60	2	26
0.5				
	100	60	3	7
0.75				
	10	60	0	20
0.75				
	10	60	0	0
1.0				
	100	60	0	0
1.0				
	100	60	0	0
1.5				

The sample of the bacteria sent to EG&G Idaho initiated a comprehensive investigation into the potential for the isolation and identification of the responsible organisms, the environmental conditions necessary for biodegradation and the mechanism of degradation with TCE cometabolism. The reaction bottles were sealed to allow sample withdrawal without sample loss or exposure. Experimentation is being conducted using milligram/liter and microgram/liter concentrations of TCE as a food source. Initial studies indicate a greater decrease in TCE concentrations occurring in tests with the bacteria than in the control tests, (i.e., no organisms). Biodegradation studies are being analyzed with gas chromatography for TCE quantification. Radiolabeled trichloroethylene is also being used to determine the TCE sorption and/or metabolism by incorporation of the Carbon-14 into the biomass or the evolution of radiolabeled carbon dioxide. Preliminary results of this investigation shows definite degradation of TCE to hydrocarbon byproducts and CO₂.

Between August and November 1982 an excessive biological accumulation appeared on the packing material in spite of the periodic chlorination. Packing was removed, cleaned and the towers repacked. Continuous chlorination was begun in January 1983 which deterred biological growth on the packing material. However, growth that occurred combined with the broken packing from the two previous packing washing, removal, and refilling operations to caused the clogging. The decision was made to change out the 16-millimeter (5/8-inch) packing for 25-millimeter (1-inch) packing in May 83.

Prior to removing the packing material, several samples of the Pall rings were collected for culturing the organisms. The packing material was washed with sterile peptone dilution water in sterile dilution bottles. This wash water was diluted 1:10, and 1.0 and 0.2 mL portions were spread onto sterile Bacto Plate Count Agar® plates for isolation. Well water samples, the tower influent, the Air Force drinking water wells (before chlorination), and a variety of deep and shallow monitoring wells were collected for GC analysis and bacterial enumeration. All samples for bacterial enumeration were taken in sterile 100 mL bottles. The monitoring wells were sampled to evaluate the normal mixed population of organisms and their numbers in the wells with respect to varying levels of contamination.

These plates were inverted and incubated at room temperature for 24 hours. Representative colonies from these plates were picked aseptically with an inoculating needle and streaked for isolation onto sterile plates of plate count agar (PCA). The plates were inverted and incubated at room temperature. Gram stains of the colonies were made to confirm isolation. Pure cultures were streaked onto new agar plates for storage. The gram stain results along with the colony characteristics identified at least 5 genera of bacteria from the water samples. No specific genus and species identification of these organisms has been done.

Water samples were filtered using a Millipore® filtration device and 0.45-micrometer Whatman® filter paper. Duplicate water samples of 0.1 and 0.5 mL were diluted to 50 mL with sterile dilution water and filtered. The filter papers were then aseptically placed onto sterile PCA plates, the plates were inverted, and incubated at room temperature. The bacterial population ranged from 2000 CFC/mL (colony forming units per milliliter) to 7000 CFC/mL (Table 10). The lowest number of organisms was isolated from a drinking well contaminated with an unidentified hydrocarbon. The sample with the highest number of organisms was a relatively clean monitoring well with a trace of TCE (<1 ppb) and traces of some other unidentified hydrocarbons.

Overall, the number and genus of bacteria in the well water samples appeared to be related to the contamination in the water, as well as the concentration of the contaminant. The fewest number of organisms per milliliter and lowest diversity of colony types were obtained from a sample with benzene as the probable contaminant. A contaminated sample, previously cultured and identified as having tetrachloroethylene contamination, also had relatively low numbers and diversity. The sample with the highest concentration of trichloroethylene also had relatively low numbers and diversity, but had more colonies than those samples with lower concentrations of TCE. The well samples with low levels of TCE or only a trace of TCE produced the most colonies.

TABLE 10. VARIATION OF COLONY APPEARANCE WITH CONTAMINATION

<u>SAMPLE</u>	<u>COLONIES PER 0.1 mL^a VOLUME SAMPLED</u>		<u>COLONY APPEARANCE</u>	<u>CONTAMINANT</u>
Tower Influent	TNTC	(TNTC)		
	480	(TNTC)		
DW Well #2	200	(240)	Large cream spreading	Benzene
	200	(300)		Suspected
DW Well #4	400	(500)	Small white	8 ppb TCE
	420	(500)		
DW Well #5	400	(500)	Small white	Trace TCE
		(510)		
H13D	596		1 round orange	Trace TCE
	387		13 large round white	
	540		Small white	
H265	580		Large	
			creamy white	10 ppb TCE
	618		few orange, small	
			white	
H30	380		Majority large	10 ppb TCE
			white/cream	
	372		cream	
H105	464		All small pinpoint	255 ppb TCE
	478		white	
R35	520			None Detected
R105	390		All small pinpoint	Large no.
	392			hydrocarbons
				& Benzene
R865	760		Few large creamy,	Trace TCE &
			rest pinpoint	hydrocarbons

TABLE 10. VARIATION OF COLONY APPEARANCE WITH CONTAMINATION (CONCLUDED)

<u>SAMPLE</u>	<u>COLONIES PER 0.1 ML^a VOLUME SAMPLED</u>	<u>COLONY APPEARANCE</u>	<u>CONTAMINANT</u>
045	560		Trace TCE
R25	452		Benzene Suspected
R855	280	Majority large	Trace TCE & maybe Tet- rachloro- ethylene
07D	548	7 Large cream, rest pinpoint	26 ppb TCE
R17D	588	8 Large cream, rest pinpoint	25 ppb TCE

^a numbers in parentheses are colonies per 0.5 mL

SECTION VII

TREATMENT COST ESTIMATE

Table 11 shows the estimated treatment costs for granular activated carbon (GAC) compared to the packed-tower air strippers. The costs for determining the extent of the contamination plume, trichloroethylene analysis, and siting and installing the purge well system are not shown, since these are common costs regardless of the treatment process used. However, these costs are not insignificant. About \$3 million has been spent on identifying the contaminated area and installing the purging system. Nevertheless, the overall treatment costs for the air strippers are nearly 10 times less than for GAC.

The carbon unit cost estimates were taken from a 1981 report to the Army Corps of Engineers (Reference 10) and are based on an influent TCE concentration of 2000 ppb, and effluent concentration below 5 ppb. Three 9100-kilogram (20,000-pound) units operating in series were needed to treat the 4540 L/min (1200 gal/min) water flow rate. Almost half of the carbon's operational cost is due to the carbon replacement, which was estimated at 81,800 kilograms (180,000 pounds) per year. Significant pretreatment of the purge well water was also anticipated to control pH and dissolved solids.

The capital costs for the air strippers reflect research costs, a turn-key contract for the units, and the packing costs for the May 1983 packing change-out. Maintenance requirements are minimal: grease the blowers' bearings and inspect the belts monthly, and replace the belts twice a year. During their normal rounds, the Wurtsmith water plant personnel check the instruments to ensure the correct air-to-water ratio is maintained. As a short-term measure, HTH[®] swimming pool chlorine was used to kill the bacterial growth on the packing. An on-line gaseous chlorination system would be easier and more cost-effective for long-term operation.

TABLE 11. TREATMENT COST ESTIMATES OF ACTIVATED CARBON VS AIR STRIPPING^a

	<u>ACTIVATED CARBON^b</u>	<u>AIR STRIPPING</u>
CAPITAL:	\$1,552,000	\$200,000 ^c
OPERATION AND MAINTENANCE:	264,600	30,000 ^d
AMORTIZED CAPITAL ^e :	204,000	26,300
TOTAL ANNUAL COST:	468,600	56,300
TREATMENT COST/1,000L	\$ 0.26	\$ 0.03
(COST/1,000 GAL):	(\$ 0.98)	(\$ 0.12)

^aBased on 5.45 ML/day (1.44 MGD) average, 340 days/year

^bCarbon system costs from Reference 10, minus sampling costs

^cIncludes May 1983 packing change

^dPower costs at \$0.05/kWh

^eAmortized over 15 years at 10%

SECTION VIII

CONCLUSIONS

As a result of this program, the following conclusions are made:

1. Air stripping is a viable, efficient method of removing trichloroethylene from groundwater.
2. Through proper design and operation, air stripping alone can remove trichloroethylene down to one part per billion levels.
3. Water temperature is dominant; the air quickly equalizes with the water temperature. Evaporation cooling is negligible.
4. Chlorination is required to prevent biological growth.
5. Calcium and other dissolved inorganics did not appear to degrade the strippers' efficiency although some precipitation on the packing and tower walls occurred. Sand from the wells may clog the retention plate over time.
6. Laboratory data can be used to directly design a full-scale packed tower, provided the packing type and air and water loading rates used in the full-scale unit are the same as those used in the laboratory.

SECTION IX

RECOMMENDATIONS

This program showed that through proper design and operation, trichloroethylene can be removed from groundwater in a cost-effective manner. However, TCE is not the only volatile organic contamination facing many Air Force bases. Benzene, xylene, 1,1,1-trichloroethane and many others have either been discovered or may be discovered through the Installation Restoration Program begun by the Department of Defense. Further research and development in air stripping of other volatile organics may open the way for another cost-effective cleanup alternative.

Specifically, research should be done in the following areas:

1. Develop mass transfer coefficients for various organics and different types of packing media.

2. Develop a generalized correlation theory that would be a useful tool in predicting packed-tower performance with little or no laboratory pilot studies.

3. Determine the dependence of Henry's Law Constants on temperature for the organic contaminants of Air Force concern. An improved method developed by Lincoff and Gossett (Reference 11) may be the easiest and most accurate to date.

4. Investigate the use of granular activated carbon or catalytic destruction to remove the air-stripped organics from the tower's effluent air stream. This will enable air stripping to be used to remove organics from groundwater where those organics may cause health effects if released to the atmosphere (i.e., carbon tetrachloride, vinyl chloride, etc.).

5. The biological growth should be studied to determine if microbiologically enhanced aeration is a feasible process.

APPENDIX A
PACKED-TOWER AIR-STRIPPING DESCRIPTION AND THEORY

APPENDIX A

PACKED-TOWER AIR-STRIPPING DESCRIPTION AND THEORY

A. PACKED TOWER DESCRIPTION

An air stripper is the generic name for a packed tower used to transfer one or more contaminants (i.e., trichloroethylene) from the water to the air. A packed tower, as illustrated in Figure A-1, has five main components: a cylindrical shell, support plate, packing media, water distributor, air blower, and water pump. The shell and support plate hold the packing media while the air and water flow over the packing. The water distributor evenly distributes the water over the top of the packing. The packing is typically an open-structured, chemically inert material (usually plastic) which helps the air and water mix more efficiently. Packing medias are usually selected to give high surface areas for good air/water contacting, while offering the least resistance (pressure drop) to the air and water flows. In counter-current operation, the water flows down over the packing while the air blower forces the air upwards. As the air and water pass each other, the contaminant (TCE) leaves the water and enters the air, where it is carried out the top of the tower.

B. AIR-STRIPPING THEORY

The physical process of moving the TCE from the water into the air is called desorption, or "air stripping." Likewise, moving a contaminant from an air stream into water (liquid phase) is called absorption. Absorption has been used for many years in chemical engineering processes, but only in recent years has desorption (air stripping) been applied to remove low levels of volatile organic solvents (like TCE) from water. Some of the more important factors which effect the removal include the amount of contact area, how well the air and water mix, the solubility of the contaminant, the diffusivity of the contaminant in the air and water, and temperature. All of these factors, except diffusivity and temperature, are influenced by the air and water flow rates and type of packing media.

How easily the contaminant moves from the water to the air is reflected by two important parameters: the mass transfer coefficient and the Henry's Law Constant. The mass transfer coefficient indicates how much contaminant is

H_C = Henry's Law Constant, (atm-m³/mole)

A_w = volumetric air-to-water ratio (G/L)

R = Universal Gas Constant, (8.206 x 10⁻⁵ m³ atm mol⁻¹ °K⁻¹)

T = temperature (°K)

The Henry's Constant is not known accurately for many organics, but Table A-1 lists some estimated values. If the temperatures differ greatly from 20°C, then the temperature effects on the H_C value must be accounted for. Unfortunately, these effects are not known for many of the organics. In the case of trichloroethylene, Gossett's experiments give the following temperature relationship for Henry's Constant (Reference 7):

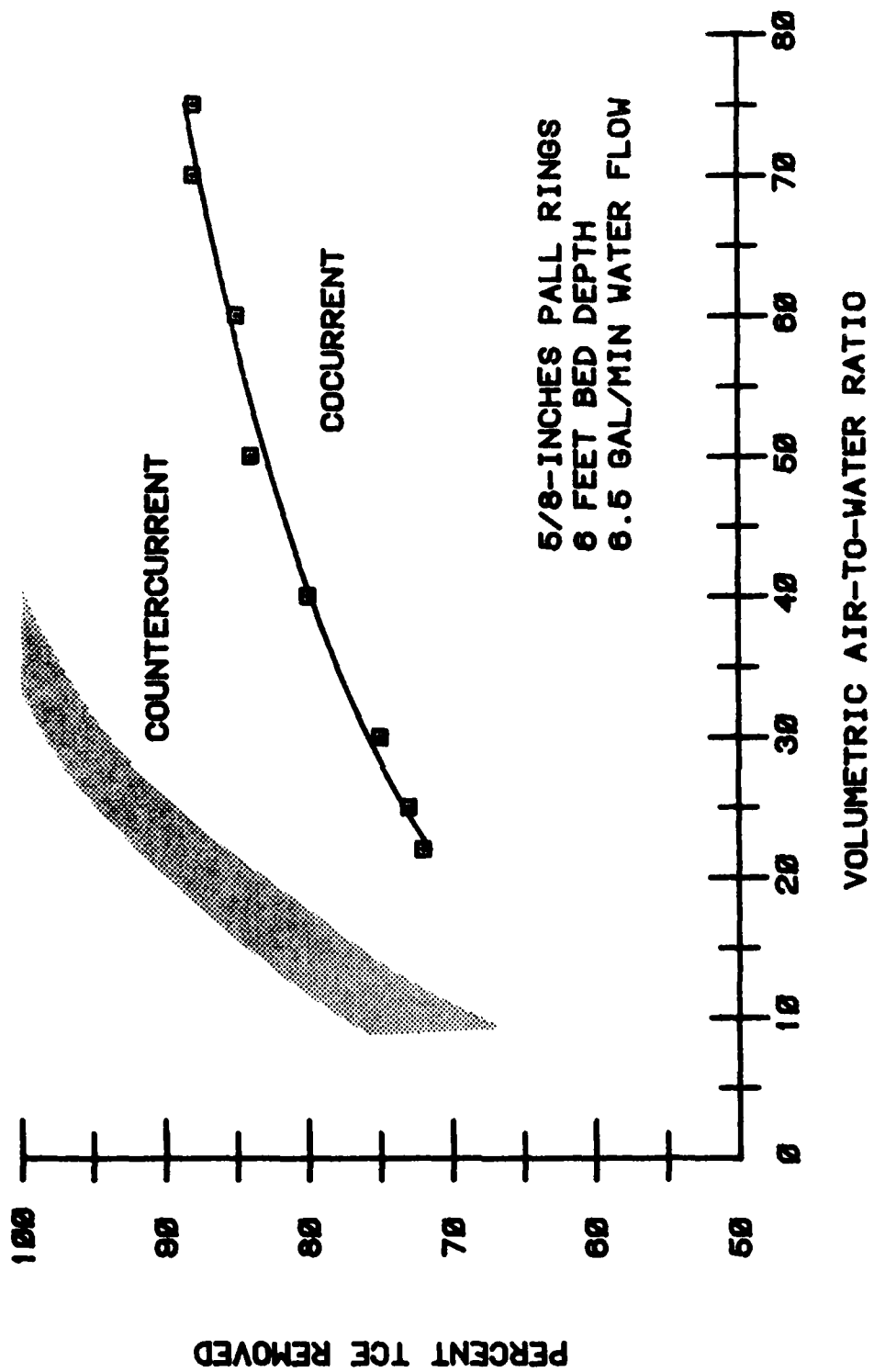
$$H_C = \exp (9.7 - 4308/T) \quad (2)$$

The next step is to calculate the amount of packing needed to obtain the removal found from Equation (1). For this, the mass transfer coefficient ($K_L a$) must be known for the type of packing media used. Again, this data is not available for many organics, but for TCE and 16-millimeter (5/8-inch) Pall rings, Gossett found:

$$K_L a = \exp (8.52 - 2515/T) \quad (3)$$

where $K_L a$ has units of inverse minutes (min⁻¹). By using the data obtained in Equations (1) to (3), the volume of packing can be estimated from (Reference 7):

$$Z_{TA} = \frac{L^*}{K_L a} \cdot \frac{\ln \left[\frac{C_1}{C_2} - \frac{RT}{A_w H_C} \left(\frac{C_1}{C_2} - 1 \right) \right]}{1 - \frac{RT}{A_w H_C}} \quad (4)$$



A-5. Removal Efficiency For Trichloroethylene During Cocurrent Operation.

d. Countercurrent vs Cocurrent

The final task compared the removal efficiencies of countercurrent and cocurrent stripping operations. In cocurrent operation, the air and water flow in the same direction. Cocurrent operation would allow much higher water and air flows in a smaller diameter tower than countercurrent without encountering flooding conditions. Flooding occurs when the air flow starts preventing the water from leaving the column, causing the water to build up in the packing. Pressure drop rises sharply and removal efficiency declines. Unfortunately, as seen in Figure A-5, cocurrent operation requires an air-to-water ratio nearly three times higher than countercurrent to achieve the same removal efficiency. This is partially due to less contact turbulence between the liquid and gas in cocurrent operations. More important, cocurrent operation is not as efficient because a unit of liquid remains in contact with a unit of gas which is steadily increasing in TCE concentration, and approaches the equilibrium mass transfer limit. In countercurrent operation, a unit of liquid encounters new units of gas with lesser TCE concentrations, allowing increased mass transfer.

D. AIR STRIPPER DESIGN CALCULATIONS

1. Equations For Packed Tower Design

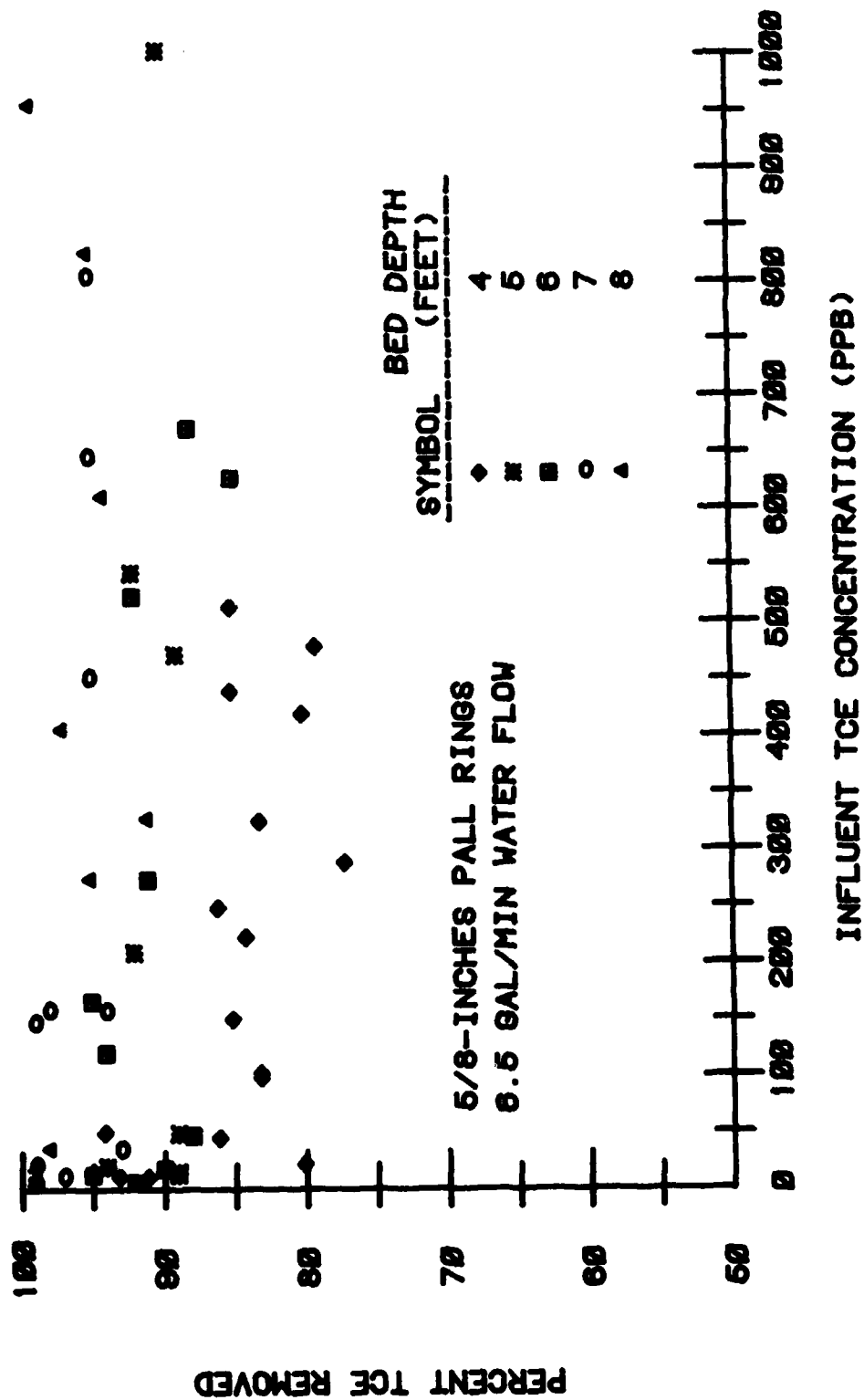
Packed-tower air strippers can be designed for a wide variety of flow ranges, temperatures and organics. One of the first steps in applying air stripping is to estimate the maximum possible removal for a given contaminant, based on its Henry's Law Constant, temperature, and volumetric air-to-water ratio. The following equation can be used (Reference 5):

$$\frac{C_2}{C_1} = (1 + H_C A_w / RT)^{-1} \quad (1)$$

where

C_2 = final concentration of organic ($\mu\text{g/L}$ or ppb)

C_1 = initial concentration of organic ($\mu\text{g/L}$ or ppb)



A-4. Removal Efficiency of Trichloroethylene Versus Influent Concentration For 16-Millimeter Pall Rings.

TABLE A-4. EFFECT OF INFLUENT CONCENTRATION ON TCE REMOVAL (CONCLUDED)

Packed Depth (ft)	Influent Concentration (ppb)	Percent Removal
7	804	95
7	645	95
7	450	95
7	146	99
7	156	94
7	157	98
7	34	93
7	20	>99
7	10	97
7	4	>99
8	956	>99
8	611	94
8	826	95
8	327	91
8	274	95
8	406	97
8	36	98
8	18	99
8	10	>99
8	5	>99

TABLE A-4. EFFECT OF INFLUENT CONCENTRATION ON TCE REMOVAL

Operating Conditions

Packing = 16-millimeter (5/8-inch) Pall rings

Volumetric Air-to-water ratio: 22:1

Water flow rate: 25 L/min (6.5 gal/min)

Temperature: 21°C (70°F)

Packed Depth (ft)	Influent Concentration (ppb)	Percent Removed
4	288	77
4	419	80
4	324	83
4	150	85
4	98	83
4	50	94
4	22	80
4	11	91
4	478	79
4	513	85
4	248	86
4	439	85
4	222	84
4	102	83
4	45	86
4	11	93
5	1003	90
5	543	92
5	471	89
5	209	92
5	49	89
5	20	94
5	15	89
5	13	89
6	671	88
6	522	92
6	627	85
6	273	91
6	166	95
6	120	94
6	47	88
6	18	90
6	13	95
6	6	92

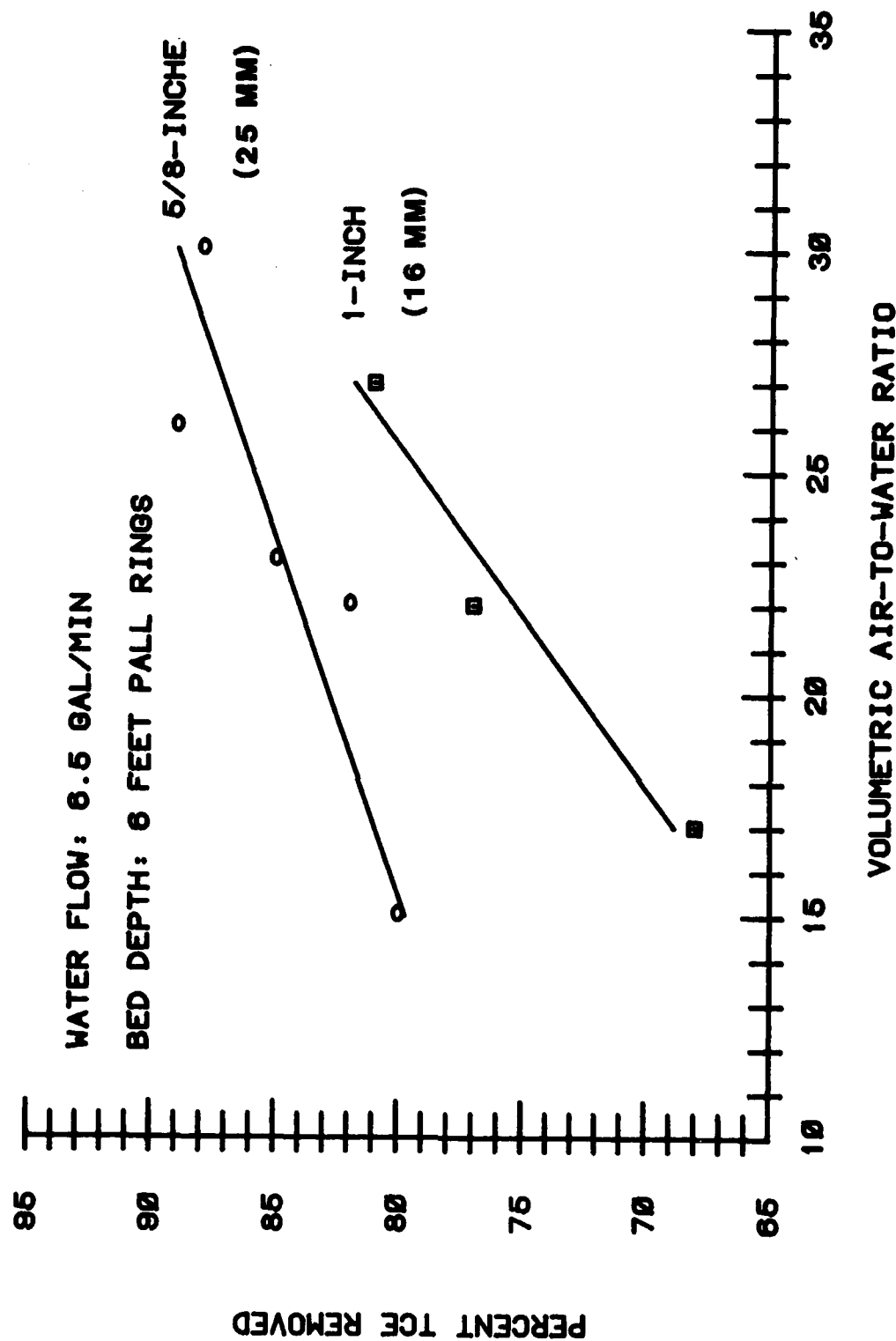


Figure A-3. Removal Efficiency of Trichloroethylene Versus Volumetric Air-to-Water Ratio For 16- and 25-Millimeter Pall Rings.

b. Air-to-Water Ratio and Removal Efficiency

The effect of air-to-water ratio on TCE removal efficiency for both 16-millimeter (5/8-inch) and 25-millimeter (1-inch) Pall rings is shown in Figure A-3. The 16-millimeter rings give a higher removal percentage which reflects the higher-wetted active surface area on the packing as compared to the 25-millimeter rings. The 16-millimeter rings, however, cause a higher pressure drop than the large rings. The smaller rings pack closer together, causing a restriction in the air flow.

c. Packed-Bed Depth and Influent Concentration

Since the mass transfer coefficient was unknown, the effect of packed-bed depth on the removal rate was determined. The effect of TCE influent concentration was also observed. The tower was filled with 16-millimeter (5/8-inch) rings at incremental 0.3-meter (1-foot) depths between 1.2 and 2.5 meters (4 and 8 feet). The TCE influent concentration varied between 10 and 1000 ppb. Table A-3 shows that the percent removal increased with bed depth until about 7 feet was reached. Eight feet of packing showed no significant change in the removal efficiency. Also, overall, the percent removal was independent of influent concentration (Table A-4 and Figure A-4).

TABLE A-3. EFFECT OF PACKED-BED DEPTH ON TCE REMOVAL

<u>Feet of Packing</u>	<u>Average Percent Removed</u>
4	84
5	90
6	91
7	97
8	97

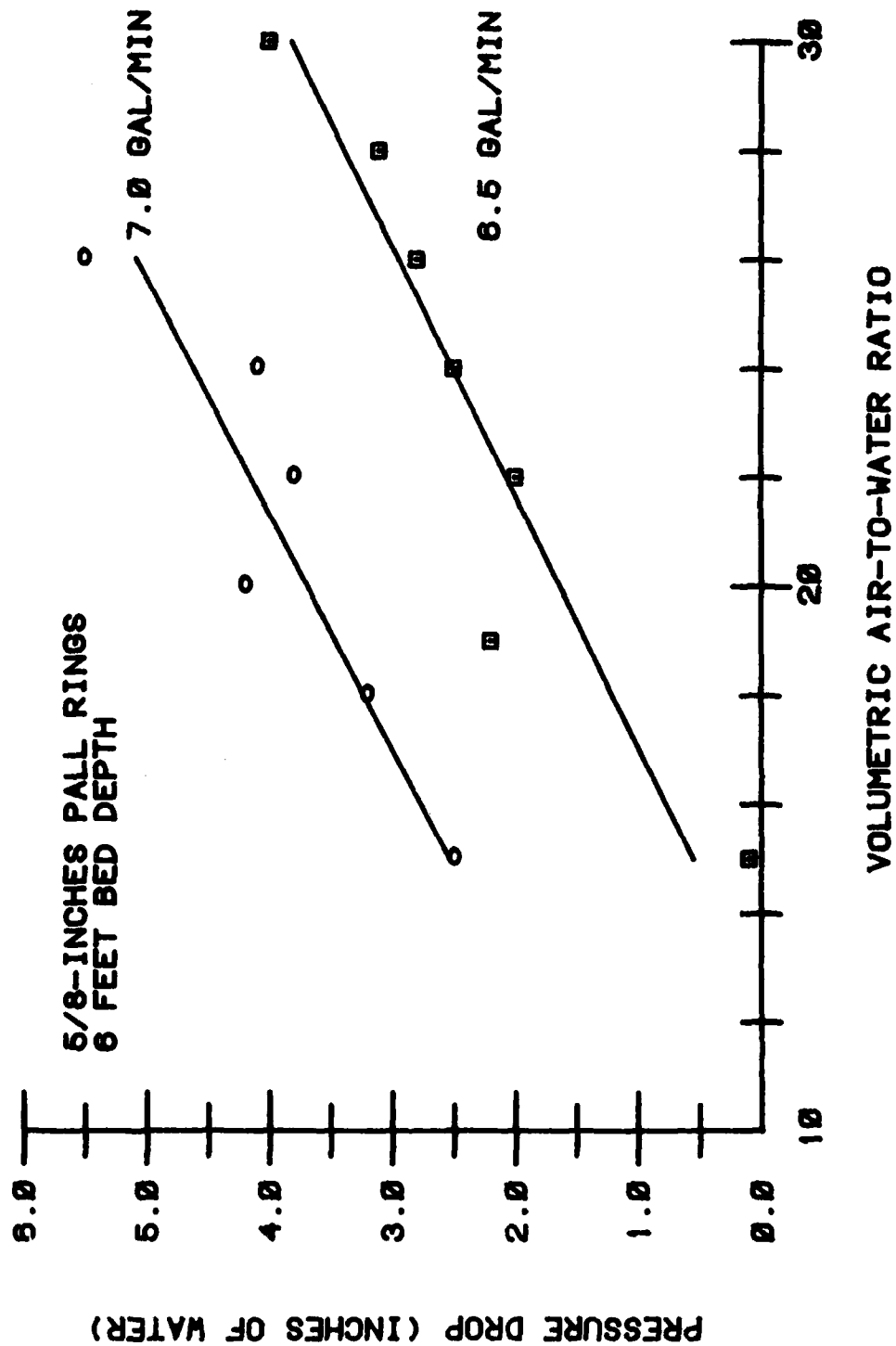


Figure A-2. Pilot-Scale Column Pressure Drops Versus Volumetric Air-to-Water Ratio.

a. Pressure Drops

Column pressure drops were measured at various air and water rates to determine the range of flow rates within the operating limits of the blower. The 25 L/min (6.5 gal/min) flow rate was chosen as a middle operating range of the column. This allowed varying the air flows (air-to-water ratios) without crossing the operational limits of the blower or the packed column. The data in Table A-2 and Figure A-2 show that an air-to-water ratio of 22:1 and 25 L/min (6.5 gal/min) are in the middle of the operating range.

TABLE A-2. PILOT-SCALE COLUMN PRESSURE DROPS

Water Flow (gpm)	Air/Water Ratio (vol:vol)	Pressure Drop (inches of water)
6.5	15	<0.1
6.5	19	2.2
6.5	22	2.0
6.5	24	2.5
6.5	26	2.8
6.5	28	3.1
6.5	30	4.0
7.0	15	2.5
7.0	18	3.2
7.0	20	4.2
7.0	22	3.8
7.0	24	4.1
7.0	26	5.5

orifice meters before and after the blower. Head loss (pressure drop) across the column packing was measured with a 25.4 centimeter (10 inches) of water full-scale Magnehelic® gauge. Trichloroethylene solutions were made in a 2000-liter (530-gallon) polypropylene tank and pumped to the top of the column with a 559-Watt (0.75-horsepower) pump. Water flow rate to the column was controlled by recycling part of the water back to the tank before the rotometer which was used for water flow measurement. Stock solutions of TCE equilibrated at least 1 hour in 1-liter flasks prior to being carefully mixed with tap water in the tank.

2. Sampling and Analysis

TCE in the influent and effluent water from the packed-tower air stripper was analyzed using direct headspace analysis (References 7,8). This procedure involved taking a 120-gram sample (120 mL) in a 240 mL bottle, giving a 50-percent by volume headspace. The bottle was immediately sealed with a Teflon®-lined silicon septum and set aside for analysis. Samples were taken from both the influent and effluent water streams at regular time intervals during the experimental runs. After shaking the bottles for at least 5 minutes to achieve a constant temperature, 0.5 mL of headspace gas was withdrawn with a 1 mL gastight syringe and injected for each analysis. The TCE concentration in the water samples was determined by comparing the TCE concentration in the sample headspace with headspace concentrations from TCE standards. The TCE in the headspace was measured with a Perkin Elmer Model 99 gas chromatograph with a flame ionization detector and a 1.8-meter (6-foot) SP-2250 Supelco® column. This gave a lower detection limit of 1 ppb.

3. Pilot-Scale Experiments

The pilot-scale experiments had four main tasks. The first task was to observe the column pressure drops as a function of air and water flow. The second task involved noting the effect of the air-to-water ratio on removal efficiency. The third task determined the effect of packed-tower height on the removal rate and the effect of influent concentration on removal efficiency. The fourth task compared countercurrent with cocurrent air stripping.

TABLE A-1. ESTIMATED HENRY'S CONSTANTS FOR VARIOUS ORGANICS AT 20°C
(REFERENCES 5, 18)

<u>Compound</u>	<u>H_c (atm-m³/mole)</u>
Vinyl chloride	6.4
Dichlorofluoromethane	2.1
1,1-dichloroethylene	1.7x10 ⁻¹
1,2-dichloroethylene	1.7x10 ⁻¹
Trichlorofluoromethane	1.1x10 ⁻¹
Methyl bromide	9.3x10 ⁻²
Carbon tetrachloride	2.5x10 ⁻²
Tetrachloroethylene	2.3x10 ⁻²
Chloroethane	1.5x10 ⁻²
Trichloroethylene	1.0x10 ⁻²
Methyl chloride	8.0x10 ⁻³
1,2-trans-dichloroethylene	5.7x10 ⁻³
Ethylbenzene	5.7x10 ⁻³
1,1-dichloroethane	5.1x10 ⁻³
Benzene	4.6x10 ⁻³
Chlorobenzene	4.0x10 ⁻³
1,1,1-trichloroethane	3.6x10 ⁻³
Chloroform	3.4x10 ⁻³
1,3-dichlorobenzene	2.7x10 ⁻³
Methylene chloride	2.5x10 ⁻³
1,4-dichlorobenzene	2.1x10 ⁻³
1,2-dichloropropane	2.0x10 ⁻³
1,2-dichloropropylene	2.0x10 ⁻³
1,2-dichlorobenzene	1.7x10 ⁻³
1,2-dichloroethane	1.1x10 ⁻³
Hexachloroethane	1.1x10 ⁻³
1,1,2-trichloroethane	7.8x10 ⁻⁴
Bromoform	6.3x10 ⁻⁴
1,1,2,2-tetrachloroethane	4.2x10 ⁻⁴
Naphthalene	3.6x10 ⁻⁴
Phenol	2.7x10 ⁻⁷

moving from the water into the air per unit volume of packing and increment of time. Several theories have been proposed to explain the mechanisms of mass transfer across a liquid/gas interface (References 12 to 17), but laboratory experiments are needed to obtain them. The ability of a contaminant to be air-stripped can be estimated from its Henry's Law Constant. This parameter is the ratio of the contaminant's concentration in the air above a volume of liquid to the concentration in the liquid, at equilibrium. A high Henry's Constant indicates the contaminant has low solubility in water, and can therefore be removed by air stripping. In general, Henry's Constant values increase with increasing temperature and decrease with increasing solubility in water. Table A-1 gives some estimated values for the Henry's Constants (References 5, 18).

The design of a packed tower to achieve a specified removal rate requires accurate values of the mass transfer coefficient (K_La) and Henry's Law Constant (H_C). Both parameters are temperature-dependent, and the value of K_La depends on both the air and water flow rates in the tower as well as the geometry of the packing media. Thus, laboratory analyses on a pilot-scale packed tower had to be done to obtain K_La values. Some additional studies were performed by Gossett to obtain values of H_C as a function of temperature (Reference 7).

C. EXPERIMENTAL PROCEDURES

1. Pilot-Scale Packed Tower

Figure 3 (Section II) shows the experimental arrangement used by Gossett (Reference 7) in the pilot-scale studies. The column was constructed of clear 19-centimeter (8-inch) inside diameter Plexiglas® pipe with an initial packed depth of 1.2 meters (4 feet) using 16-millimeter (5/8-inch) polypropylene Pall ring packing. This is a commonly used packing and is readily available.

The column was operated under a slight negative pressure with the blower situated at the top of the column. Air flow rates were controlled by varying blower speed with a Variac® voltage controller. Flow rate was measured with a pitot tube and a 0.83 centimeters (0.25 inches) of water full-scale Magnehelic® differential pressure guage. The Magnehelic® guage was calibrated with an inclined manometer and the flow rate was checked using two

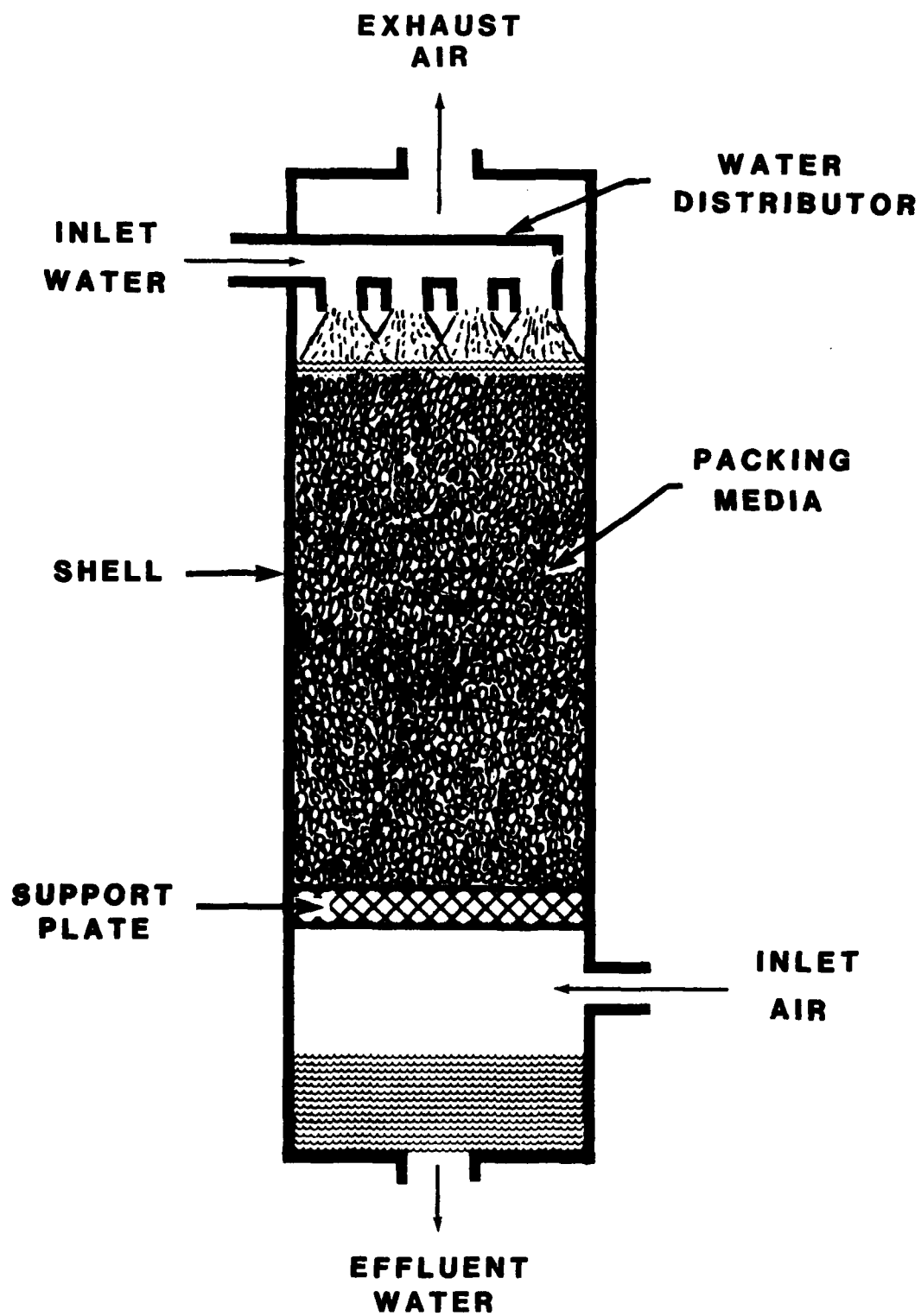


Figure A-1. Typical Packed Tower.

where

Z_T = height of the packing, (meters)

A = cross-sectional area of the tower, (m^2)

L^* = volumetric water flow rate, (m^3/min)

Once the packing volume has been calculated, the tower diameter can be found from the desired pressure drop calculated in Equations (5) and (6) and Figure A-6 (Reference 16). This figure is a generalized correlation for predicting pressure drop in packed towers; Equations (5) and (6) are the x- and y-axis values, respectively.

$$X = \frac{L}{G} \left[\frac{\rho_g}{\rho_l} \right]^{0.5} = \frac{1}{A_w} \left[\frac{\rho_l}{\rho_g} \right]^{0.5} \quad (5)$$

where

X = x-axis value on Figure A-6

L = water loading rate, $lb\ ft^{-2}\ s^{-1}$

G = air loading rate, $lb\ ft^{-2}\ s^{-1}$

ρ_g = air density, lb/ft^3

ρ_l = water density, lb/ft^3

$$Y = \frac{G^2 F \mu^{0.2}}{\rho_g \rho_l g_c} \quad (6)$$

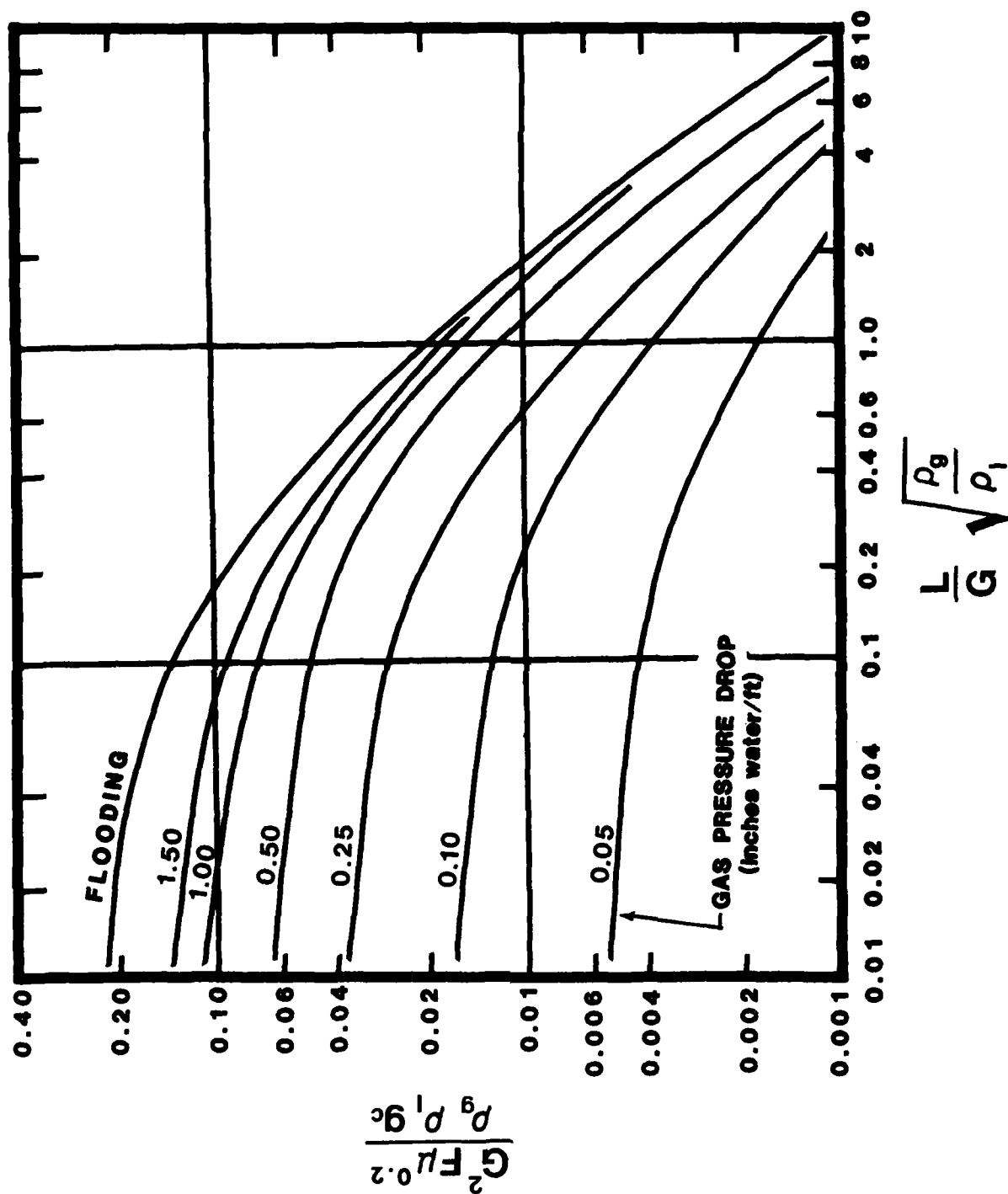
where

Y = y-axis value on Figure A-6

F = packing factor (97 for 16 mm (5/8-inch) Pall rings)

μ = water viscosity, centipoise

g_c = gravitational acceleration constant, $32.2\ ft/s^2$



A-6. Generalized Flooding and Pressure Drop Curves For Packed Towers.

The packing factor is unique to the type of packing and can usually be obtained from the manufacturer. Table A-5 gives some data on commonly used packings. Generally, the larger the packing factor, the smaller the packing size and the higher the pressure drop.

To estimate the tower size, an allowable pressure drop value is chosen. Usually a pressure drop in the range of 0.6 to 1.3 centimeters (0.25 to 0.50 inches) of water per foot of packed bed gives an average size tower and a flexible operating range. Once the pressure drop is chosen, the x-axis value for Figure A-6 is calculated from Equation (5). A vertical line is drawn from the x-axis to the intersection of the pressure drop curve corresponding to the selected value. At this intersection, the y-axis value is read. Equation (6) is rearranged and solved for G.

$$G = \left[\frac{Y^0_g \rho_{19c}}{F \mu^{0.2}} \right]^{0.5} \quad (7)$$

The tower cross-sectional area is found by dividing the air flow rate by G and the diameter is calculated from the area. The total packed bed depth is calculated by dividing the volume of packing by the cross-sectional area. The total pressure drop is the pressure drop per foot of packing times the packed bed depth. The following example illustrates the calculations involved.

2. Tower Design Example

The following example demonstrates the use of the equations and methods previously discussed. The example also shows how simply and quickly a packed tower design can be estimated for removal of trichloroethylene.

Assume the following criteria:

Water Flow Rate (L^*): 1.89 m³/min (500 gal/min)

Influent TCE Level: 1000 ppb (1000 µg/L)

Desired Effluent TCE Level: 100 ppb (100 µg/L)

Water Temperature: 15°C (288 °K); viscosity: 1.1 cp

Air Temperature: 25°C (293 °K)

Packing Media: 16 mm (5/8-inch) Pall rings

TABLE A-5. CHARACTERISTICS OF RANDOM, WET-DUMPED COMMERCIAL PACKINGS^a

<u>Packing</u>	<u>5/8</u>	Nominal Size (Inches)	
		<u>1 or #1</u>	<u>2 or #2</u>
Pall rings ^b			
<u>plastic</u>			
F	97	52	25
ε	0.87	0.90	0.92
a _p	104	63	31
<u>Metal</u>			
F	70	48	20
ε	0.93	0.94	0.96
a _p	104	63	31
Super Intalox ^c			
Saddles			
<u>plastic</u>			
F		33	21
ε		0.90	0.93
a _p		63	33
Flexisaddles ^d			
<u>plastic</u>			
F		30	20
ε		0.91	0.93
a _p		63	33
Tri-pack ^e			
<u>plastic</u>			
F		28	15
ε		0.91	0.96
a _p		85	48

^a F = packing factor (ft^{-1}); ϵ = voidage; a_p = surface area (ft^2/ft^3)

^b Norton Company Chemical Process Products Bulletin PR-16

^c Norton Company Chemical Process Products Bulletin SI-72

^d Koch Engineering Company Bulletin FS-1

^e Jaeger Tri-Packs, Inc. Technical Bulletin; 1-inch nominal is Jaeger #1/2, 2-inch nominal is #1.

STEP 1:

Estimate the volumetric air-to-water ratio from Equation (1), with a Henry's Constant from Equation (2). Since the air temperature will quickly equilibrate with the water, 15°C (288 °K) will be operating temperature. From Equation (2) at 288 °K, H_C is 0.0052 m³-atm/mole. Rearrange Equation (1) and solve for A_w :

$$\begin{aligned} A_w &= \frac{RT}{H_C} \left(\frac{C_1}{C_2} - 1 \right) \\ &= \frac{(8.206 \times 10^{-5})(288)}{0.0052} \left(\frac{1000}{100} - 1 \right) \\ &= 40.9 \end{aligned}$$

Since this equation tends to be conservative, an A_w of 40 is acceptable. Knowing the volumetric water flow rate, the volumetric air flow rate is (40)x(1.89) or 75.6 m³/min (2670 ft³/min).

STEP 2:

Estimate the mass transfer coefficient and volume of packing. From Equation (3) at 288 °K, $K_L a$ is 0.808 min⁻¹. Substituting into Equation (4) gives the packing volume:

$$\begin{aligned} Z_T A &= \frac{1.89}{0.808} \cdot \frac{\ln \left[\frac{1000}{100} - \frac{(8.206 \times 10^{-5})(288)}{(40)(0.0052)} \left(\frac{1000}{100} - 1 \right) \right]}{1 - \frac{(8.206 \times 10^{-5})(288)}{(40)(0.0052)}} \\ &= 5.48 \text{ m}^3 \text{ (195 ft}^3\text{)} \end{aligned}$$

STEP 3:

Select pressure drop and calculate tower size. Assume a allowable pressure drop per foot of packing is 1.3 centimeters (0.5 inches) of water. At 15°C, the air density is 0.0766 lb/ft³ and the water density is 62.4 lb/ft³. Equation (5) gives the x-axis value for Figure A-6.

$$X = \frac{1}{40} \sqrt{\frac{62.4}{0.0766}} = 0.71$$

A vertical line on Figure A-6 from 0.71 intersects the 0.5 pressure drop curve at a y-axis value of about 0.018. Equation (7) gives the air loading rate (G), using a packing factor of 97:

$$G = \left[\frac{(0.018)(0.0766)(62.4)(32.2)}{(97)(1.1)^{0.2}} \right]^{0.5}$$
$$= 0.17 \text{ lb ft}^{-2}\text{s}^{-1}$$

In Step 2, the volumetric air flow rate was 75.6 m³/min (2670 ft³/min) or 3.41 lb/s. Dividing this number by G gives the tower cross-sectional area: 1.86 m² (20 ft²). The tower diameter is 1.54 meters (5 feet). The packed bed depth is (5.48)/(1.86) or 3.0 meters (9.7 feet). Using 3.1 meters (10 feet) of packing, the total pressure drop is 12.7 centimeters (5.0 inches) of water.

In summary, the preliminary design will be:

Water Flow Rate: 1.89 m³/min (500 gal/min)

Air Flow Rate: 75.6 m³/min (2670 ft³/min)

Tower Diameter: 1.54 meters (5 ft)

Packed Bed Depth: 3.1 meters (10 ft)

Pressure Drop Through Packing: 12.7 cm (5.0 in.) of water

Percent TCE Removed: 90

E. SUMMARY

The goal of this initial research effort was to determine if air stripping can be an efficient alternative in the cleanup of TCE-contaminated groundwater. This effort found that a pilot-scale countercurrent packed-tower air stripper has TCE removal efficiencies of greater than 90 percent. Also, an upscaled prototype field air stripper designed from the pilot-scale data should achieve the same high removal efficiency.

As a result of these studies, several observations on air stripping were noted:

1. Column pressure drop increases with an increase in air or water flow. Water flow has a greater impact on the pressure drop than air flow.

2. In general, the higher the air-to-water ratio the more TCE is removed.

3. An increase in packed-bed depth increases the removal efficiency. However, beyond a certain packed height, the addition of more packing does not significantly increase the percent removal.

4. The influent TCE concentration levels do not affect the overall removal percentage.

5. Countercurrent air stripping is much more effective than cocurrent air stripping.

APPENDIX B

LABORATORY ANALYSES AND SAMPLING METHODOLOGY

APPENDIX B

LABORATORY ANALYSES AND SAMPLING METHODOLOGY

A. ANALYTICAL TECHNIQUE AND EQUIPMENT

The ability to accurately determine the concentration of volatile organics in water was critical to the overall success of the air stripping studies. In Gossett's work (Reference 7) to determine the mass transfer coefficients (K_La), nine samples had to be analyzed to obtain one K_La value. Although the purge-and-trap method is most widely used for quantifying many purgeable organics, analysis times generally exceed 20 minutes. Clearly, this method was unsuitable for obtaining large amounts of data in a reasonable period of time. A relatively fast and simple analytical method was needed, especially for sampling on site at Wurtsmith Air Force Base.

Gossett's analytical method, adapted from Dietz and Singley (Reference 8) and also adopted for the onsite evaluations, used direct headspace analysis on a gas chromatograph (GC) with a flame ionization detector. A 1.8-meter (6-foot) stainless steel chromatographic column containing 10 percent SP-1000 on 100/120 Supelcoport® was operated at a constant 120°C. Trichloroethylene retention time on the column was about 2 minutes at a 40 mL/min carrier flow rate. The initial tests were done on an AID Model 511 portable GC, the others on a Hewlett-Packard Model GC. A Varian strip chart recorder was also used. The equipment was set up in the Wurtsmith Bioenvironmental Engineering office. Since the building was originally used as base housing, the office had a separate kitchen with a double sink and electric oven. The kitchen served as the laboratory because it could be isolated from the rest of the offices. This aided temperature control and restricted the access of nonessential personnel. About 4 times as many samples could be analysed using the headspace method in the same amount of time, as compared to the purge-and-trap method.

The reason why direct headspace analysis works is due to the volatility of the organic and its Henry's Law Constant (H_C). Henry's Law relates the concentration of the TCE in the air above a volume of liquid to the TCE concentration in the liquid at equilibrium. Trichloroethylene has only limited solubility in water (1100 ppm at 25°C: Reference 9), so at equilibrium, some TCE will be in the water and some in the air (headspace).

How much in each phase is determined by the value of H_C and the temperature. Ideally, if an accurate value for Henry's Constant was known, and the headspace concentration could be measured, then the liquid concentration could be calculated. Unfortunately, Henry's Constant values are not well known and measuring air concentrations is just as difficult as the liquid. Henry's Law, though, can be used to indirectly measure the water's TCE concentration. By making standards of known concentration, samples of the headspace can be taken and a corresponding peak height obtained on the GC. Peak height actually corresponds to the TCE concentration in the headspace, but as long as the temperature and headspace volumes remain constant, it is also is proportional (by Henry's Law) to the TCE concentration in the water.

B. STANDARDS PREPARATION

To determine the concentration of TCE in the water, standards were prepared to calibrate the GC response. First, a supply of organic-free water was needed to prepare the standards. Bottled water was found to be acceptable. The quality of the water was checked by injecting some of the headspace above the water into the GC and looking for interfering peaks at the TCE elution time. A 200 mL BOD bottle was filled with the clean water and enough TCE was added to form a small bubble on the bottom. A magnetic stirring rod was inserted, the bottle tightly capped with no air bubbles, and placed on a magnetic stirrer for at least 24 hours. After stirring, the bottle was allowed to rest for at least a day to allow any small liquid droplets suspended in the water to settle. A small bubble of TCE on the bottom ensured saturation.

Successive dilutions were made using this saturated stock solution to produce primary stock solutions of different concentrations. Five 1000 mL volumetric flasks were used. In Flask 1, 900 grams of clean water were weighed out on an analytical scale. Using a pipette, 100 grams (100 mL) of saturated stock solution were placed in the flask while still on the scale. Care was taken not to disturb the saturated liquid and the contents of the pipette were discharged below the surface of the liquid. The flask was immediately stoppered, inverted several times to mix, and allowed to rest several minutes. Similarly in Flask 2, 900 grams of clean water were added. Using another pipette, 100 grams of the solution from Flask 1 were placed in Flask 2. This procedure was used successively for all five flasks to obtain

the primary stock solutions of 1100 ppm (saturated), 110 ppm, 11 ppm, 1.1 ppm (1100 ppb), 0.11 ppm (110 ppb) and 0.011 ppm (11 ppb). A new pipette was used for each solution to prevent contamination. The dilution scheme is shown in Table B-1.

The primary solutions were then used to prepare the standards used to calibrate the gas chromatograph (GC). Amber-colored 240 mL bottles with Teflon®-lined silicone septa in screw caps were used for the standards. These bottles were the same type used in the sampling procedure, described in the next section. Again, the bottles were placed on the scales and the solutions were added on a mass basis. Each bottle was quickly capped, shaken, and allowed to rest for several minutes before being sampled. This allowed the headspace to come to equilibrium with the liquid. Each standard bottle contained 120 grams (120 mL) of liquid and 120 mL of headspace, which corresponded to the amount of sample to be taken (Table B-1). The proportion of liquid to headspace must be the same for the calibration standards and the actual samples for the peak height versus concentration correlation to be valid. Also, the temperatures must be equal.

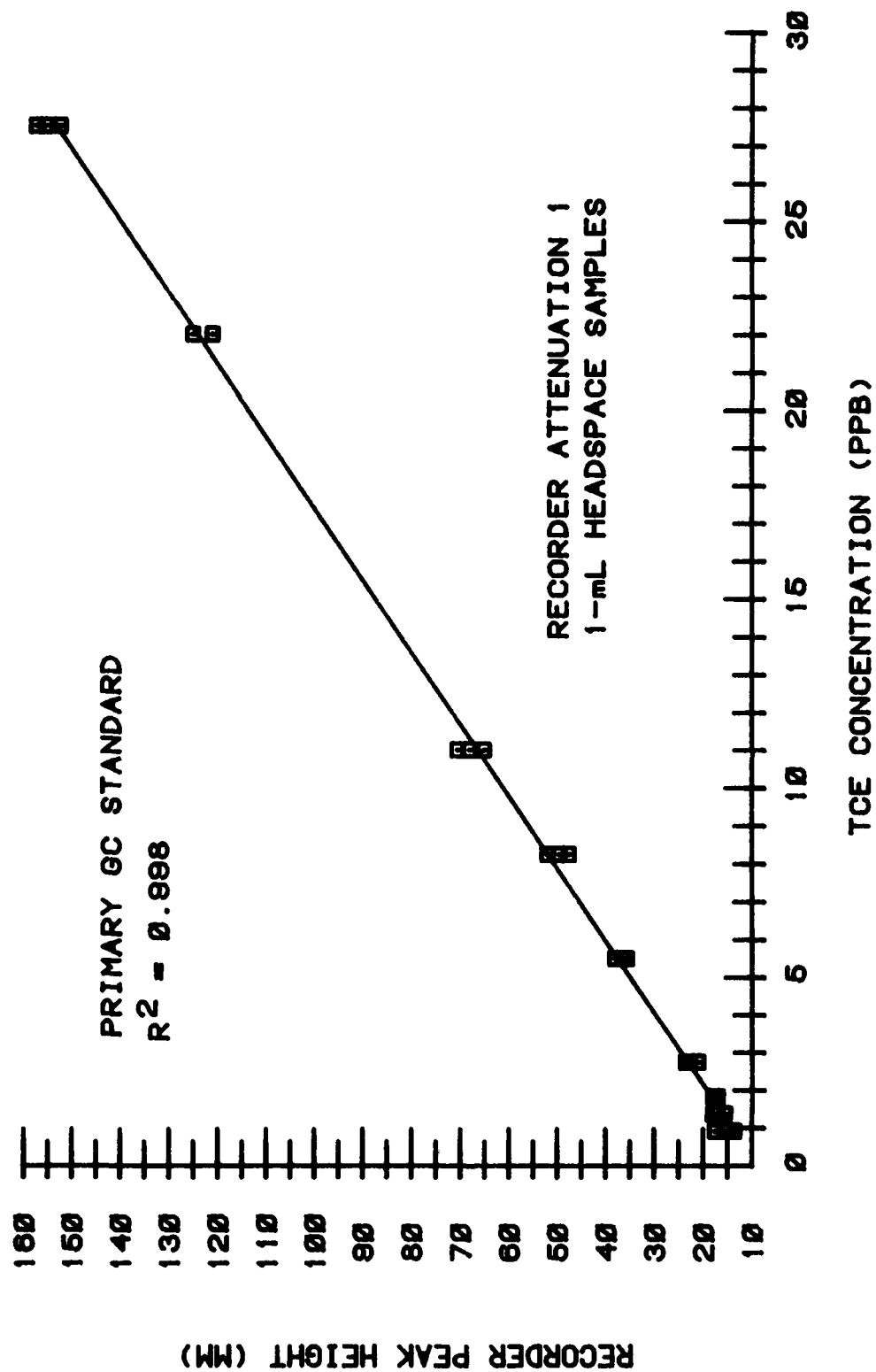
C. GAS CHROMATOGRAPH CALIBRATION

Headspace samples were obtained by inserting a gastight syringe through the Teflon®-lined silicone septa and withdrawing either 0.5 mL (for high TCE concentrations) or 1.0 mL (low TCE concentration). The sample was immediately injected on the GC. At least three injections were made for each bottle, and the resulting peak heights plotted. Figure B-1 shows a typical calibration curve. These ranges were selected so that all peak heights corresponding to the TCE concentrations in any one range would fit on the strip chart on a single attenuation. Thus, any error in the GC's attenuator was eliminated. Typically, an attenuation of 1, 8, and 64 was used for the low, middle, and high ranges, respectively. As the concentration in the purge-well system decreased over time, Attenuations 1, 8, and 16 were used. The excellent linearity of the calibration curves indicated a consistent instrument response, which verified the accuracy of the standards preparation technique. The calibration curves were spot-checked daily against the primary standards used to make the calibration standards. When they differed by more than 10 percent, new spot-check standards were made from the saturated solution. The primary

TABLE B-1. DILUTION SCHEME FOR PRIMARY AND GAS CHROMATOGRAPH STANDARDS

<u>Primary Solution (PS) Concentration (ppm)</u>	<u>Mass PS Added (g)</u>	<u>Total Mass of Standard (g)</u>	<u>Resulting Standard Concentration (ppb)</u>
1100 (saturated)	100	1000	(110 ppm)*
110	100	1000	(11 ppm)*
11 (11,000 ppb)	100	1000	(1.1 ppm)*
	120	120	11,000
	60	120	5,500
	30	120	2,750
1.1 (1,100 ppb)	100	1000	(0.11 ppm)*
	120	120	1,100
	60	120	550
	48	120	440
	30	120	275
	24	120	220
0.11 (110 ppb)	100	1000	(0.011 ppm)*
	120	120	110
	60	120	55
	48	120	44
	30	120	27.5
	24	120	22
0.11 (110 ppb)	120	120	11
	90	120	8.3
	60	120	5.5
	48	120	4.4
	30	120	2.8
	10	120	0.9

* Used in subsequent dilutions as a primary stock solution



B-1. Typical Gas Chromatograph Calibration Curve.

standards usually lasted about 3 days at room temperatures. Generally, these fresh standards agreed with the original calibrations. If there was still a difference of more than 10 percent, all new primary standards were made and new calibration curves developed.

D. SAMPLING PROCEDURES

Due to the volatility of TCE, a simple and repeatable sampling method was needed to obtain accurate concentration levels. In the earlier laboratory studies (Reference 7), 120 mL liquid samples were taken with a graduated cylinder and placed in the 240 mL amber-colored sample bottles. Since this technique was already proven, and was very simple, it was adapted for the onsite investigations.

Three 100 mL graduated cylinders were filled with 120 grams (120 mL) of water on an analytical scale. The water level was marked and a 6-millimeter (0.25-inch) hole drilled in each cylinder. When the cylinder was filled, any excess water over 120 mL would leak out the hole. Water samples only varied by ± 0.5 mL at most. To prevent any cross-contamination, a cylinder was dedicated to the influent water samples, and one to each of the effluent samples from the bottom of the towers.

Taking the water samples required some care to prevent any aeration and loss of TCE. First, the sample stream was set to a smooth, even flow with no air bubbles entrained near the mouth of the sample tap. The tap was allowed to run for at least 1 minute. The graduated cylinder was rinsed twice before taking the sample. The cylinder was tipped about 45 degrees to allow the sample stream to flow smoothly down the cylinder's side. Turbulence at the surface of the liquid and the intersection of the sample stream was avoided to prevent any aeration of the sample. Average sampling time was about 15 seconds. Once the sample was taken, the cylinder was turned upright to allow excess water to escape through the hole. The sample was then carefully poured into the sample bottle, again allowing the water to flow smoothly down the side with a minimum of turbulence. The bottles were immediately capped with a minimum amount of movement, and labeled. When samples were taken from the bottom of the towers, at least five volume changes of the wet wells were allowed between replicable samples. When either the water or air flows in the towers were changed, at least 10 minutes were allowed for flow stabilization and water change-out in the wet wells.

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DEVELOPMENT OF PACKED-TOWER AIR STRIPPERS FOR
TRICHLORDETHYLENE REMOVAL A. (U) AIR FORCE ENGINEERING
AND SERVICES CENTER TYNDALL AFB FL ENGI. R L GROSS
AUG 85 AFESC/ESL-TR-85-28 F/G 13/2

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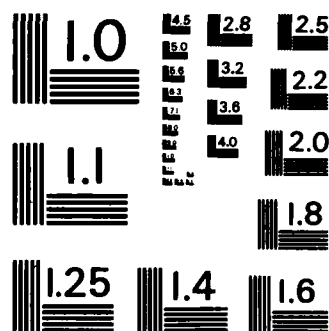
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MICROCOPY RESOLUTION TEST CHART
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E. SAMPLE ANALYSIS

The sample bottles were returned to the laboratory and placed on a shaker table. They were shaken for at least 5 minutes to allow the water temperature to equilibrate with the laboratory's. The samples were then allowed to rest for an additional 5 minutes so the headspace and liquid could equilibrate. A gastight syringe was inserted directly through the septum and either 0.5 or 1.0 mL of headspace removed. If the TCE concentration in the liquid was expected to be low, 1.0 mL of headspace was withdrawn; 0.5 mL was used for high TCE levels. The headspace was injected immediately onto the GC. At least two headspace samples were taken from each bottle. If the peak heights differed by more than 10 percent, a third sample was taken. All peak heights were averaged and compared to the calibration curve to obtain the TCE concentration in the water. On an average day, over 60 samples could be taken and analyzed.

After the data were logged, the sample bottles were emptied into the sink and the used septum was discarded. The bottles and plastic screw caps were washed in hot, soapy water and thoroughly rinsed. The bottles were placed in a tray in the electric oven and allowed to bake overnight at about 120°C. In the morning, they were removed from the oven, cooled, and fitted with new septa.

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