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LOW VOLATILE ORGANICS IN GROUNDWATER TECHNO-ECONOMIC EVALUATION OF AN INNOVATIVE TREATMENT PROCESS

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LOW VOLATILE ORGANICS IN GROUNDWATER-TECHNO-ECONOMIC EVALUATION OF AN INNOVATIVE TREATMENT PROCESS

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ABSTRACT

Conventional air stripping and granular activated carbon adsorption are two of the best available technologies for removing organic contaminants from water. The air-stripping process is uneconomical for contaminants of low volatility, and the adsorption process is considerably more expensive. An innovative process introduced as "cascade air stripping" was demonstrated to be more efficient than the conventional air-stripping process in removing contaminants of semi and low volatility. In this research, design, scale-up and engineering procedures for the cascade air-stripping process are developed and verified using laboratory and field scale systems. In addition, it is compared with the conventional air stripping and adsorption processes on the basis of capital, operating and overall treatment costs.

The process model and the scale-up procedures developed in this study were found to work well for the laboratory- and full-scale systems. For the five typical contaminants evaluated, cascade air-stripping system was found to be consistently more cost-effective than conventional air stripping and granular activated carbon adsorption.

Keywords: Groundwater, low volatile organics, cascade air stripping, air stripping, carbon adsorption, cost analysis.

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CHAPTER 1
INTRODUCTION

1.1 GENERAL

Air stripping (A/S) has been practiced as a unit operation in the chemical engineering industry for more than 50 years. During the past 10 years, air stripping has been adopted and modified by environmental engineers to treat groundwater contaminated with volatile organic chemicals. The process has been identified by the U.S. Environmental Protection Agency (US EPA) as one of the best available, least cost technologies (BATs) for removing many commonly encountered volatile organic chemicals (VOCs) from ground water (US EPA. 1984). The process is based on sound theoretical concepts validated in many pilot and full-scale applications (Cummins and Westrick 1983; Lamarre et al. 1983; Roberts et al. 1985; Wallman and Cummins 1985; Hand et al. 1986).

Air stripping is a mass transfer process where the contaminant is transferred from the liquid phase to the gas phase driven by the concentration gradient. The process configuration consists of a counter-current tower filled with a packing medium to enhance the mass transfer rate. Contaminated water is pumped to the top of the tower and dispensed above the packing to flow under gravity. Air is drawn through the packing, counter-current to the water flow, through vents at the base of the tower. As the air flows upward under a pressure gradient, it "strips" the contaminant from the water, and is vented to the atmosphere through the top of the tower or collected for further treatment. Treated water exits the base of the tower where it is collected for use or reinjected into the ground.

The economic viability of the conventional A/S process, however, is limited to VOCs of Henry's Constant values, H, greater than 50 atmospheres (atm) (Bower et al. 1988). For less volatile organic compounds (H less than 50 atm), theoretical and practical considerations require very high air flow rates to maintain adequate stripping factors, and large packing depths to achieve nominal removal efficiencies. These operating conditions lead to excessive pressure loss and power requirements, making the conventional A/S process uneconomical and forcing the use of more complex, expensive treatment processes such as activated carbon or steam stripping (Jang et al. 1990). Cascade A/S extends the range of applicability of the conventional A/S process to contaminants of low volatility.

1.2 DEVELOPMENT OF THE CASCADE SYSTEM

Cascade A/S is a simple modification of the conventional A/S system, conceived and advanced by researchers at Drexel University, Philadelphia, PA, in 1986. Developed from theoretical considerations, the cascade A/S system has been demonstrated to be more cost efficient than the conventional A/S process in removing volatile as well as low- and semi-volatile organic contaminants (Nirmalakhandan et al., 1990; 1991; 1992a; and, 1992b). This is achieved by the systematic distribution of fresh air along the height of the tower at discrete levels or "cascades." This novel modification allows considerably larger air flow through the tower, thus providing increased mass transfer and achieving higher removal efficiencies at nominal energy inputs. As a result of this simple modification of the conventional A/S system, a whole new class of organic contaminants can now be treated cost effectively.

Nirmalakhandan et al. (1990) developed a process model for the cascade A/S system based on fundamental mass transfer concepts utilizing "two-film resistance theory." According to this theory, the mass transfer rate across a gas-liquid interface under steady-state conditions is given by

$$J = K_La\,(C_1 - C^*_1)$$

where

J = rate of transfer of solute from the liquid phase to the gas phase (μg / L-s)

K_La = overall mass transfer coefficient referred to the liquid phase (s^{-1})

C_1 = concentration of the solute in water (μg / L)

and C^*_1 = equilibrium concentration of the solute in water (μg / L)

To maximize the rate of transfer, J, the mass transfer coefficient, K_La, and/or the concentration difference or gradient, $(C_1 - C^*_1)$, must be maximized. Since K_La is limited by the mass transfer characteristics of commercially available packing materials, the only alternative is to maximize the quantity $(C_1 - C^*_1)$.

The quantity $(C_1 - C^*_1)$ is referred to as the "driving force" which represents the departure of the gas-liquid system from steady-state equilibrium, as shown in Figure 1.1. Slope of the equilibrium line represents the Henry's Constant of the contaminant. Slope of the operating line represents the inverse of the volumetric air:water ratio. From Figure 1.1, it can be seen that by increasing the air:water ratio, the slope of the operating line can be reduced, increasing the driving force and thus improving the mass transfer rate of the counter-current system.

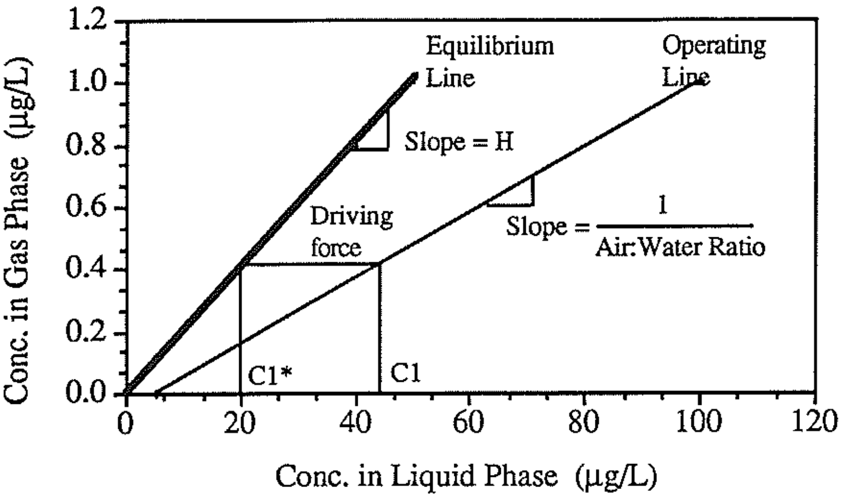

Figure 1.1 Driving Force in Counter-current System

The air:water ratio, however, can be increased only to certain limits. Excessive air:water ratios result in substantial pressure head requirements, operating expense and eventual failure of the system due to flooding. This problem is exacerbated in the case of low- to semi-volatile organics, because their low H values require a very high air:water ratio to achieve even modest removal efficiencies. The solution to this problem is to maintain the high driving force, yet maintaining nominal pressure head requirements and high removal efficiencies.

Nirmalakhandan and Speece (1987) based their initial design on a two-stage counter-current A/S system whereby VOC removal is split between two separate towers. This two-tower system allows operation at lower air:water ratios and lower pressure head requirements in each tower, while maintaining the same overall removal efficiency. The cascade A/S system was ultimately developed by extending this principle of two-stage operation to one of multi-stage operation in one tower. Fresh air is admitted along the entire length of the tower in "cascades," thus, air flow increases toward the top of the tower, maintaining the desired large driving force.

Nirmalakhandan et al. (1990) evaluated and predicted the performance of the cascade A/S system by developing a mathematical model. This model was used to illustrate theoretical advantages of the cascade A/S system by comparing it under various design and operating conditions against the conventional A/S system. Derivation of this mathematical model and rigorous treatment of these tests and their results are reported in detail in the literature (Nirmalakhandan et al., 1990, 1991; 1992a; and 1992b). Distinct features and potential advantages of the cascade A/S system over the conventional A/S system that are documented are as follows:

1) The cascade system accommodates 35% - 50% more air than the conventional system, when compared under equal air-side energy input and equal packing depth;
2) The gas phase pressure drop in the cascade system is 50% of that in the conventional system when compared under equal air-side energy input and equal packing depth;
3) The cascade system achieves higher removals than the conventional system when compared on the basis of equal air-side energy input and equal packing depth;
4) The cascade system can achieve removals of low volatile compounds comparable to or greater than the conventional system, even with packing depth reductions of up to 50%.

1.3 LIMITATIONS OF PREVIOUS RESEARCH

Practical applications of the above studies are somewhat limited due to the small diameter packing utilized: all previous studies used 1 inch (25mm) nominal diameter at pilot scale level. At least 2 inch (50mm) diameter packing would be preferable for larger, full-scale field applications. Water loading rates and air:water ratios were also much smaller than those that would be used in full-scale systems. In order to facilitate the engineering design and scale-up procedures for full-scale systems, pressure loss at higher air:water ratios should be evaluated under more realistic conditions. The current research was undertaken to address these limitations.

1.4 OBJECTIVES OF CURRENT RESEARCH

Regulatory agencies and water utilities are often reluctant to adapt new and innovative technologies unless their technical feasibility and economical advantages over existing technologies are demonstrated and documented adequately. The current research was undertaken to perform a techno-economic analysis of the cascade A/S system for comparison with existing technologies. The major objectives were to develop design, engineering and scale-up procedures to enable the cascade system to be taken from proof-of-concept level to prototype testing and demonstration under typical field conditions. Specific research objectives include the following:

1. To build and operate a prototype system to demonstrate and document the technical feasibility of the cascade A/S system under field conditions.
2. Develop procedures for sizing the air inlet ports along the packing and to estimate pressure drop for the cascade system, and verify the procedures on a lab scale system.
3. Establish guidelines for design and scale-up, and operating procedures for the full-scale cascade system.

4. Compare the cascade system with the conventional A/S system and the granular activated carbon (GAC) adsorption system in terms of removal capabilities, energy requirements, capital, operating and overall treatment costs for five commonly encountered synthetic organic chemicals (SOCs).
5. Verify the hypothesis that the cascade system has an economic advantage over existing conventional treatment technologies.
6. Conduct a sensitivity analysis to determine optimal water loading conditions for the cascade A/S process.

CHAPTER 2

LABORATORY STUDIES ON PRESSURE DROP

2.1 OBJECTIVES

Pressure drop is an important process parameter in air stripping. Numerous studies have been done on the pressure drop in the conventional A/S process, and correlations and charts have been published for its estimation. In the cascade mode, such data should be generated for use in design, scale-up, engineering and optimization procedures. The primary objective of this section of the study was to develop a method to predict pressure drop in the cascade system under a range of air and water loading conditions typical of field conditions. An experimental study in a lab scale cascade A/S system was conducted to generate the data for this purpose. Using this data, a numerical procedure for estimating pressure drop was developed and validated.

2.2 DESIGN OF LABORATORY SYSTEM

The tower shell was constructed from 1.5 feet diameter PVC light-wall pipe, 20 feet tall. The tower was placed on end in a 6-foot diameter water trough, 2 feet in depth. A total of 16 air inlet ports, 2 inches in diameter, were fitted along the tower wall at eight levels or "cascades," spaced 2 feet apart, with two diametrically opposed ports at each level. Butterfly valves installed on these inlet ports enabled controlled amounts of air to be admitted through the system. A blower capable of 990 cfm at 15 inches water column (WC) was installed to provide the air flow and was connected by an 8-inch diameter PVC duct to the top of the tower.

The tower was filled to a depth of 16 feet with 2 inch diameter Tri-Pack polypropylene packing material. This packing provides a void volume of 93% and a surface area of 48 ft^2/ft^3. The packing to tower diameter ratio was 1:9 which is adequate to maintain uniform water distribution without any channeling. Redistributor rings were installed as recommended in the Chemical Engineers Handbook (1984). Water was pumped to the top of the tower by means of a Teel 1/2 HP, submersible pump where it was dispensed over the top of the packing through a distributor fabricated from 2-inch PVC pipe. Water flow rate was adjusted by means of a 2-inch gate valve installed on the downstream side of a dial flow meter. The system was designed to handle water flows ranging from 15 to 50 gpm. and volumetric air:water ratios from 40 to 350.

A water-filled manometer was used to measure drops in air pressure along the packing depth. One leg of the manometer was permanently connected to the base of the packing and the other end to each successive 2-foot packing interval. Pressure drop was measured as the difference in the water level between the two manometer legs. Air velocities were measured using an Omega air-flow meter (Model HHF-610, Stamford, CT). The probe of the air-flow meter was inserted to 85% radial depth of each of the 2-inch air inlets and the 8-inch exhaust line to read mean air velocities. A schematic arrangement of the laboratory cascade A/S system is shown in Figure 2.1.

2.21 Laboratory System Operation

The laboratory system was designed specifically to measure pressure drop along the packing under different air and water loading rates. A total of 56 runs were conducted at all combinations of seven air flow rates and eight water flow rates ranging from 15 to 50 gpm at 5 gpm increments. Air and water flow rates for each test are tabulated in Table 2.1.

TABLE 2.1 Air and Water Flow Rates for Laboratory Tests

Test	Air Flow Through Each 2 Inch Inlet [cfm]	Total Air Flow Through System [cfm]	Water Flow Rates [gpm]
Run 1	43.6	698	15 to 50
Run 2	39.3	628	15 to 50
Run 3	34.9	558	15 to 50
Run 4	30.5	489	15 to 50
Run 5	26.2	419	15 to 50
Run 6	21.8	349	15 to 50
Run 7	17.4	279	15 to 50

The first step of each run was to adjust the water flow into the laboratory system. Initial water flow rate was set at 50 gpm. As the test progressed, flow rate was decreased by increments of 5 gpm to the final flow rate of 15 gpm.

The second step of each run was to control the air flow into the system by adjusting each of the 16 butterfly valves on the air inlet ports at the eight cascade levels. Each valve was individually adjusted such that all 16 inlets admitted the same volume of air into the system. This was determined by measuring the velocity of the air stream at each 2-inch inlet and multiplying by the area of cross section of the port.

The third step of each run was to verify volume balance between the air entering the system through the 16 inlets and the air exiting the top of the tower through the exhaust line. Typical results of volume balance studies are shown in Table 2.2. The difference between total volume flow through the air inlets and the exhaust volume flow ranged from 2.5% to 6.1%, averaging <4%. This was within the accuracy of the air flow meter, and was considered adequate for scale-up and engineering design purposes.

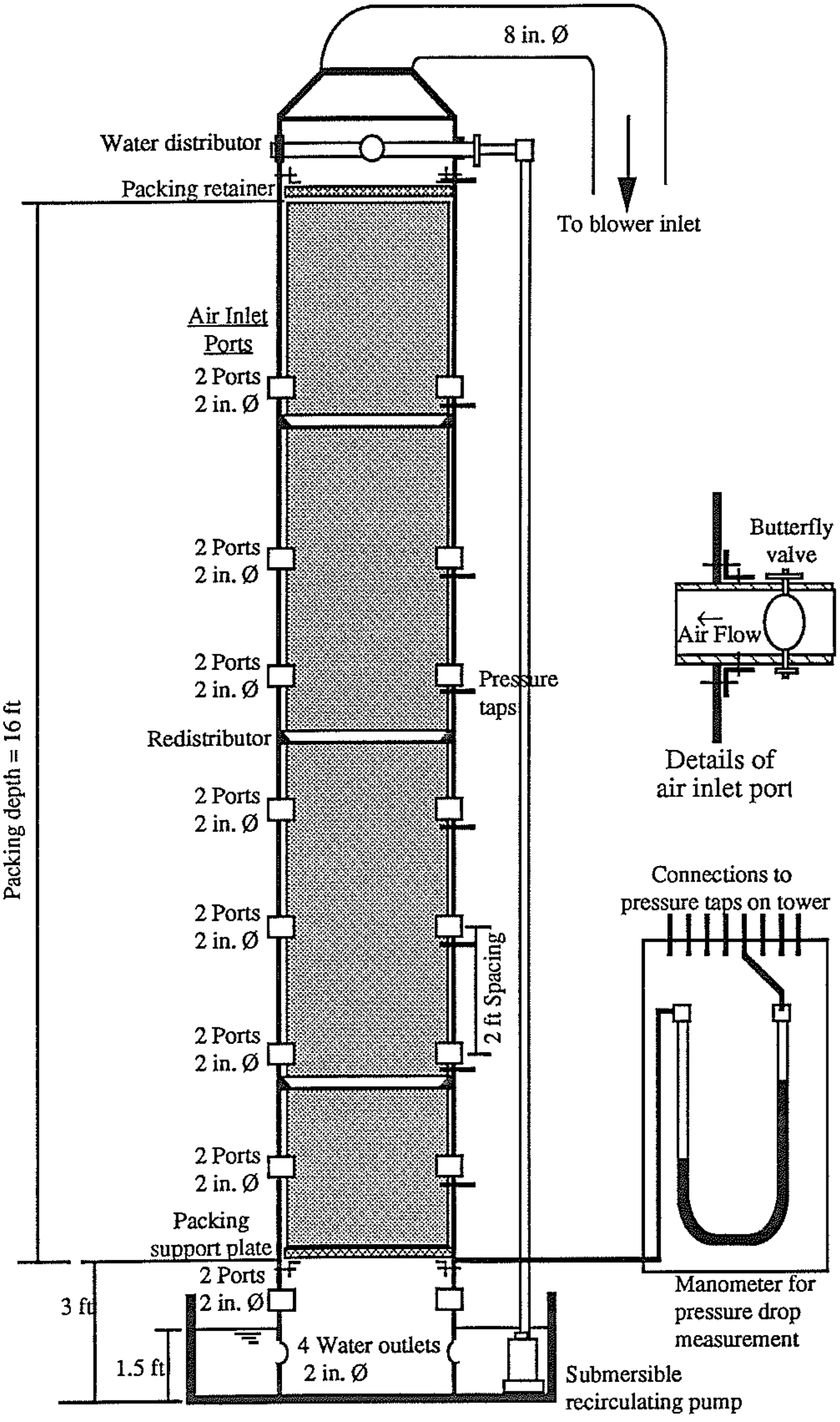

Figure 2.1. Schematic of Laboratory System

TABLE 2.2 Results of Volume Balance Studies

Test	Total Volume via 2 in. Inlets [cu ft/min.]	Average Exhaust Volume Flow [cu ft/min.]	Average Difference [cu ft/min.]	Average Difference %
Run 1	698	716	18	2.5
Run 2	628	646	18	2.8
Run 3	558	576	18	3.1
Run 4	489	506	17	3.4
Run 5	419	436	17	3.9
Run 6	349	367	18	4.9
Run 7	279	297	18	6.1
		Average	18	4

Once volume balance was achieved and the system was operating at steady state, pressure drop in inches WC was recorded for each successive packing interval, e.g., for Run 1, pressure drop was recorded as a function of packing depth in increments of 2, 4, 6, 8, 10, 12, 14, and 16 feet measured from the base of the packing.

2.3 RESULTS OF LABORATORY STUDIES

The laboratory runs were made for a matrix of eight water loading rates by seven air flow rates. For each of these 56 loading conditions, duplicate pressure drop values were recorded at each of the eight cascade levels, yielding a total of 896 readings and 448 data points. These results are tabulated in Appendix A which shows that the pressure drop variation over the full range of water loading rates is consistent in each run. These test conditions ranged from 20% to 50% of flooding for the 2-inch Tri-Packs packing media, typical of field level conditions.

Data in Appendix A were used to develop overall pressure drop curves for the cascade system. Overall pressure drop at equal water loading was plotted against the total air loading for each run. A power regression was performed for each series of data. The result is a family of overall pressure drop curves at water loading rates ranging from 8.5 to 28.3 gpm/ft^2 as shown in Figure 2.2. It should be noted, however, that these curves are applicable strictly to 2-inch (50 mm) Tri-Pack packings in the range of loadings used to develop these curves.

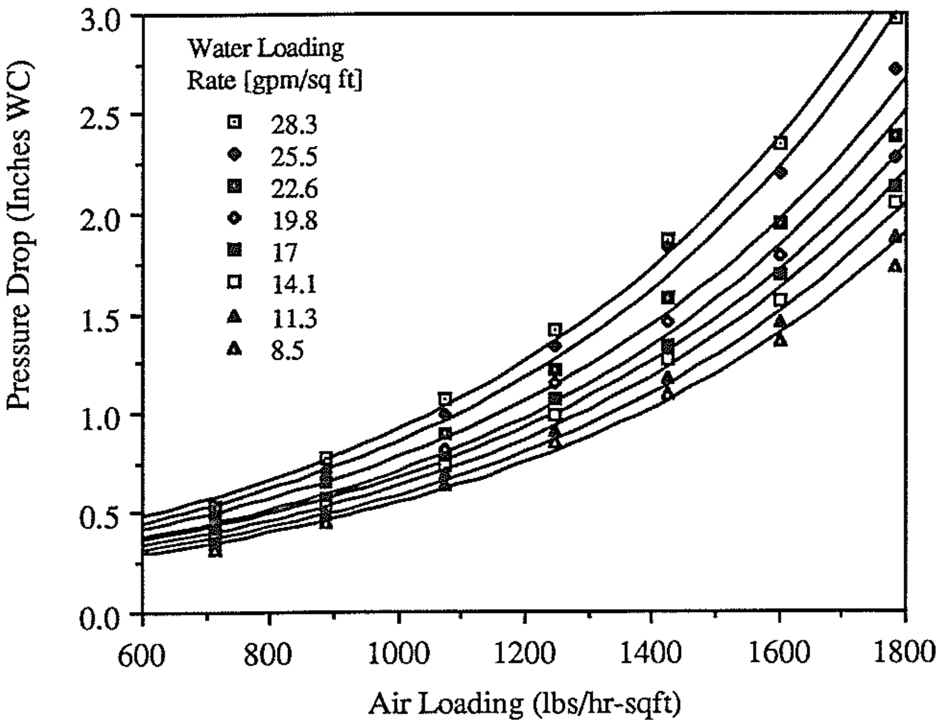

Figure 2.2 Overall Pressure Drop at Various Air and Water Loading Rates

2.4 DEVELOPMENT OF PRESSURE DROP MODEL

In order to develop design and optimization procedures, a numerical model was developed to predict pressure drop over a range of air and water loading conditions. The model was derived by considering the cascade system shown in Figure 2.3 and by utilizing published pressure drop curves for 2-inch polypropylene Tri-Packs (Jaeger Products, Inc., Spring, TX) in the conventional A/S configuration. (The manufacturer's technical data sheet is reproduced in Figure 2.4.)

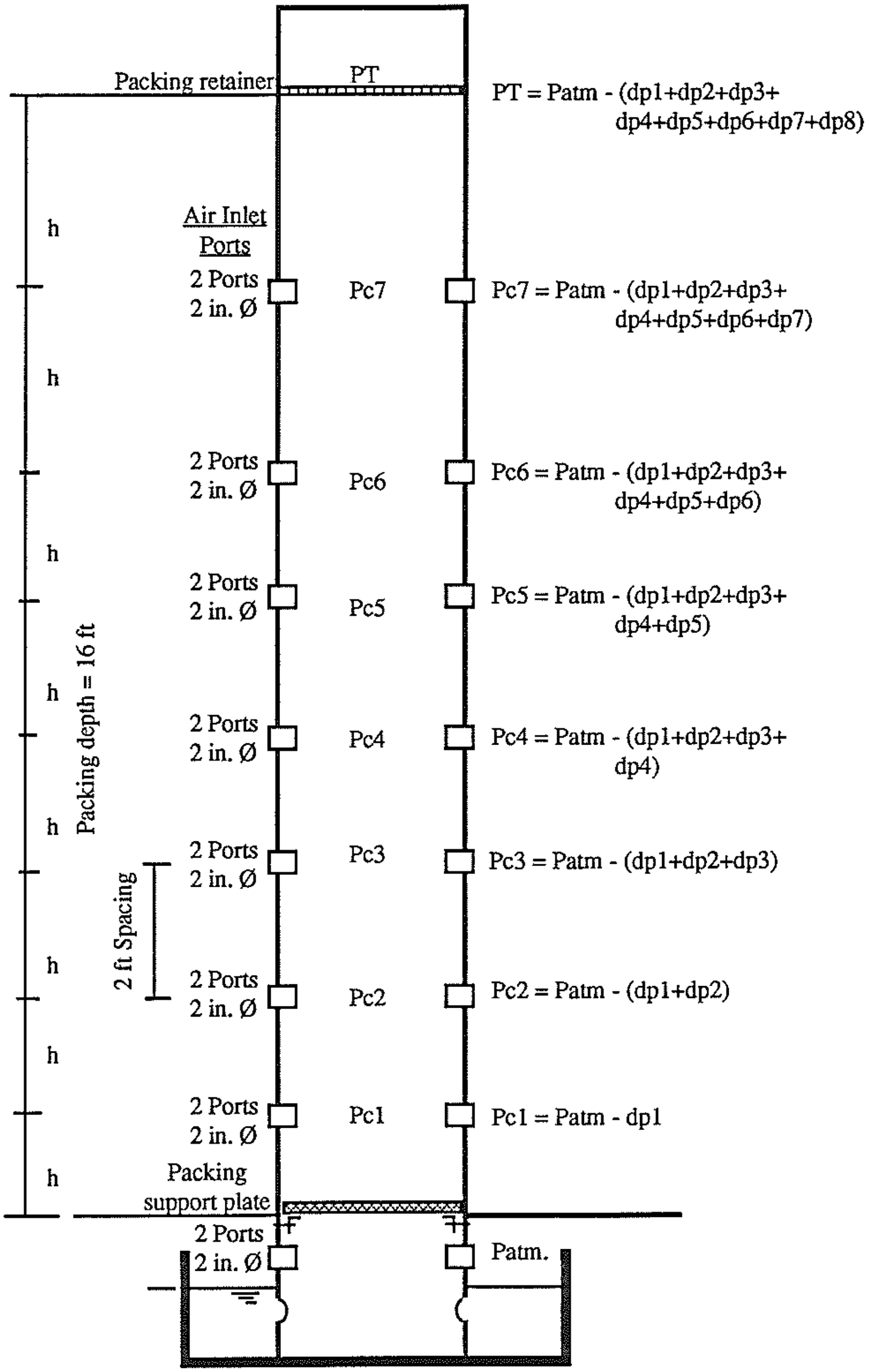

Figure 2.3 Schematic Of Cascade System For Pressure Drop Modelling

Assuming atmospheric pressure at the base of the packing, the pressure at cascade 1, P_{C1}, is equal to the atmospheric pressure, P_{atm}, less the pressure drop, d_{p_1}, due to the air and water loading rate along the depth of packing, h_1, to cascade 1:

$$P_{C1} = (P_{atm} - d_{p_1})$$

d_{p_1} is obtained from Figure 2.4 by locating the overall air loading rate for cascade 1, q_1, in lbs/hr-ft^2 on the abscissa, intersecting the proper water loading rate curve on the graph in lbs/hr-ft^2, and reading the corresponding pressure drop in inches on the ordinate. This pressure drop, dpg, is then multiplied by the depth of packing to cascade 1:

$$d_{p_1} = (d_{pg} . h_1)$$

Advancing to cascade 2,

$$P_{C2} = P_{atm} - (d_{p_1} + d_{p_2})$$

where

$$d_{p_2} = (d_{pg} . h_2)$$

and d_{pg} is obtained from Figure 2.4 at an overall air loading rate of $(q_1 + q_2)$, where q_2 is the overall air loading rate for cascade 2.

Advancing to cascade 3,

$$P_{C3} = P_{atm} - (d_{p_1} + d_{p_2} + d_{p_3})$$

where

$$d_{p_3} = (d_{pg} . h_3)$$

and d_{pg} is obtained from Figure 2.4 at an air loading rate of $(q_1 + q_2 + q_3)$, where q_3 is the overall air loading rate for cascade 3.

This numerical procedure is continued to obtain the total pressure, P_T, at the full depth of the packing,

$$P_T = P_{atm} - (d_{p_1} + d_{p_2} + d_{p_3} + \dots\dots\dots\dots + d_{p_8})$$

Model calculations at the various air and water loading conditions for the laboratory tests are detailed in Appendix B.

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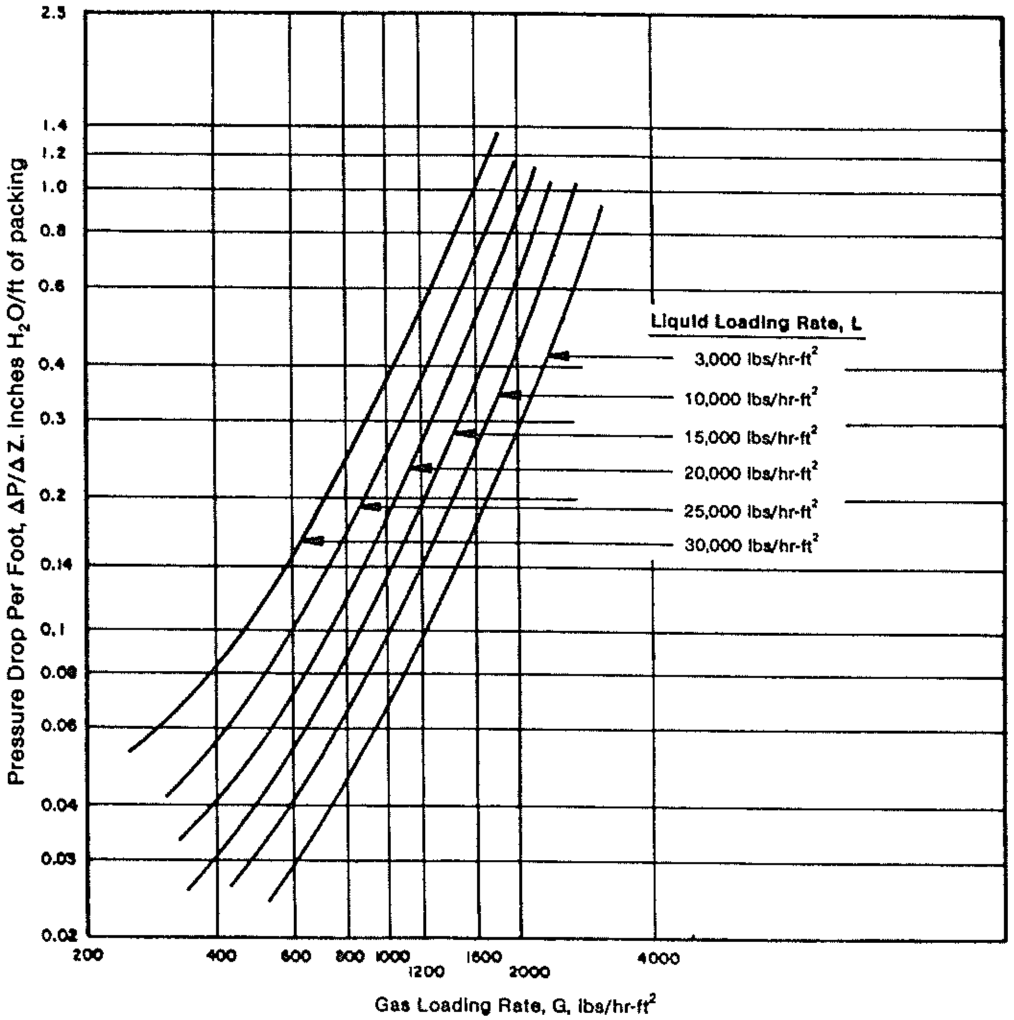

Figure 2.4 Pressure Drop Curves For 2" Tri-Packs In Conventional A/S
[Source: Jaeger]

2.5 VALIDATION OF PRESSURE DROP MODEL

Model results were calculated for each test under identical air and water loading conditions and compared with those obtained from the laboratory system. Experimental and calculated overall pressure drop are compared for Runs 1 through 7 in Figure 2.5, indicating close agreement between the experimental and calculated pressure drops. Detailed calculations of the pressure drops at each cascade level are presented in Appendix B. These data also confirm the close agreement between the experimental and predicted data, thus validating the numerical model.

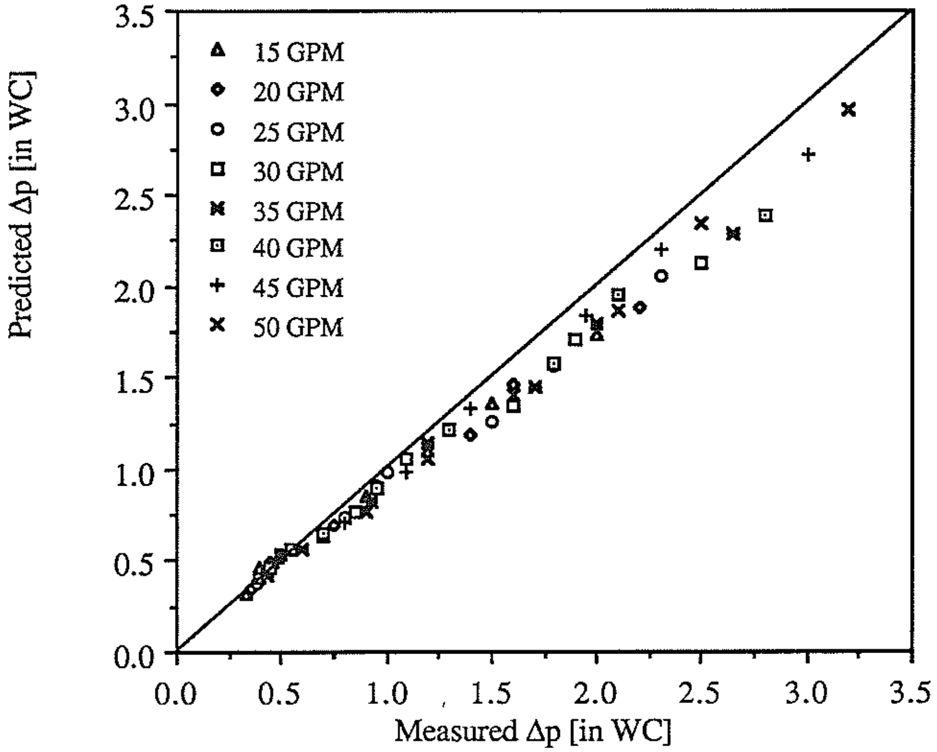

Figure 2.5. Comparison Between Predicted and Measured Overall Pressure Drop

CHAPTER 3
LABORATORY STUDIES ON AIR FLOWS

3.1 OBJECTIVE

In the laboratory system, the air inlet ports were fitted with butterfly valves to control the amount of air input to the system. In a field system, it is preferable to size the air inlet ports in advance to allow predetermined equal amounts of air at each cascade level. Any change in overall air flow may then be achieved by damping the blower outlet. The objective of the following studies was to develop and validate a procedure to size the air inlet ports to provide a desired air distribution pattern in the cascade A/S system. Air flow data presented in Chapter 2 were used to calibrate and validate the model.

3.2 DEVELOPMENT OF AIR FLOW MODEL

The air inlet ports were modeled as orifices. By combining the energy equation and the continuity equation the following orifice equation can be derived:

$$D = 12 \sqrt{\frac{4\,q}{\pi\, C_D \sqrt{2g\ \Delta P}}}$$

where,

D = Port diameter (in)

q = Volumetric flow rate through the port (cfs)

ΔP = Pressure drop across the port (ft)

C_D = Coefficient of discharge

g = Acceleration due to gravity (ft/s^2)

In the design of the cascade system, to determine the port size at any level for a desired air input of q, the pressure drop has to be calculated first using the procedure described in Chapter 2. Then, the above equation may be used to find the diameter, D. The above equation can be rearranged to determine the air flow through each port in the experimental system using the known D and the measured ΔP. This enabled validation of the above procedure using the experimental data.

3.3 VALIDATION OF AIR FLOW MODEL

The data generated using the laboratory system were used to validate the above procedure. The laboratory system consisted of 16 air inlets (2 inlets at each cascade level) of 2-inch diameter as shown in Figure 2.1. The coefficient of discharge for the analysis was assumed to be 0.65. The theoretical air flow was calculated at each cascade for different water flow rates using the pressure drops calculated according to the procedures described in Chapter 2. The results of this calculation are tabulated in Appendix C. The theoretical and measured air flow rates are compiled for comparison in scatter diagram, Figure 3.1, for water flow rates ranging from 15 to 50 gpm. It can be seen from this diagram that the agreement between the experimental and predicted air flow rates is satisfactory: the r^2 for the correlation between the predicted and experimental values ranging from 0.962 to 0.998 for the eight water flow rates.

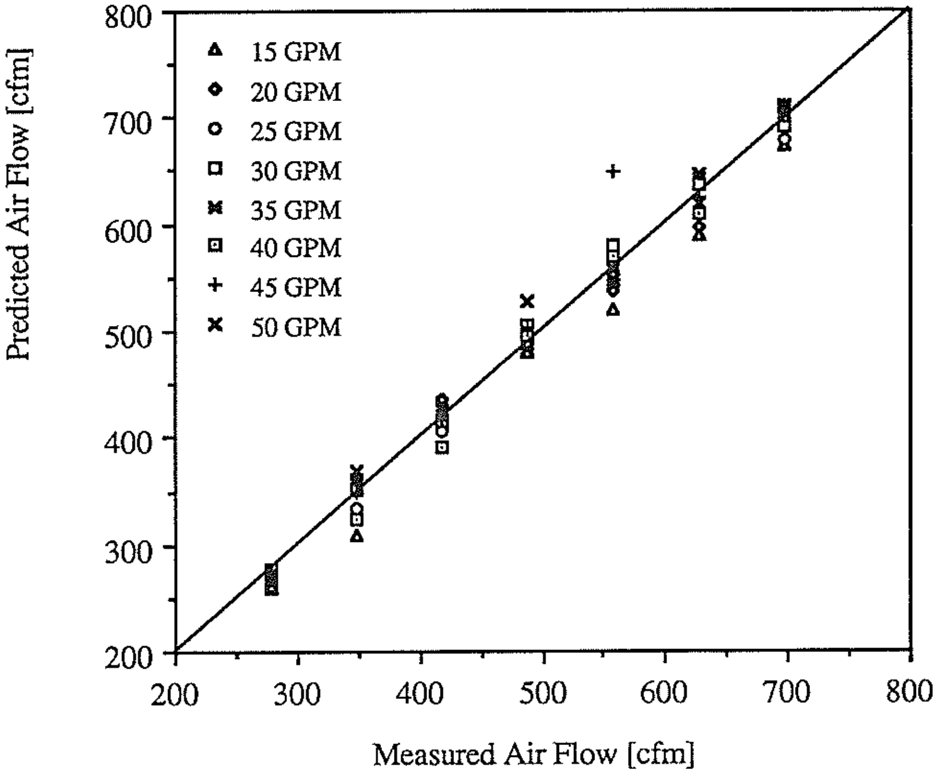

Figure 3.1 Comparison Between Predicted and Experimental Air Flows.

CHAPTER 4
FIELD STUDIES

4.1 OBJECTIVE

The studies described in this section were conducted to demonstrate the technical feasibility of the cascade system and to validate the process model, pressure drop model and the air flow model under full scale, field conditions. This study was partly funded by NASA and conducted in collaboration with Geoscience Consultants Ltd. The sampling and laboratory analysis were conducted by Lockheed Ltd., as an independent contractor to NASA.

4.2 BACKGROUND

In 1985, a large subsurface plume of organic chemicals was discovered at the NASA White Sands Test Facility (WSTF) in south-central New Mexico. Since discovery, many environmental studies have been conducted to characterize the nature and extent of the contamination. Primary contaminants identified in the groundwater at this site include Freon-11, Freon-113, trichloroethylene (TCE), and tetrachloroethylene (PCE).

To evaluate the hydraulic characteristics of the contaminated area, a groundwater pumping test was conducted at this site. Because of the high concentrations of the four contaminants expected, the New Mexico Environmental Improvement Division (now referred to as the New Mexico Environmental Department) required the pumped waters be treated before surface discharge. Three processes for on-site remediation of the pumped water were evaluated by NASA: GAC, conventional A/S, and cascade A/S. Based on preliminary estimates of capital and operating costs, the cascade A/S process was chosen. The system was designed and fabricated at the Civil, Agricultural and Geological Department at New Mexico State University.

4.3 DESIGN OF FIELD SYSTEM

The full-scale field system was designed to remove four contaminants at this site, TCE, PCE, Freon-11, and Freon-113. TCE was chosen as the target contaminant because it had the lowest Henry's Constant. The process model developed previously was used to design the basic system. Detailed design calculations involving pressure drop and the air inlet port sizing were done according to the procedures described in Chapters 2 and 3. Design parameters are summarized in Table 4.1, and the system's main features are summarized in Table 4.2.

TABLE 4.1 Design Parameters for Field Cascade System

Total Gas Loading Rate	2,546 lbs/hr-sq ft		
Water Loading Rate	21,238 lbs/hr-sq ft		
Depth of Packing	17 ft		
Diameter of Tower	3 ft		
Target Contaminant	TCE		
Henry's Constant	450 atm.		
Expected Treatment:			
	Influent [ppb]	Effluent [ppb]	Removal [%]
TCE	430	5.0	98.8
PCE	24	0.2	99.4
Freon-11	340	0.5	> 99.9
Freon-113	1,600	2.2	> 99.9

TABLE 4.2 Main Features of the Field System

Packing depth	17	ft
Tower diameter	3	ft
Packing type	Jaeger Tripack	
Packing material	Polypropylene	
Nominal packing size	2	in
Packing/Tower diameter ratio	1:18	in/in
Water flow rate	150 to 450	gpm
Air:water ratio	60 to 90	vol/vol

The field system was constructed from galvanized steel culvert, 3 feet diameter x 24 feet long. The tower was placed on end in a circular water trough 6 feett diameter and 2 feet deep. A 3,500 RPM, 9.6 kW blower rated at 6,000 ft^3/min. at 8 inches WC was installed alongside the tower and connected by a 1-foot diameter air line to the top of the tower to provide air flow through the tower. Packing material was 2-inch Tri-Packs. Influent was distributed over the top of the packing through a distributor fabricated from 4-inch PVC pipe. Effluent was collected at the base of the tower in the trough and discharged by means of a 6-inch PVC pipeline into a surface trench 1,500 feet from the site. A schematic arrangement of the field system is shown in Figure 4.1.

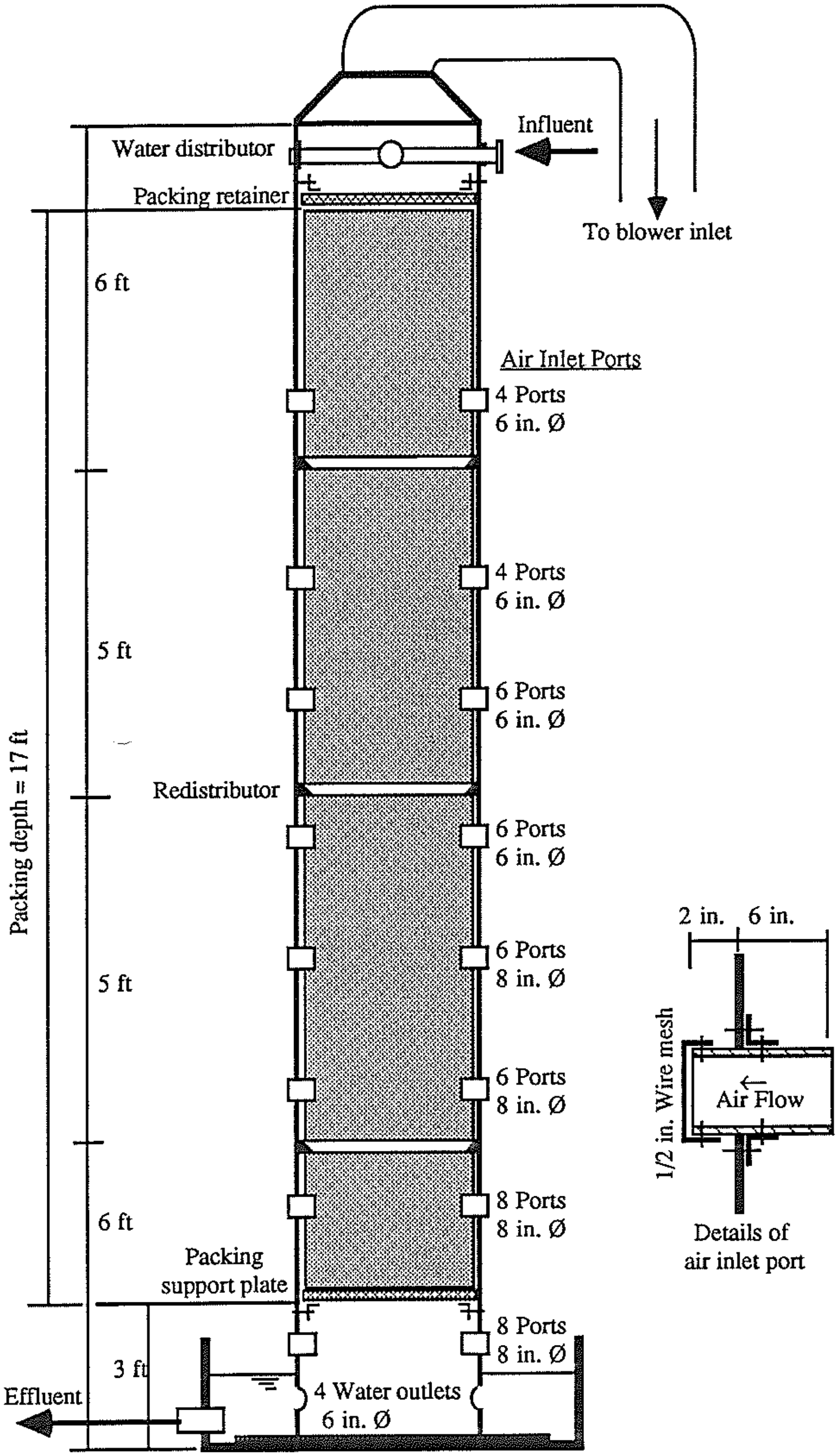

Figure 4.1 Schematic of Field System

4.31 Sampling of Field System

Sampling ports were installed at the top and at the base of the packing to collect untreated influent and treated effluent, respectively. Influent and effluent samples were collected, preserved and transferred to the laboratory where analyses were conducted according to US EPA method 601.

4.32 Operation of Field System

Two brief initial stripping tests were conducted to practice sampling methodology and to test the system's hydraulic integrity. The first lasted an hour. Water flow rate was initially set at 185 gpm and was increased in stages to 360 gpm. Influent and effluent samples were taken at 5-minute intervals to test for short-term variations in influent concentration.

The second test was 3.5 hours long, during which time several water flow rates ranging from 150 to 450 were evaluated. Influent and effluent samples were taken during successive stages of water flow rate adjustment.

The actual test of the field cascade system was expected to last 14 days at the design water flow rate of 300 gpm. During initial testing, however, the field system achieved effluent levels well below the surface discharge limits set by NM Environmental Department. Final testing of the field system was therefore conducted at 400 gpm, enabling the actual test to be completed in four days. During the actual test, the field system was monitored on a 24-hour basis and influent and effluent samples were taken at regularly scheduled intervals.

4.4 RESULTS OF FIELD TESTS

Results from the field tests are shown in Figure 4.2 and 4.3. Figure 4.2 represents variation in removal efficiency with water flow rate for the initial 3.5-hour test as well as the 4-day actual test. Removal efficiencies predicted by the process model, represented by the solid line, are included in this figure. Results from the initial 3.5 hour test fall just below the model prediction. This is probably due to channeling through the packing since the water flow rate was well below the design point of 300 gpm (shown in the figure). Results for the actual 4-day test fall uniformly above and below the model prediction within a range of ± 1.5%. The large dat spread could be due to fluctuations in the power supply leading to surges in the water flow rate or marked variations in desert temperature during the duration of the test.

Influent and effluent concentration profiles for TCE are shown in Figure 4.3 for the 4-day test. Effluent concentrations consistently remain well below NM Environmental Department surface standards of 100 ppb and very close to US EPA drinking water standards of 5 ppb. The other three contaminants, PCE, Freon-11, and Freon-113, were removed to below laboratory detection limits.

These field data not only demonstrate the technical feasibility of the cascade A/S system under normal operating conditions but also the flexibility of the system. These data reflect an average water flow rate of 400 gpm, which is 33% higher than the original design water flow rate of 300 gpm. Results of this field study fall reasonably close to the model predictions over the wide range of water loadings investigated. Procedures developed in this study thus can be considered adequate for future full-scale applications.

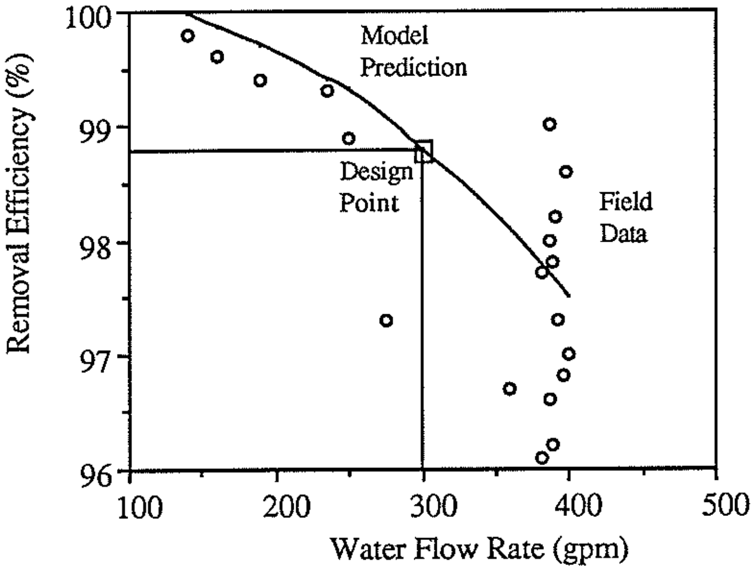

Figure 4.2 Effect of Water Flow Rate on Removal Efficiency

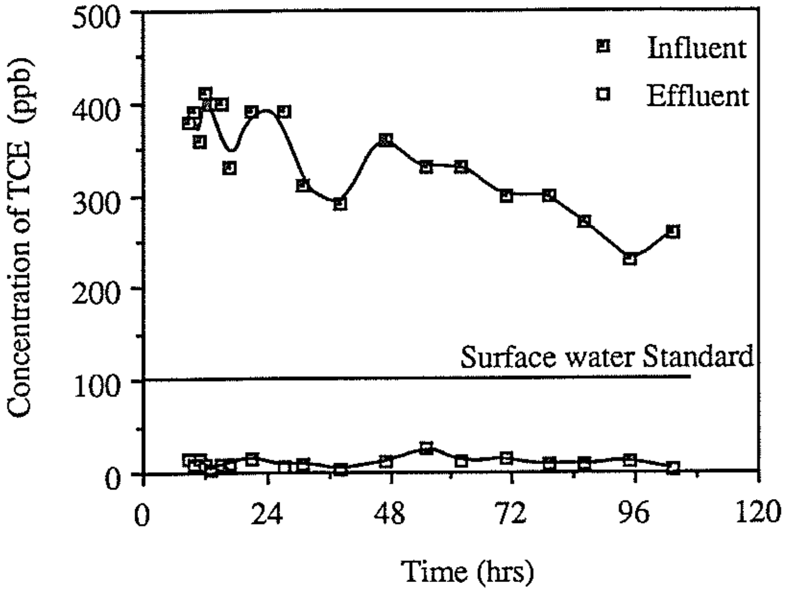

Figure 4.3 Field Results from 4-Day Test

CHAPTER 5
ECONOMIC ANALYSIS

5.1 OBJECTIVE

The objective of the economic analysis was to compare the conventional A/S, cascade A/S and the GAC processes on a common basis. Capital, operating and overall treatment costs of five common organic contaminants by the above three technologies were estimated for different plant sizes and at different removal efficiencies. The compounds selected were: xylene, chlorobenzene, and 1,2-dichloropropane, ethylene dibromide (EDB), and 1,2 dibromo-3-chloropropane (DBCP). These contaminants represented a wide range of volatility from moderate to very low.

5.2 COST ESTIMATION PROCEDURES

In the following analysis the "module technique" proposed by Guthrie (1974) was used to estimate cost factors for the conventional A/S and the cascade A/S systems. It is a fast, accurate and consistent method for cost estimation, the assumptions and applications of which are discussed in detail by Guthrie (1969; 1974). Cost factors for the GAC process were obtained directly from the literature (Adams and Clark, 1989).

The design characteristics of the conventional and the cascade air stripping system were determined using computer programs developed earlier (Nirmalakhandan et al. 1987; 1990). The construction and equipment cost data for these designs were obtained from the literature and handbooks (Guthrie 1974). The annual cost for the treatment was calculated by summing the amortized capital cost and the annual operational cost. Final treatment cost was calculated as cents per 1000 gal.

Direct capital cost of the conventional and cascade air-stripping system included the tower construction and installation cost, blower cost, pump cost, and the packing cost. Information for the tower construction and installation, blower, and pump costs were taken from the Process Plant Evaluation and Control (Guthrie, 1974) and updated to 1990 values using the ENR Construction Cost Index. Packing cost for 2-inch Tri-Pack, $ 30 per cu ft, was obtained from the manufacturer (Jaeger Tri-Pack® Inc.). Capital amortization cost was included at a rate of 10% over 20 years of operation.

The major component of the direct operating cost in air stripping is the power cost. In general, the power cost would be site specific, but for the analysis presented below, an average cost of $0.08/Kw-hr has been assumed. Other direct costs such as labor and maintenance were not included as they are site specific. Indirect operational costs such as overhead and insurance, working capital, engineering and construction overhead costs, contractor's fee, consultation fee, and start-up costs also were not included.

5.3 COST ESTIMATIONS FOR CONVENTIONAL AIR STRIPPING

5.31 Design Considerations

Cost estimations for the treatment of volatile chemicals (i.e., xylene, chlorobenzene, and 1,2-dichloropropane) by conventional A/S process were made from the computer cost model published previously (Nirmalakhandan 1987). A sample output from this program summarizing all the input parameters and the design outputs is shown in the Appendix D. As the cost associated with the conventional A/S model does not account for the inflation increases in construction costs and other hardware costs, these were updated using the procedure suggested by Guthrie (1969).

The conventional A/S program (Nirmalakhandan 1987) can be used only for chemicals having Henry's constant greater than 100 atm. Hence the cost estimates for the treatment of semi-volatile ($H < 100$) chemicals, (i.e., EDB and DBCP), were made in this study by modifying the computer program for the cascade A/S process. In the analysis of the low-volatile contaminants, the air was introduced only in the bottom port, keeping the other air ports closed and the relative depth was calculated. Detailed calculations and results of the analysis are presented in Appendix E.

From the computer program, optimum tower diameter, packing depth and the air flow were determined which were then used to calculate pump power and blower power, assuming efficiencies of 60% and 70%, respectively:

Pump power [HP] = Water flow, gpm x packing depth, ft /(3960 x 0.60)

Blower power [HP] = 0.000157 x Air flow cfm x Δp / 0.70

Pressure drop, Δp, was estimated from manufacturers technical data sheets. Packing volume was calculated from the tower diameter and packing depth as:

Packing volume [cu ft] = $(\pi/4)$ (Tower dia., ft)^2 (packing depth, ft)

5.32 Cost Estimations

The treatment costs obtained from the above analysis used a cost data base for 1988. The costs were updated to 1990, and the overall treatment costs were calculated using the procedure described below.

Tower shell cost, '90 [$] = 1.4873 x Tower shell cost, '73 (Guthrie, 1974, p 192)
Pump cost, '90 [$] = 1.4873 x Pump Cost, '73 (Guthrie, 1974, p 157)
Blower cost, '90 [$] = 1.4873 x Blower Cost, '73 (Guthrie, 1974, p 162)
Packing cost, '90 [$] = $30 x Packing volume
Total capital cost, '90 [$] = Tower shell cost, '90, $ + Pump cost, '90, $
+ Blower cost, '90, $ + $30 x Packing volume, $

Annual capital cost [$/yr] = 0.117 x Total capital cost, '90, $

Annual operating cost [$/yr] = Total HP x 0.747 kW/HP x 0.08 $/kW-hr x (24 x 365) hrs/yr

Annual total cost [$/yr] = Annual capital cost , $/yr + Annual operating cost, $/yr

Treatment cost [¢/1,000 gal] = {Annual total cost $/yr x 100 ¢/$} ÷ {MGD x 1,000 x 365}

5.4 COST ESTIMATIONS FOR CASCADE AIR STRIPPING

5.41 Design Considerations

A computer model for cascade A/S developed by the Nirmalakhandan (1990) was used for the cost analysis of the five volatile and semi-volatile contaminants. In this model the tower diameter and the air flow through the system were the variable parameters. The analysis for the above five chemicals was done for water flow rates of 1 to 50 million gallons per day (MGD). The design analysis was done using the same tower diameter (ft.), water loading rate (gpm/ft^2) and removal efficiency as in the conventional air-stripping system. The air flow (cfm) in the cascade A/S process was about 40%-50% more than the conventional A/S process. The air at the bottom of the tower was maintained close to a stripping factor R = 1. This is done as the stripping factor in the tower should be greater than or equal to 1 to ensure a positive removal potential at the bottom of the tower. The remainder of the air was distributed equally through the other ports, located 2 ft. apart. The tower depth was then calculated from the computer model for the corresponding removal efficiency. An iterative method was employed to find the largest reduction in the depth within the 40%-50% increase in the air flow.

Once the depth of the tower was determined, the other design parameters were calculated as follows: pressure drop was estimated using the procedure described in Chapter 2; pump and blower HP were calculated as indicated above for the conventional system; packing volume was estimated from the tower diameter and packing depth as before.

5.42 Cost Estimations

Treatment costs were calculated using the above design parameters and the cost estimating procedures outlined earlier for the conventional system.

5.5 GRANULAR ACTIVATED CARBON COST DATA

Cost and performance data of the GAC system were taken from Adams et al.,1989, as this was the best and the latest data available. One of the critical parameters in determining the cost of the GAC treatment is the GAC use rate, that is, the quantity of carbon required to treat a specified volume of water or the bed life of the activated carbon (Adams and Clark, 1989). A constant pattern homogeneous surface diffusion model (CPHSDM) and pore surface diffusion flux ratio model (PSDFR) were used to determine the GAC use rate for a single solute SOCs. The input parameters required by the CPHSDM model were the Freundlich Isotherm K and 1/n values. Assumptions for the data presented in Table 5.1 for the use rates were 1) a single full scale GAC contactor with an empty bed contact time (EBCT) of 15 minutes and 2) a hydraulic loading of 4 gpm / sq-ft (9.6 m/h)

Table- 5.1 Predicted Full Scale GAC Use Rates

Contaminant	Freundlich Isotherm Model Parameters		Influent Conc. Co (µg/L)	Effluent Conc. Ce (µg/L)	Usage Rate (lb/1000 gal)	Bed Life (days)
	K	1/n				
Xylene	611.0	0.46	1000	50	0.049	878
Chlorobenzene	381.0	0.31	600	6	0.074	580
1,2-dichloropropane	35.8	0.48	100	5	0.233	184
Ethylenedibromide	69.3	0.54	50	0.5	0.733	587
Dibromochloropropane	206.0	0.46	20	0.2	0.011	3708

(Source: Adams et al., 1989)

5.6 COMPARISON OF OVERALL TREATMENT COSTS

5.61 Comparison at Various Plant Sizes

In this section, the three technologies are compared on the basis of capital, operating and overall treatment cost, at various plant capacities ranging from 1.0 to 50 MGD for comparable removals of the five typical contaminants. The results of this comparison are summarized in terms of overall treatment costs in Table 5.2 and the advantage of the cascade system is clearly illustrated in Figures 5.1 to 5.5.

Table 5.2 Overall Treatment Costs for Three Technologies
at Various Plant Sizes

Groundwater Contaminant	Decontamination Technology	Treatment Cost (¢/1000 gal)					
		Plant Size (MGD)					
		1	5	10	15	25	50
Xylene	Conventional A/S	8	5	4	3	3	2
H = 347 atm; Eff. = 95%	Cascade A/S	7	3	2	2	2	1
Inf. = 1000 μg/L; Eff. = 50 mg/L	GAC adsorption	29	22	20	18	14	11
Chlorobenzene	Conventional A/S	12	6	5	4	3	3
H = 264 atm; Eff. = 99%	Cascade A/S	8	4	3	3	3	2
Inf. = 600 μg/L; Eff. = 6 μg/L	GAC adsorption	43	32	29	23	21	17
1,2 Dichloropropane	Conventional A/S	10	5	4	3	3	2
H = 162 atm; Eff = 95%	Cascade A/S	7	3	3	2	2	2
Inf. = 100 μg/L; Eff. = 5 μg/L	GAC adsorption	57	45	41	31	26	22
Ethylenedibromide	Conventional A/S	14	7	6	5	4	3
H = 37 atm; Eff = 90%	Cascade A/S	10	5	4	4	3	2
Inf. = 50 μg/L; Eff. = 5 μg/L	GAC adsorption	36	24	23	21	18	15
Dibromochloropropane	Conventional A/S	43	32	30	21	20	15
H = 7 atm; Eff = 90%	Cascade A/S	34	18	14	14	13	10
Inf. = 20 μg/L; Eff. = 2 mg/L	GAC adsorption	47	35	32	27	23	18

Table 5.2 indicates that the overall treatment cost in the cascade air-stripping system for various water flow rates is about 20% lower than the conventional air-stripping system. This cost advantage is due to reduction in the packing height, which directly affects the capital cost of the system, reduction in the pressure drop of around 50%, which affects the blower capacity, and the reduced height over which the water has to be pumped. The operating costs were lower by about 10%-15%. Figures 5.1 to 5.5 illustrate the advantage of the cascade system for the five

contaminants over the full range of water flow rates considered. It can be seen that the cost for the GAC system is about 40% higher than the cascade air-stripping system for contaminants with H > 100 atm., and about 20% higher for the contaminants with H < 100 atm.

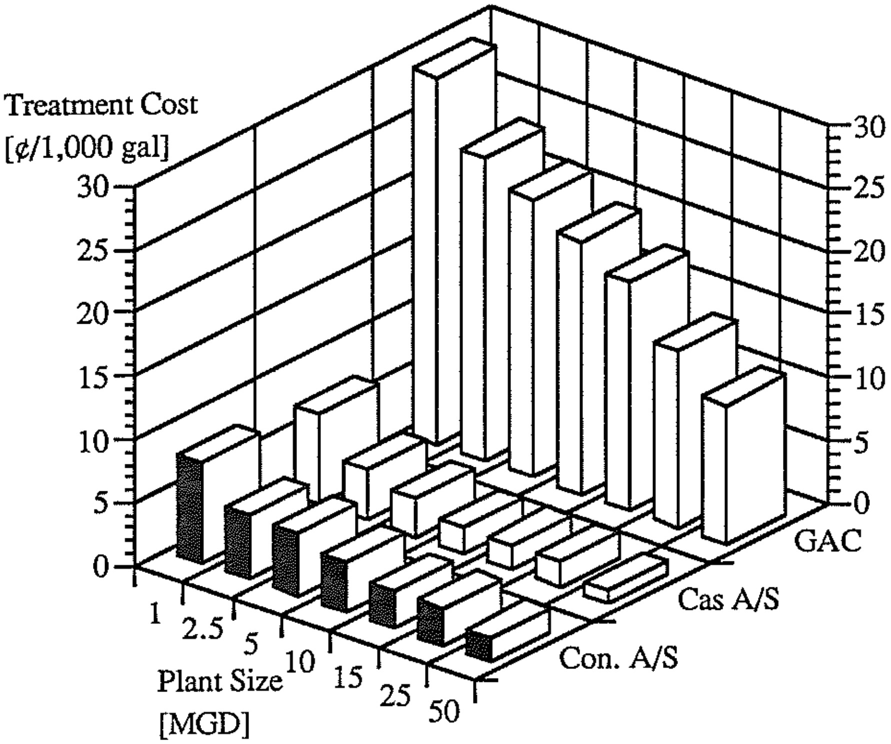

Figure 5.1 Treatment Costs for Xylene

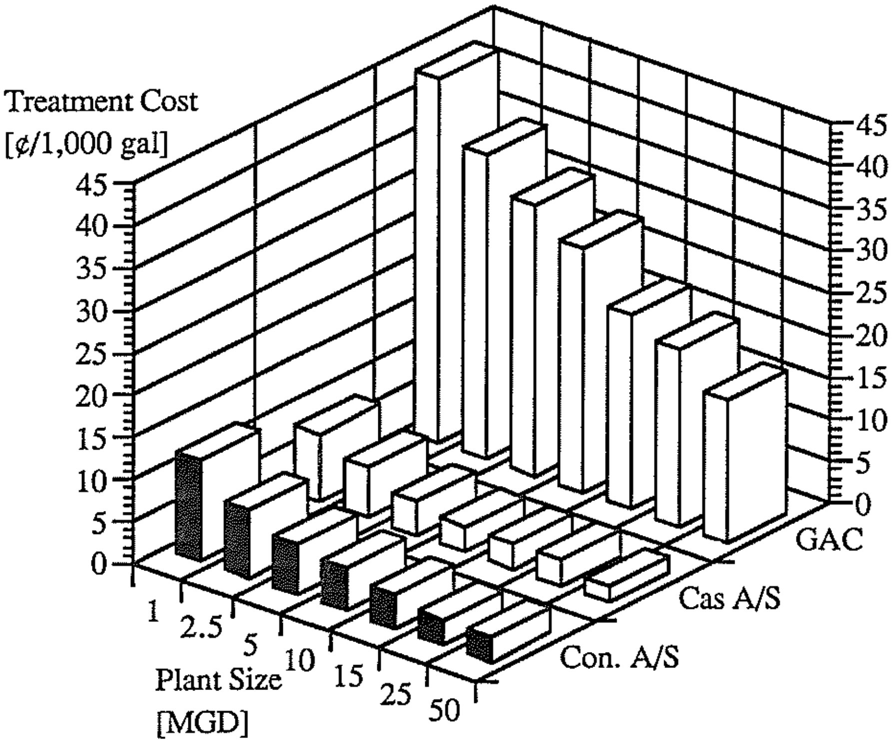

Figure 5.2 Treatment Costs for Chlorobenzene

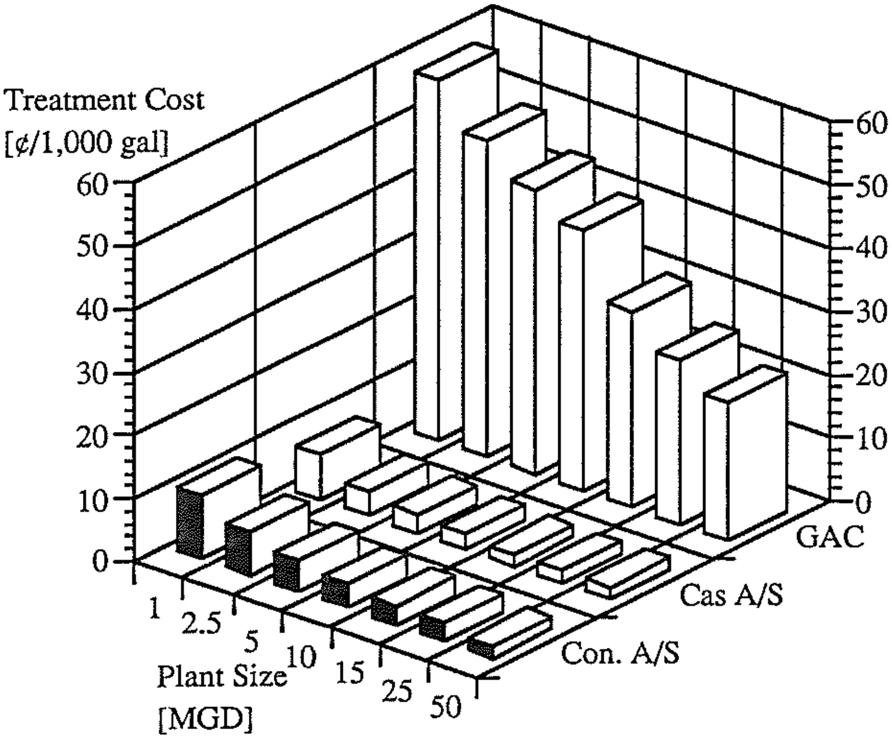

Figure 5.3 Treatment Costs for 1,2 Dichloropropane

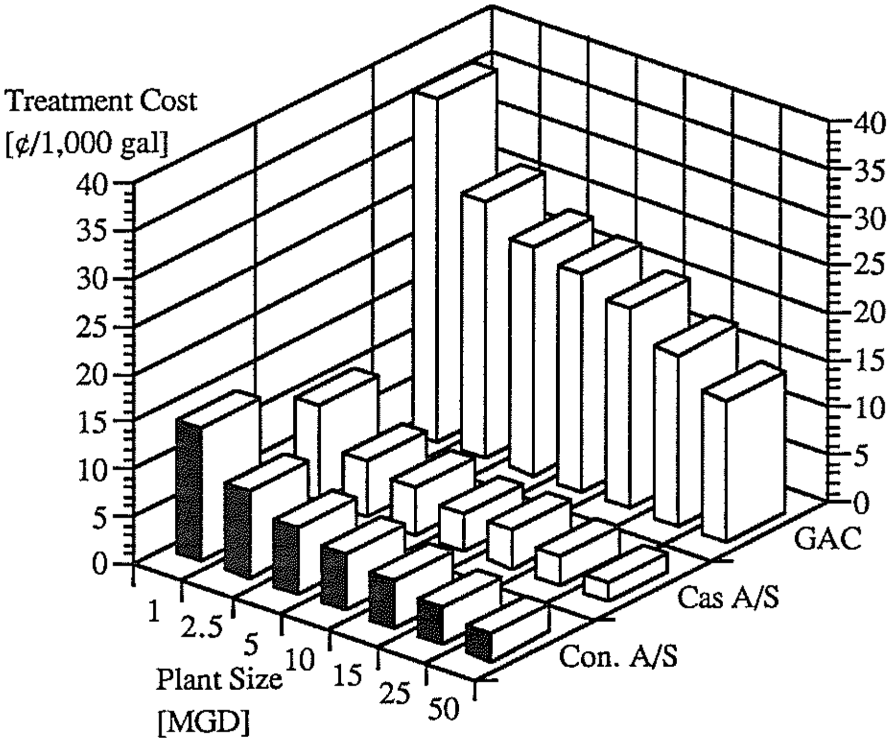

Figure 5.4 Treatment Costs for Ethylenedibromide

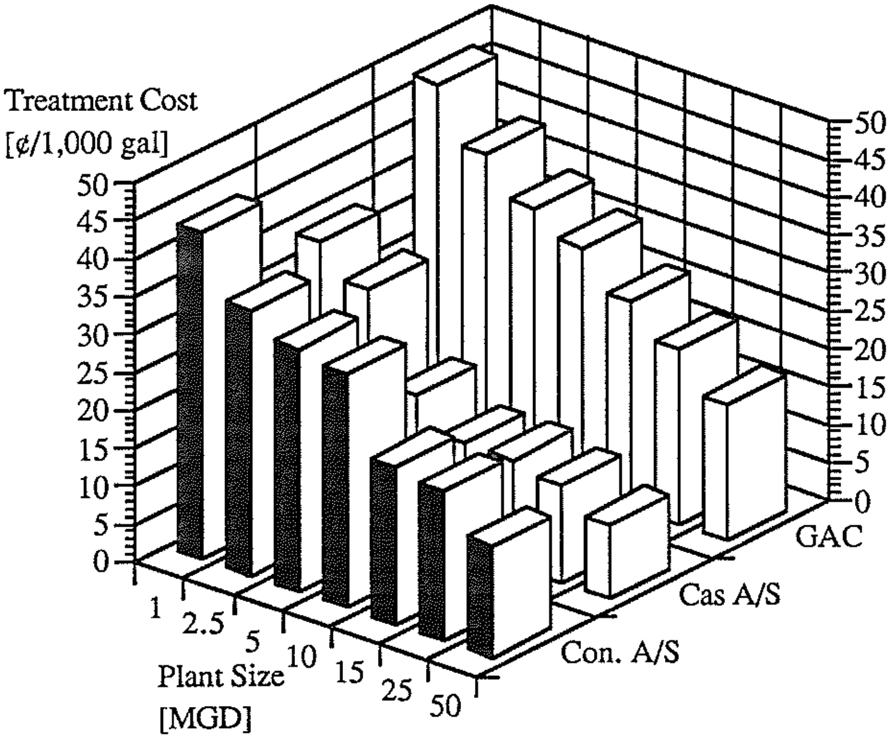

Figure 5.5 Treatment Costs for Dibromochloropropane

5.62 Comparison at Various Removal Efficiencies

A similar analysis was performed on the above five contaminants for various removal efficiencies ranging from 75% to 99%, at a fixed plant size of 5 MGD. Analysis results are summarized in Table 5.3 in terms of overall treatment costs. Here also, the cost of the cascade A/S system was found to be lower than the other two processes except in the case of DBCP. Because DBCP is a highly adsorbable contaminant, the cost of using the GAC was found to be lower for a removal efficiency greater than 90%. Figures 5.6 to 5.10 illustrate the advantages of the cascade system for the five contaminants over the full range of removal efficiencies considered.

Table 5.3. Overall Treatment Costs for Three Technologies
at Various Removal Efficiencies

Groundwater Contaminant	Decontamination Technology	Treatment Cost (¢/1000 gal)					
		Removal Efficiency (%)					
		75	80	85	90	95	99
Xylene	Conventional A/S	2	2	3	3	4	6
H = 347 atm; Q = 5 MGD	Cascade A/S	2	2	2	3	3	5
Inf. = 1000 µg/L	GAC adsorption	7	11	14	18	28	47
Chlorobenzene	Conventional A/S	2	3	3	3	4	7
H = 264 atm; Q = 5 MGD	Cascade A/S	2	2	2	3	4	6
Inf. = 600 µg/L	GAC adsorption	12	15	18	22	25	32
1,2 Dichloropropane	Conventional A/S	2	3	3	4	5	8
H = 162 atm; Q = 5 MGD	Cascade A/S	2	2	3	3	4	6
Inf. = 100 µg/L	GAC adsorption	35	32	36	41	54	93
Ethylenedibromide	Conventional A/S	4	5	5	6	8	12
H = 37 atm; Q = 5 MGD	Cascade A/S	3	4	4	5	7	10
Inf. = 50 µg/L	GAC adsorption	13	17	20	25	29	32
Dibromochloropropane	Conventional A/S	12	14	17	21	29	35
H = 7 atm; Q = 5 MGD	Cascade A/S	9	11	14	19	22	29
Inf. = 20 µg/L	GAC adsorption	18	23	31	35	36	36

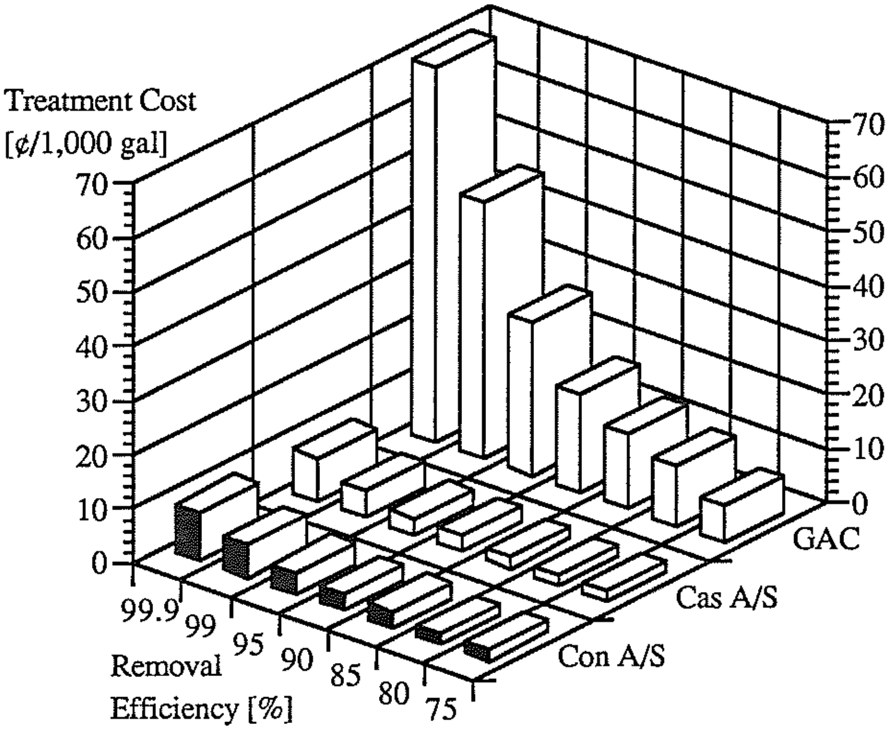

Figure 5.6 Treatment Costs for Xylene at Various Removal Efficiencies

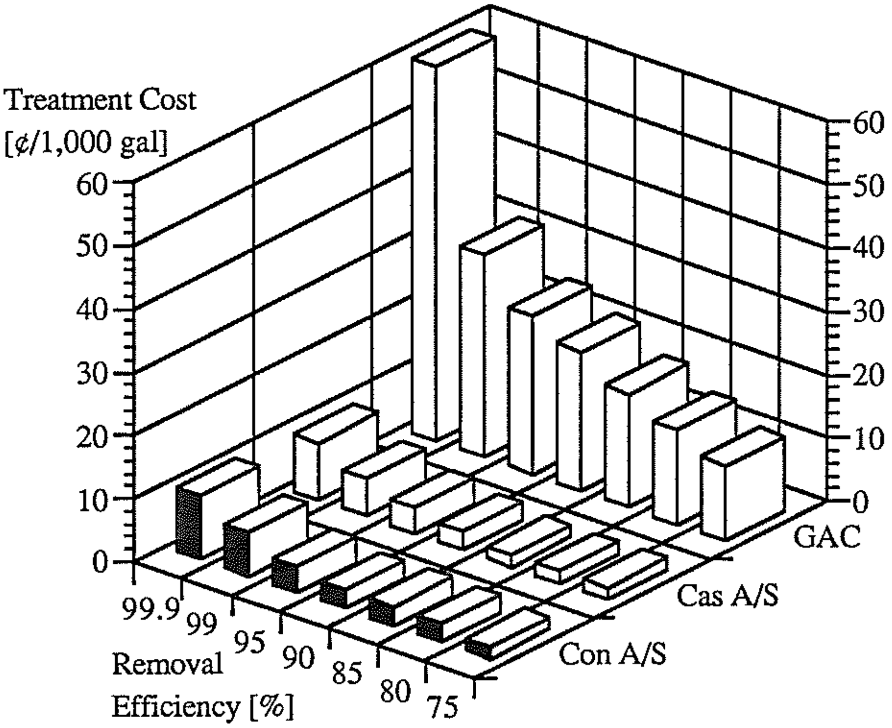

Figure 5.7 Treatment Costs for Chlorobenzene at Various Removal Efficiencies

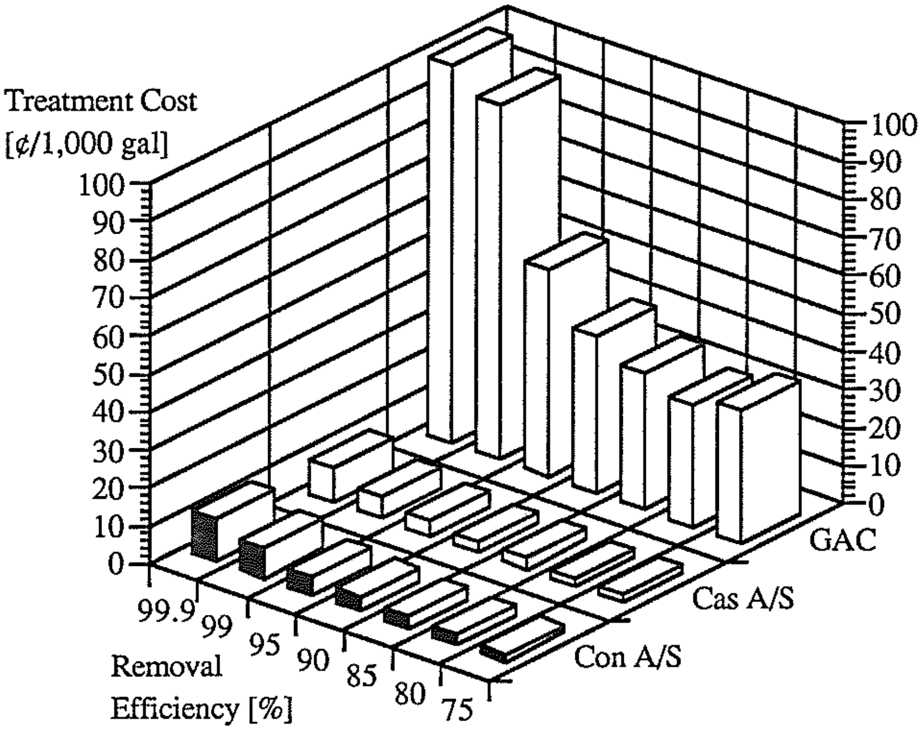

Figure 5.8 Treatment Costs for 1,2 Dichloropropane at Various Removal Efficiencies

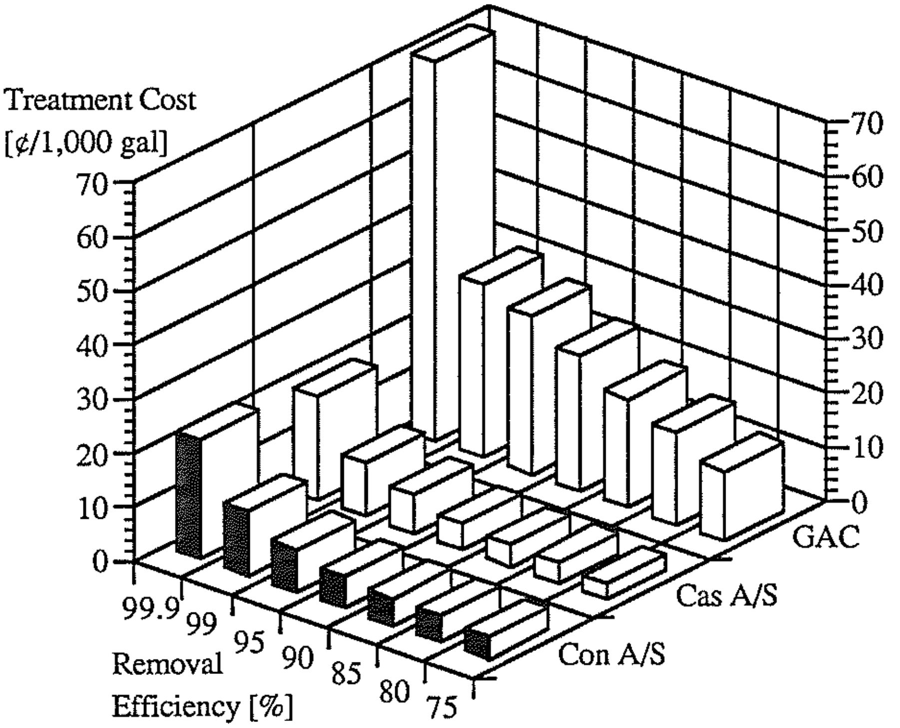

Figure 5.9 Treatment Costs for Ethylenedibromide at Various Removal Efficiencies

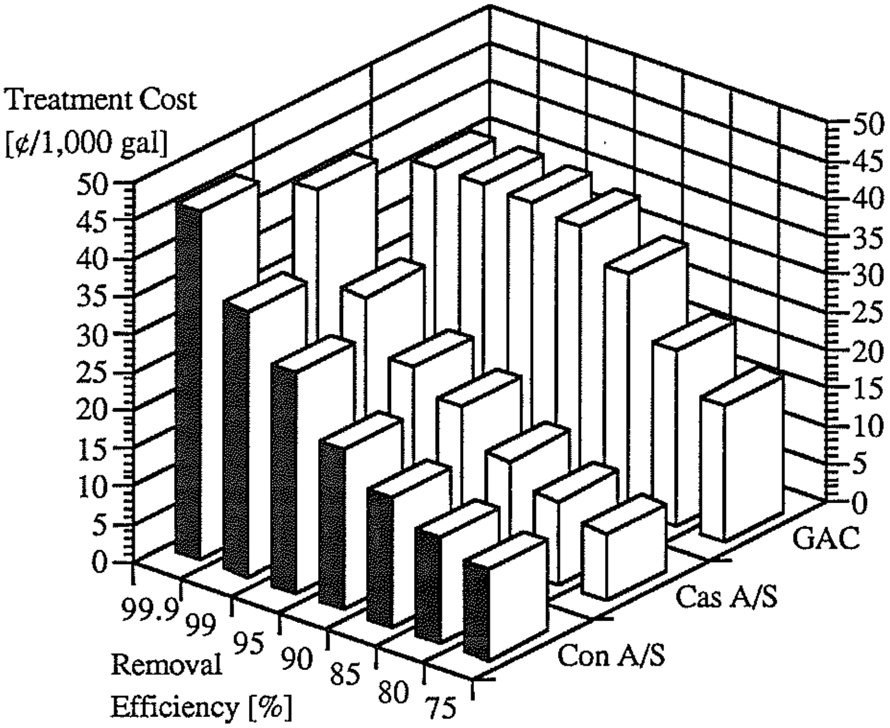

Figure 5.10 Treatment Costs for Dibromochloropropane at Various Removal Efficiencies

5.63 Limitations of the Above Analysis

The results from this analysis are intended to provide a general indication of the relative cost of using the above three processes. For contaminants with a higher H, the cost of treatment will be much lower and vice versa. Treatment costs also vary considerably as the operating temperature changes. The cost estimates presented above are in general site specific, and hence it is suggested that the analysis conclusion of the analysis should be used only for comparison purposes.

CHAPTER 6
SENSITIVITY ANALYSIS

6.1 OBJECTIVES

The objective of this section of the study was to perform sensitivity analysis to elucidate the effect of water loading rate on the performance of the cascade and conventional A/S processes. For this exercise, the two lowest volatile contaminants, ethylenedibromide (EDB) and dibromochloropropane (DBCP) were selected. Cost estimates were made as before for a plant size of 5 MGD operating under a range of water loading rates.

6.2 PROCEDURES FOR SENSITIVITY ANALYSIS

Water loading rate is an important variable in the air-stripping process. For a given total water quantity, the tower diameter is dependent on the water loading rate. Thus the capital cost is directly related to water loading. The operating pressure drop also is dependent on the water loading rate, which in turn affects the operating cost. Therefore, the overall treatment cost is a strong function of the water loading rate. Water loading rates used in the analysis of the cascade air-stripping system in earlier chapters were the same as those for the conventional system. These water loading rates were obtained from the computer simulation for the conventional air-stripping system, the analysis of which gives the least cost for a particular contaminant by considering all the input parameters. In this Chapter, this constraint is removed and the two processes are optimized independently to determine the best water loading rate to achieve comparable removal efficiencies at a given total water flow rate of 5 MGD.

6.21 Results of Sensitivity Analysis - EDB

Detailed calculations at different water loadings are presented in Appendix E. Table 6.1 summarizes EDB treatment costs for conventional and cascade A/S systems at various water loading rates. Figure 6.1 and Figure 6.2 show the capital, operating, and annual cost curves for 90% removal of EDB by the two air-stripping processes. Figure 6.3 compares the annual cost for the two processes at various water loading rates for a water flow rate of 5 MGD. It can be seen that the treatment cost is lower in the cascade A/S system at a higher water loading rate compared to the least cost for the corresponding water loading rate in the conventional A/S system. This indicates that more water can be treated using the cascade system for a given volume of the tower.

Table 6.1 Overall Treatment Costs for EDB
Water Flow - 5 MGD; Removal Efficiency = 90%

Plant Size MGD	Water loading Rate gpm/ft^2	Conventional ¢/1000 gals	Cascade ¢/1000 gals
5.0	50.0	13	8
5.0	45.0	12	7
5.0	40.0	11	7
5.0	35.0	8	6
5.0	30.0	7	5
5.0	25.0	6	5
5.0	20.0	6	4
5.0	15.0	6	4
5.0	10.0	6	5
5.0	5.0	8	7

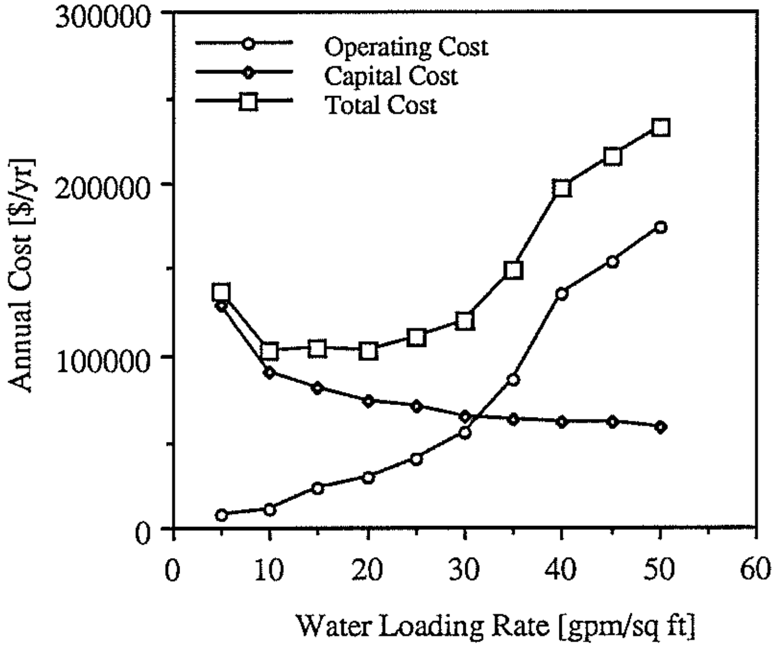

Figure 6.1 Annual Cost vs. Water Loading
Process- Conventional A/S; Chemical- EDB; Water Flow- 5 MGD; Removal- 90%

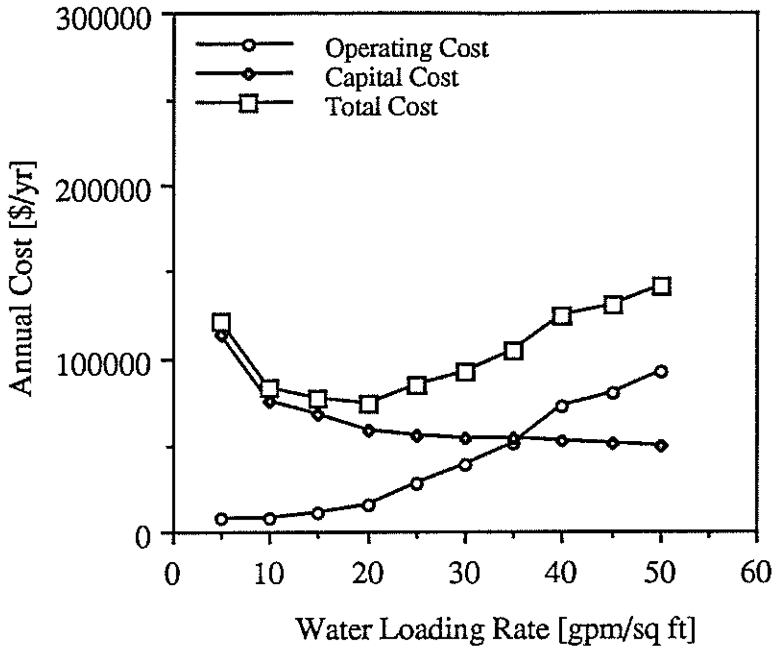

Figure 6.2 Annual Cost vs. Water Loading
Process- Cascade A/S; Chemical- EDB; Water Flow- 5 MGD; Removal- 90%

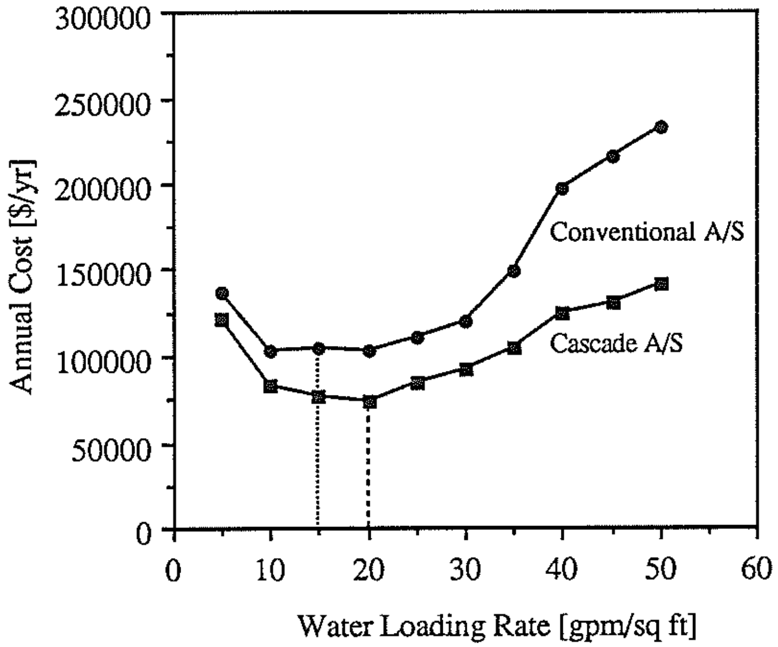

Figure 6.3 Annual Cost vs. Water Loading for Conventional and Cascade A/S Processes
Chemical- EDB; Water Flow- 5 MGD; Removal- 90%

6.22 Results of Sensitivity Analysis - DBCP

Detailed calculations at different water loadings are presented in Appendix F. Table 6.2 summarizes DBCP treatment costs for conventional and cascade A/S systems at the various water loading rates. Figure 6.4 and Figure 6.5 show capital, operating, and annual cost curves for 90% removal of DBCP by the two air-stripping processes. Figure 6.6 compares the annual cost for the two processes at various water loading rates for a water flow of 5 MGD. It can be seen that the treatment cost is lower in the cascade A/S system at a higher water loading rate compared to the least cost for the corresponding water loading rate in the conventional A/S system, once again indicating that more water can be treated using the cascade system for a given volume of the tower.

Table 6.2 Overall Treatment Cost For DBCP
Water Flow - 5 MGD; Removal Efficiency = 90%

Plant Size MGD	Water loading Rate gpm/ft^2	Conventional ¢/1000 gals	Cascade ¢/1000 gals
5.0	55.0	33	33
5.0	45.0	27	27
5.0	35.0	24	22
5.0	30.0	23	19
5.0	25.0	21	16
5.0	20.0	20	15
5.0	15.0	20	15
5.0	12.5	19	19
5.0	10.0	19	21
5.0	7.5	18	21
5.0	5.0	21	24
5.0	2.5	31	33

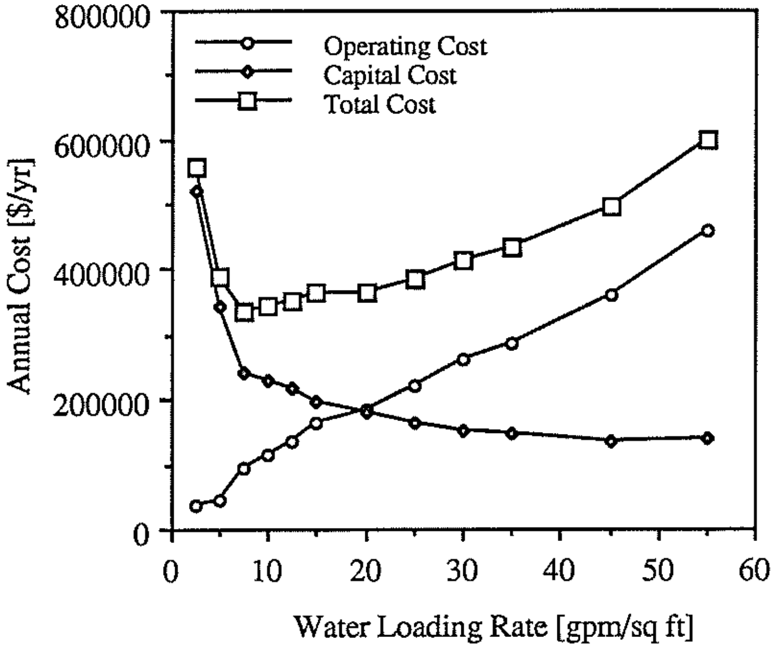

Figure 6.4 Annual Cost vs. Water Loading
Process- Conventional A/S; Chemical- DBCP; Water Flow- 5 MGD; Removal- 90%

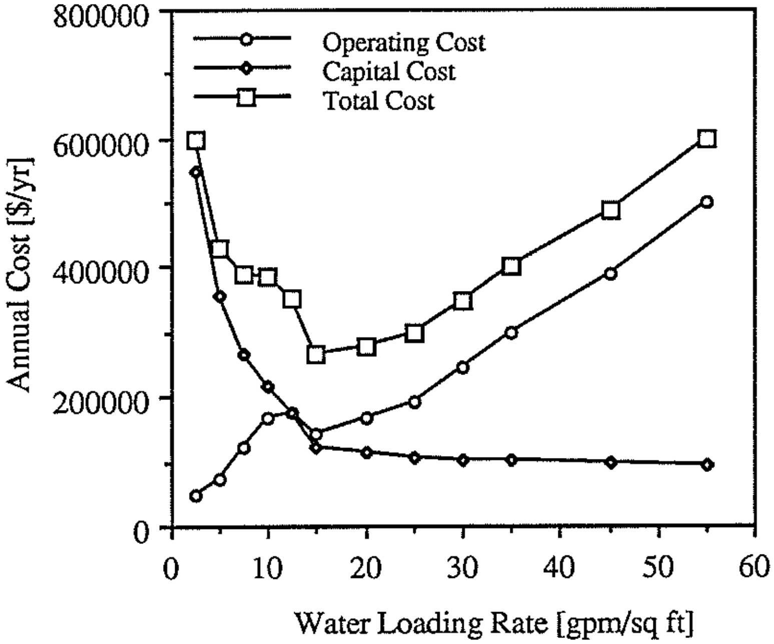

Figure 6.5 Annual Cost vs. Water Loading
Process- Cascade A/S; Chemical- DBCP; Water Flow- 5 MGD; Removal- 90%

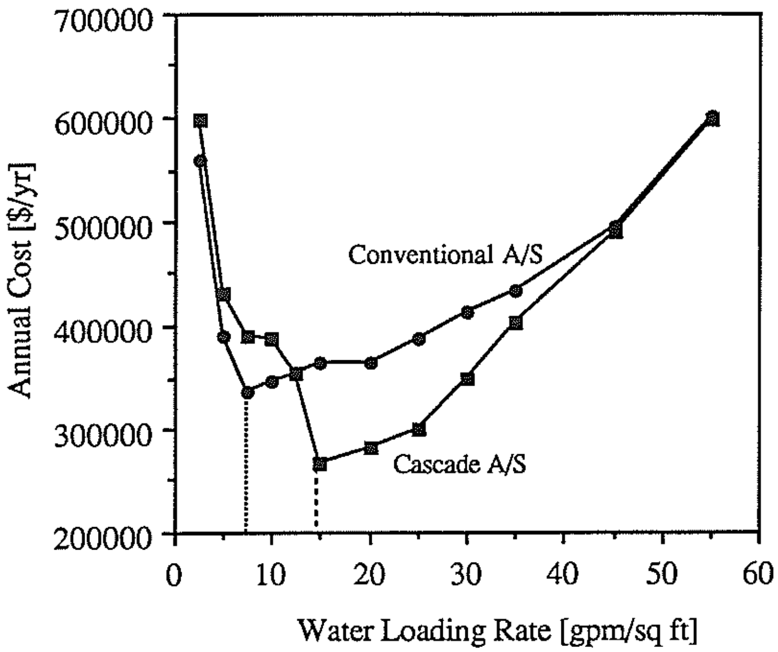

Figure 6.6 Annual Cost vs. Water Loading for Conventional and Cascade A/S Processes
Chemical- DBCP; Water Flow- 5 MGD; Removal- 90%

CHAPTER 7
CONCLUSIONS

The primary objective of this research was to generate technical and economic data to advance the cascade A/S process to full-scale application level. The technical feasibility of the cascade A/S system was evaluated under realistic air and water loading rates, utilizing more practical, larger diameter packing material.

Pressure drop characteristics of the cascade system over an 8x7 matrix of water and air loadings were established in the laboratory, and a process model was developed to predict these characteristics. Study results were used to develop overall pressure drop curves for use in future designs. The model predictions were found to agree well with the experimentally measured data.

Using the above pressure drop model, a procedure was established to size the individual air inlet ports of the cascade system. The procedure's validity was demonstrated by comparing the predicted air flow rates in the laboratory system against the measured ones. The agreement between the two were found to be satisfactory.

The above two procedures were integrated into the process model developed previously to design a full-scale field system. This integrated design procedure was verified using the data obtained under field conditions. The agreement between predicted and measured removal efficiencies was found again to be acceptable.

The economic feasibility of the cascade air-stripping system in terms of ¢ per 1000 gals of treated water was estimated under different water flow rates and removal efficiencies and compared with corresponding costs for conventional air-stripping and GAC processes. Results from these analysis showed that the cascade air-stripping process was generally more cost effective than the conventional air-stripping and GAC processes. A sensitivity analysis was performed on several low volatile contaminants for different water loading rates showing that higher water loading rates could be used in the cascade system than the conventional system for a given volume of the tower and removal efficiency.

Study results may benefit water utilities and regulatory agencies when evaluating the proposed cascade air-stripping process against the other two available technologies and in designing full-scale systems based on the procedures developed and validated here.

BIBLIOGRAPHY

Adams, J. O.; and Clark, R. M.; 1989, Cost Estimation for GAC Treatment Systems, *Jour. AWWA*, 81(1):35.

Adams, J. Q.; Clark, R. M.; and Miltner, R. J.; 1989, Controlling Organics with GAC: A Cost and Performance Analysis; 81(4): 132.

Ball, W.P.; Jones, M. D.; and Kavanaugh, M. C.; 1984, Mass Transfer of Volatile Organic Compounds in Packed Towers, *Jour. WPCF*, 56:127.

Bower, E.; Mercer, J.; Kavanaugh, M. C.; and DiGiano, F.; 1988, Coping with Groundwater Contamination, *Jour. WPCF*, 60:1415.

Cummins, M.D. and Westrick, J.J., 1983, Trichloroethylene Removal by Packed Column Air Stripping: Field Verified Design Procedure, Proc. ASCE Env. Engry. Conf.

Hand, D.W.; Crittendedn, J. C.; and Gehin, J. L.; 1986, Design and Evaluation of an Air Stripping Tower for Removing VOCs from Ground Water, *Jour. AWWA*, 78(9):87.

Guthrie, K. M.; 1969, Data and Techniques for Preliminary Capital Cost Estimating; 1, 143.

Guthrie, K. M.; 1974, Process Plant Estimating, Evaluation and Control; Craftsman Book Company of America, CA.

Jang, W.; Nirmalakhandan, N.; and speece, R. E.; 1990, Cascade Air-Stripping for Removal of Semi-Volatile Organic Contaminants: Feasibility Study, AWWARF Project Report, Contract Nº 327-87, Denver, CO.

Kavanaugh, M.C. and Trussell, R.R., 1980, Deslgn of Aeration Towers to Strip Volatile Contaminants from Drinking Water, *Jour. AWWA*, 72(12):684.

Lamarre, B.L.; McGarry, F. J.; and Stover, L. E.; 1983, Design, Operation and Results of a Pilot Plant Removal of Contaminants from Ground Water, 3rd Natl. Symp. on Aquifer Restoration and Ground Water Monitoring, Columbus, OH.

McCabe, W.L., and Smith, J.C., 1976, Unit Operations in Chemical Engineering, 3rd Ed., McGraw-Hill Book Co., New York.

Nirmalakhandan, N. and Speece, R.E., 1987, Enhanced Removals of Semi-Volatile Organic Contaminants from Water by Cascade Air Stripping, Proc. AWWARF Symp. on Water Reuse, Denver, CO.

Nirmalakhandan, N.; Lee, Y. H.; and Speece, R. E.; 1987, Designing a Cost-Efficient Air-Stripping Process,*Jour. AWWA*, 79(1):56.

Nirmalakhandan, N.; Jang, W.; and Speece, R. E.; 1990, Counter-current Cascade Air-Stripping of Low Volatile Organic Contaminants, *Wat Res.*, 24: 615.

Nirmalakhandan, N.; Jang, W.; and Speece, R. E.; 1991, Cascade Air-Stripping- Pilot and Prototype Scale Experience, *J. Env. Engrg., ASCE*, 117, 6, 788.

Nirmalakhandan, N.; Jang, W.; and Speece, R. E.; 1992, Removal of 1,2 Dibromo-3-chloropropane by Cascade Air-Stripping, J. Env. Engrg., ASCE, 118, 2, 226.

Nirmalakhandan, N.; Peace, G. L.; Shanbhaj, A.; and Speece, R. E.; 1992, Cascade Air-Stripping: Techno-Economic Evaluation of a New Groundwater Treatment Process, *Groundwater Monit. Rev.*, 100, Spring.

Onda, K.; Takeuchi, H.; and Okumoto, Y.; 1968, Mass Transfer Between Gas and Liquid Phases in Packed Columns, *Jour. Chem. Engrg. Japan* 1:56.

Perry R. H.; and Green, D.; 1984, Perry's Chemical Engineers Handbook, McGraw Hill, Inc., New York, NY.

Roberts, P.V.; Hopkins, G. D.; Munz, C.; and Riojas, A. H.; 1985, Evaluating Two Resistance Models for Air Stripping of Volatile Organic Contaminants in a Counter Current Packed Column, *Env. Sci. Technol.*, 19:164.

Treybal, R.E., 1980, Mass Transfer Operations, 2nd Ed., McGraw-Hill Book Co., NY.

US EPA, 1984, Research Outlook, EPA-600/9/84-004.

Wallman, H., and Cummins, M.D., 1985, Design Scale-up Suitability for Air-Stripping Columns, EPA Report CR810247-01.

APPENDIX A

Experimental Pressure Drop Data At Eight Water Loading Rates and Seven Air Loading Rates

RUN 1- Total Air Flow = 698 cfm

Cascade	50 GPM	45 GPM	40 GPM	35 GPM	30 GPM	25 GPM	20 GPM	15 GPM
ft	Change in Pressure in Inches Water							
2	ND	ND	ND	ND	ND	ND	ND	ND
4	0.10	0.10	0.10	0.10	0.10	0.10	0.05	0.05
6	0.20	0.20	0.20	0.20	0.20	0.20	0.15	0.10
8	0.40	0.40	0.40	0.38	0.35	0.30	0.28	0.25
10	0.70	0.68	0.65	0.60	0.60	0.60	0.58	0.50
12	1.10	1.10	1.00	1.00	1.00	1.00	1.00	0.90
14	2.00	1.80	1.60	1.50	1.40	1.30	1.20	1.20
16	3.20	3.00	2.80	2.65	2.50	2.30	2.20	2.00

RUN 2- Total Air Flow = 628 cfm

Cascade	50 GPM	45 GPM	40 GPM	35 GPM	30 GPM	25 GPM	20 GPM	15 GPM
ft	Change in Pressure in Inches Water							
2	0.05	0.05	0.05	0.05	0.05	0.05	0.05	ND
4	0.10	0.10	0.10	0.10	0.10	0.10	0.05	0.05
6	0.20	0.15	0.15	0.15	0.15	0.15	0.10	0.10
8	0.35	0.30	0.30	0.30	0.30	0.25	0.20	0.20
10	0.60	0.50	0.50	0.50	0.50	0.45	0.40	0.40
12	1.00	0.85	0.80	0.80	0.80	0.70	0.60	0.60
14	1.60	1.40	1.30	1.20	1.10	1.00	0.90	0.90
16	2.50	2.30	2.10	2.00	1.90	1.80	1.60	1.50

RUN 3- Total Air Flow = 558 cfm

Cascade	50 GPM	45 GPM	40 GPM	35 GPM	30 GPM	25 GPM	20 GPM	15 GPM
ft	Change in Pressure in Inches Water							
2	ND	ND	ND	ND	ND	ND	ND	ND
4	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
6	0.15	0.15	0.15	0.10	0.10	0.10	0.10	0.10
8	0.30	0.30	0.25	0.25	0.25	0.20	0.20	0.20
10	0.50	0.50	0.50	0.50	0.50	0.45	0.40	0.40
12	0.80	0.80	0.70	0.65	0.60	0.50	0.50	0.50
14	1.40	1.30	1.20	1.05	1.05	1.00	0.90	0.80
16	2.10	1.95	1.80	1.70	1.60	1.50	1.40	1.20

RUN 4- Total Air Flow = 489 cfm

Cascade	50 GPM	45 GPM	40 GPM	35 GPM	30 GPM	25 GPM	20 GPM	15 GPM
ft	Change in Pressure in Inches Water							
2	ND	ND	ND	ND	ND	ND	ND	ND
4	0.050	0.050	0.050	0.050	0.050	0.050	0.050	ND
6	0.100	0.100	0.100	0.100	0.100	0.100	0.100	0.050
8	0.250	0.200	0.200	0.200	0.200	0.150	0.175	0.150
10	0.400	0.350	0.350	0.350	0.300	0.325	0.300	0.275
12	0.600	0.600	0.550	0.550	0.500	0.500	0.500	0.400
14	1.000	0.900	0.900	0.800	0.800	0.700	0.600	0.600
16	1.600	1.400	1.300	1.200	1.100	1.000	0.950	0.900

RUN 5- Total Air Flow = 419 cfm

Cascade	50 GPM	45 GPM	40 GPM	35 GPM	30 GPM	25 GPM	20 GPM	15 GPM
ft	Change in Pressure in Inches Water							
2	ND	ND	ND	ND	ND	ND	ND	ND
4	0.050	0.050	0.050	0.050	0.050	0.050	ND	ND
6	0.100	0.100	0.100	0.100	0.075	0.075	0.075	0.050
8	0.150	0.150	0.150	0.150	0.150	0.150	0.150	0.125
10	0.300	0.300	0.275	0.250	0.250	0.250	0.200	0.200
12	0.450	0.450	0.350	0.400	0.400	0.400	0.350	0.300
14	0.700	0.700	0.600	0.600	0.600	0.500	0.500	0.500
16	1.200	1.100	0.950	0.925	0.850	0.800	0.750	0.700

RUN 6- Total Air Flow = 349 cfm

Cascade	50 GPM	45 GPM	40 GPM	35 GPM	30 GPM	25 GPM	20 GPM	15 GPM
ft	Change in Pressure in Inches Water							
2	ND	ND	ND	ND	ND	ND	ND	ND
4	ND	ND	ND	ND	ND	ND	ND	ND
6	0.10	0.10	0.05	0.05	0.05	0.05	0.05	0.05
8	0.15	0.15	0.10	0.10	0.10	0.10	0.10	0.10
10	0.25	0.20	0.20	0.20	0.20	0.15	0.15	0.15
12	0.40	0.35	0.35	0.35	0.30	0.25	0.25	0.20
14	0.60	0.55	0.50	0.40	0.40	0.40	0.35	0.30
16	0.90	0.80	0.70	0.60	0.55	0.50	0.45	0.40

RUN 7- Total Air Flow = 279 cfm

Cascade	50 GPM	45 GPM	40 GPM	35 GPM	30 GPM	25 GPM	20 GPM	15 GPM
ft	Change in Pressure in Inches Water							
2	ND	ND	ND	ND	ND	ND	ND	ND
4	ND	ND	ND	ND	ND	ND	ND	ND
6	ND	ND	ND	ND	ND	ND	ND	ND
8	0.100	0.100	0.075	0.050	0.050	0.050	0.050	0.050
10	0.150	0.150	0.125	0.125	0.125	0.125	0.100	0.075
12	0.250	0.250	0.200	0.175	0.200	0.175	0.175	0.175
14	0.350	0.325	0.300	0.300	0.275	0.275	0.275	0.275
16	0.500	0.475	0.450	0.425	0.400	0.375	0.350	0.325

APPENDIX B

Pressure Drop Calculations

RUN 1: Model Predicti		Water Loading Rate, 14,163 lbs/hour-sqft		
Packing Depth	Air Loading Rate	dp-graph	dp/dx	Sum dp
feet	lbs/hour-sqft	inch	inch	inch
2	223	0.015	0.030	0.030
4	446	0.034	0.070	0.100
6	668	0.064	0.130	0.220
8	891	0.105	0.210	0.430
10	1114	0.152	0.300	0.740
12	1337	0.230	0.460	1.200
14	1560	0.330	0.660	1.860
16	1782	0.460	1.110	2.970

RUN 1: Model Predicti		Water Loading Rate, 12,746 lbs/hour-sqft		
Packing Depth	Air Loading Rate	dp-graph	dp/dx	Sum dp
feet	lbs/hour-sqft	inch	inch	inch
2	223	0.014	0.027	0.030
4	446	0.032	0.063	0.090
6	668	0.058	0.116	0.206
8	891	0.095	0.190	0.396
10	1114	0.140	0.280	0.676
12	1337	0.210	0.420	1.100
14	1560	0.300	0.600	1.700
16	1782	0.420	1.020	2.720

RUN 1: Model Predicti		Water Loading Rate, 11,330 lbs/hour-sqft		
Packing Depth	Air Loading Rate	dp-graph	dp/dx	Sum dp
feet	lbs/hour-sqft	inch	inch	inch
2	223	0.0125	0.024	0.024
4	446	0.0285	0.057	0.080
6	668	0.052	0.104	0.184
8	891	0.087	0.174	0.352
10	1114	0.130	0.260	0.618
12	1337	0.180	0.360	0.978
14	1560	0.260	0.520	1.498
16	1782	0.370	0.894	2.392

RUN 1: Model Prediction		Water Loading Rate, 9,914 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	223	0.0115	0.023	0.023
4	446	0.0275	0.055	0.078
6	668	0.050	0.100	0.178
8	891	0.080	0.160	0.338
10	1114	0.120	0.240	0.586
12	1337	0.175	0.350	0.936
14	1560	0.250	0.500	1.430
16	1782	0.350	0.846	2.280

RUN 1: Model Prediction		Water Loading Rate, 8,497 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	223	0.011	0.022	0.022
4	446	0.026	0.052	0.074
6	668	0.046	0.092	0.170
8	891	0.075	0.150	0.320
10	1114	0.110	0.220	0.540
12	1337	0.165	0.330	0.870
14	1560	0.230	0.460	1.330
16	1782	0.330	0.798	2.130

RUN 1: Model Prediction		Water Loading Rate, 7,081 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	223	0.010	0.020	0.020
4	446	0.024	0.048	0.070
6	668	0.043	0.086	0.154
8	891	0.070	0.140	0.300
10	1114	0.105	0.210	0.500
12	1337	0.158	0.316	0.820
14	1560	0.220	0.440	1.300
16	1782	0.310	0.740	2.050

RUN 1: Model Prediction		Water Loading Rate, 5.665 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	223	0.0094	0.020	0.020
4	446	0.022	0.044	0.063
6	668	0.040	0.080	0.143
8	891	0.066	0.132	0.275
10	1114	0.096	0.192	0.500
12	1337	0.145	0.290	0.800
14	1560	0.200	0.400	1.700
16	1782	0.280	0.677	1.880

RUN 1: Model Prediction		Water Loading Rate, 4,250 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	223	0.0085	0.017	0.017
4	446	0.020	0.040	0.057
6	668	0.037	0.074	0.131
8	891	0.061	0.122	0.253
10	1114	0.088	0.176	0.430
12	1337	0.130	0.260	0.700
14	1560	0.185	0.370	1.100
16	1782	0.260	0.628	1.730

RUN 2: Model Prediction		Water Loading Rate, 14,162 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	200.000	0.013	0.026	0.026
4	400.000	0.030	0.060	0.086
6	600.000	0.052	0.104	0.190
8	800.000	0.084	0.168	0.360
10	1000.000	0.130	0.260	0.620
12	1200.000	0.180	0.360	0.980
14	1400.000	0.260	0.520	1.500
16	1600.000	0.350	0.840	2.350

RUN 2: Model Prediction		Water Loading Rate, 12,746 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	200.000	0.012	0.024	0.024
4	400.000	0.027	0.054	0.078
6	600.000	0.048	0.096	0.174
8	800.000	0.078	0.156	0.330
10	1000.000	0.112	0.224	0.554
12	1200.000	0.170	0.340	0.890
14	1400.000	0.240	0.480	1.400
16	1600.000	0.330	0.798	2.200

RUN 2: Model Prediction		Water Loading Rate, 11,330 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	200.000	0.011	0.022	0.022
4	400.000	0.025	0.050	0.072
6	600.000	0.044	0.088	0.160
8	800.000	0.070	0.140	0.300
10	1000.000	0.105	0.210	0.510
12	1200.000	0.150	0.500	0.810
14	1400.000	0.220	0.440	1.250
16	1600.000	0.290	0.701	1.950

RUN 2: Model Prediction		Water Loading Rate, 9,914 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	200.000	0.010	0.020	0.020
4	400.000	0.0235	0.047	0.067
6	600.000	0.042	0.084	0.150
8	800.000	0.065	0.130	0.280
10	1000.000	0.098	0.196	0.500
12	1200.000	0.140	0.280	0.760
14	1400.000	0.190	0.380	1.140
16	1600.000	0.270	0.653	1.790

RUN 2: Model Prediction		Water Loading Rate, 8,497 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	200.000	0.0094	0.0188	0.020
4	400.000	0.022	0.044	0.0628
6	600.000	0.039	0.078	0.140
8	800.000	0.062	0.124	0.260
10	1000.000	0.094	0.188	0.450
12	1200.000	0.130	0.260	0.710
14	1400.000	0.180	0.360	1.100
16	1600.000	0.250	0.604	1.700

RUN 2: Model Prediction		Water Loading Rate, 7,081 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	200.000	0.0088	0.018	0.018
4	400.000	0.0205	0.041	0.060
6	600.000	0.036	0.072	0.130
8	800.000	0.057	0.114	0.240
10	1000.000	0.087	0.174	0.420
12	1200.000	0.120	0.240	0.660
14	1400.000	0.170	0.340	1.000
16	1600.000	0.230	0.556	1.560

RUN 2: Model Prediction		Water Loading Rate, 5,665 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	200.000	0.008	0.016	0.016
4	400.000	0.019	0.038	0.054
6	600.000	0.034	0.068	0.122
8	800.000	0.053	0.106	0.228
10	1000.000	0.082	0.164	0.392
12	1200.000	0.115	0.230	0.620
14	1400.000	0.155	0.310	0.930
16	1600.000	0.220	0.532	1.460

RUN 2: Model Prediction		Water Loading Rate, 4,250 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	200.000	0.0076	0.015	0.015
4	400.000	0.017	0.034	0.050
6	600.000	0.031	0.062	0.111
8	800.000	0.049	0.098	0.210
10	1000.000	0.078	0.156	0.365
12	1200.000	0.110	0.220	58.000
14	1400.000	0.145	0.290	0.875
16	1600.000	0.200	0.483	1.360

RUN 3: Model Prediction		Water Loading Rate, 14,163 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	178	0.012	0.024	0.024
4	356	0.003	0.052	0.076
6	534	0.044	0.088	0.164
8	713	0.070	0.140	0.300
10	891	0.105	0.210	0.510
12	1069	0.150	0.300	0.810
14	1248	0.205	0.410	1.220
16	1426	0.270	0.653	1.870

RUN 3: Model Prediction		Water Loading Rate, 12,746 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	178	0.011	0.022	0.022
4	356	0.025	0.050	0.072
6	534	0.042	0.084	0.156
8	713	0.066	0.132	0.288
10	891	0.094	0.188	0.476
12	1069	0.145	0.290	0.766
14	1248	0.190	0.380	1.200
16	1426	0.260	0.628	1.830

RUN 3: Model Prediction		Water Loading Rate, 11,330 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	178	0.010	0.020	0.020
4	356	0.022	0.044	0.064
6	534	0.038	0.076	0.140
8	713	0.060	0.120	0.260
10	891	0.083	0.166	0.430
12	1069	0.120	0.240	0.670
14	1248	0.170	0.340	1.000
16	1426	0.240	0.580	1.580

RUN 3: Model Prediction		Water Loading Rate, 9,914 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	178	0.009	0.018	0.018
4	356	0.020	0.040	0.058
6	534	0.035	0.070	0.128
8	713	0.056	0.112	0.240
10	891	0.080	0.160	0.400
12	1069	0.110	0.220	0.620
14	1248	0.155	0.310	0.930
16	1426	0.215	0.520	0.145

RUN 3: Model Prediction		Water Loading Rate, 8,497 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	178	0.0084	0.017	0.017
4	356	0.019	0.038	0.054
6	534	0.033	0.066	0.120
8	713	0.052	0.104	0.225
10	891	0.075	0.150	0.375
12	1069	0.105	0.210	0.585
14	1248	0.145	0.290	0.875
16	1426	0.200	0.483	1.340

RUN 3: Model Prediction		Water Loading Rate, 7,081 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	178	0.0078	0.016	0.016
4	356	0.018	0.036	0.052
6	534	0.031	0.062	0.114
8	713	0.049	0.098	0.210
10	891	0.070	0.140	0.350
12	1069	0.096	0.192	0.540
14	1248	0.140	0.280	0.820
16	1426	0.180	0.435	1.260

RUN 3: Model Prediction		Water Loading Rate, 5,665 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	178	0.0072	0.014	0.014
4	356	0.017	0.034	0.050
6	534	0.029	0.058	0.110
8	713	0.046	0.092	0.200
10	891	0.066	0.132	0.330
12	1069	0.090	0.180	0.510
14	1248	0.130	0.260	0.770
16	1426	0.170	0.411	1.180

RUN 3: Model Prediction		Water Loading Rate, 4,250 lbs/hour-sqft		
Packing Depth feet	Air Loading Rate lbs/hour-sqft	dp-graph inch	dp/dx inch	Sum dp inch
2	178	0.0067	0.013	0.013
4	356	0.0155	0.030	0.044
6	534	0.028	0.056	0.100
8	713	0.043	0.086	0.186
10	891	0.061	0.122	0.310
12	1069	0.084	0.168	0.500
14	1248	0.120	0.240	0.700
16	1426	0.160	0.387	1.100

APPENDIX C

Air Flow Model Calculations

Water Treated	Air Flow at each cascade	Theoretical Air Flow at Each Cascade								Total Air in Tower Thereo.	Total Air in Tower Actual
gpm	cfm	c1 cfm	c2 cfm	c3 cfm	c4 cfm	c5 cfm	c6 cfm	c7 cfm	c8 cfm	cfm	cfm
15	87.2	ND	28.9	40.9	64.6	91.4	122.6	141.6	182.8	673	698
20	87.2	ND	27.7	48.1	65.1	94.1	124.1	135.9	184.0	679	698
25	87.2	ND	37.3	52.8	64.7	91.4	118.0	134.6	179.0	678	698
30	87.2	ND	37.1	52.4	69.3	90.8	117.2	138.7	185.3	691	698
35	87.2	ND	37.1	52.4	71.8	90.8	117.2	143.5	190.8	704	698
40	87.2	ND	36.5	51.6	73.0	93.1	115.5	146.1	193.2	709	698
45	87.2	ND	35.4	50.1	70.8	92.0	117.5	150.3	194.0	710	698
50	87.2	ND	34.7	49.1	69.4	91.8	115.1	155.2	196.4	712	698

Water Treated	Air Flow at each cascade	Theoretical Air Flow at Each Cascade								Total Air in Tower Thereo.	Total Air in Tower Actual
gpm	cfm	c1 cfm	c2 cfm	c3 cfm	c4 cfm	c5 cfm	c6 cfm	c7 cfm	c8 cfm	cfm	cfm
15	78.6	ND	28.9	40.9	57.8	81.7	100.1	122.6	158.3	590	628
20	78.6	ND	28.9	40.9	57.8	81.7	100.1	122.6	163.5	596	628
25	78.6	ND	38.1	46.7	60.3	80.9	100.9	120.6	161.8	610	628
30	78.6	ND	38.1	46.7	66.1	85.3	107.9	126.5	166.3	637	628
35	78.6	ND	38.1	46.7	66.1	85.3	107.9	132.1	170.6	647	628
40	78.6	ND	35.4	43.4	61.4	79.2	100.2	127.7	162.3	610	628
45	78.6	ND	35.4	43.4	61.4	79.2	103.3	132.5	169.9	625	628
50	78.6	ND	32.7	46.2	61.2	80.1	103.4	130.8	163.5	618	628

Water Treated	Air Flow at each cascade	Theoretical Air Flow at Each Cascade								Total Air in Tower Thereo.	Total Air in Tower Actual
gpm	cfm	c1 cfm	c2 cfm	c3 cfm	c4 cfm	c5 cfm	c6 cfm	c7 cfm	c8 cfm	cfm	cfm
15	69.8	ND	27.0	38.1	53.9	76.3	85.3	107.9	132.1	521	558
20	69.8	ND	27.0	38.1	53.9	76.3	85.3	114.4	142.7	538	558
25	69.8	ND	27.0	38.1	53.9	80.9	85.3	120.6	147.7	554	558
30	69.8	ND	27.0	38.1	60.3	85.3	93.4	122.1	152.6	579	558
35	69.8	ND	25.0	35.4	56.0	79.2	90.3	114.8	146.1	547	558
40	69.8	ND	25.0	43.4	56.0	79.2	93.7	122.7	150.3	570	558
45	69.8	ND	23.1	40.0	56.6	73.1	92.5	117.9	144.4	548	558
50	69.8	ND	23.1	40.0	56.6	73.1	92.5	122.3	149.8	558	558

Water Treated gpm	Air Flow at each cascade cfm	Theoretical Air Flow at Each Cascade								Total Air in Tower Thereo. cfm	Total Air in Tower Actual cfm
		c1 cfm	c2 cfm	c3 cfm	c4 cfm	c5 cfm	c6 cfm	c7 cfm	c8 cfm		
15	61	ND	ND	30.8	53.4	72.3	87.2	106.8	130.8	481	489
20	61	ND	28.5	40.3	53.3	69.8	90.2	98.8	124.3	505	489
25	61	ND	27.0	38.1	46.7	68.8	85.3	100.9	120.6	488	489
30	61	ND	27.0	38.1	53.9	66.1	85.3	107.9	126.5	505	489
35	61	ND	25.0	35.4	50.1	66.3	83.1	100.2	122.7	483	489
40	61	ND	25.0	35.4	50.1	66.3	83.1	106.3	127.7	494	489
45	61	ND	25.0	35.4	50.1	66.3	86.8	106.3	132.5	502	489
50	61	ND	25.0	35.4	56.0	70.8	86.8	112.0	141.7	528	489

Water Treated gpm	Air Flow at each cascade cfm	Theoretical Air Flow at Each Cascade								Total Air in Tower Thereo. cfm	Total Air in Tower Actual cfm
		c1 cfm	c2 cfm	c3 cfm	c4 cfm	c5 cfm	c6 cfm	c7 cfm	c8 cfm		
15	52.4	ND	ND	29.7	46.9	59.3	72.7	93.8	111.0	414	419
20	52.4	ND	ND	36.3	51.4	59.3	78.5	93.8	114.9	434	419
25	52.4	ND	25.0	30.7	43.4	56.0	70.8	79.2	100.2	405	419
30	52.4	ND	25.0	30.7	43.4	56.0	70.8	86.8	103.3	416	419
35	52.4	ND	25.0	35.4	43.4	56.0	70.8	86.8	107.7	425	419
40	52.4	ND	23.1	32.7	40.0	54.2	61.2	80.1	100.8	392	419
45	52.4	ND	23.1	32.7	40.0	56.6	69.4	86.5	108.4	417	419
50	52.4	ND	23.1	32.7	40.0	56.6	69.4	86.5	113.3	422	419

Water Treated gpm	Air Flow at each cascade cfm	Theoretical Air Flow at Each Cascade								Total Air in Tower Thereo. cfm	Total Air in Tower Actual cfm
		c1 cfm	c2 cfm	c3 cfm	c4 cfm	c5 cfm	c6 cfm	c7 cfm	c8 cfm		
15	43.6	ND	ND	27.0	38.1	46.7	53.9	66.1	76.3	308	349
20	43.6	ND	ND	27.0	38.1	46.7	60.3	71.4	80.9	325	349
25	43.6	ND	ND	27.0	38.1	46.7	60.3	76.3	85.3	334	349
30	43.6	ND	ND	27.0	38.1	53.9	66.1	76.3	89.5	351	349
35	43.6	ND	ND	27.0	38.1	53.9	71.4	76.3	93.4	360	349
40	43.6	ND	ND	23.1	32.7	46.2	61.2	73.1	86.5	323	349
45	43.6	ND	ND	32.7	40.0	46.2	61.2	76.7	92.5	349	349
50	43.6	ND	ND	32.7	40.0	51.7	65.4	80.1	98.1	368	349

Water Treated gpm	Air Flow at each cascade cfm	Theoretical Air Flow at Each Cascade								Total Air in Tower Thereo. cfm	Total Air in Tower Actual cfm
		c1 cfm	c2 cfm	c3 cfm	c4 cfm	c5 cfm	c6 cfm	c7 cfm	c8 cfm		
15	34.8	ND	ND	ND	28.9	35.4	54.1	67.8	73.7	260	279
20	34.8	ND	ND	ND	28.9	40.9	54.1	67.8	76.5	268	279
25	34.8	ND	ND	ND	28.9	45.7	54.1	67.8	79.1	276	279
30	34.8	ND	ND	ND	27.0	42.7	53.9	63.3	76.3	263	279
35	34.8	ND	ND	ND	27.0	42.7	50.5	66.1	78.6	265	279
40	34.8	ND	ND	ND	33.0	42.7	53.9	66.1	80.9	277	279
45	34.8	ND	ND	ND	35.4	43.4	56.0	63.9	77.2	276	279
50	34.8	ND	ND	ND	34.3	42.0	54.3	64.2	76.8	272	279

APPENDIX D

Sample Output from Computer Program for Conventional Air-Stripping Process

INPUT DATA

HENRY'S CONST.	350	atm. AT TEMPERATURE	25	deg C;	PACKING SELECTED IS
INLET CONC.	1000	ug/L; OUTLET CONC.	50	ug/L;	2 in TRIPACK
WATER TREATED	5	MGD. AT UTILIZATION	100	%;	OF SPECIFIC SURFACE
POWER COST	.08	$/Kw.Hr; PACKING COST	30	$/cu ft;	AREA (sq m/cu m)
AMORTIZED FOR	20	YEARS, AT RATE OF	10	%;	157.4

OPTIMUM DESIGN SPECIFICATIONS

WATER LOADING RATE	60	gpm/sq ft	PUMP CAPACITY	3457	gpm
AIR/WATER RATIO	11	vol/vol	PUMP DELIVERY HEAD	17	ft
MASS TRANSFER COEFF.	2	1/min	PUMP POWER	20	HP
REMOVAL EFFICIENCY	95	%	PUMP EFFICIENCY	60	%
TOWER DIAMETER	7	ft	BLOWER CAPACITY	5054	cfm
PACKING DEPTH	15	ft	BLOWER OUTLET HEAD	4.4	in H2O
PACKING VOLUME	778	cu ft	BLOWER POWER	9	HP
PRESSURE LOSS GRADIENT	.25	in H2O/ft	BLOWER EFFICIENCY	70	%
ANNUAL TOTAL COST	58533	$/year	TREATMENT COST	3.2	¢/1000 gal

APPENDIX E

Cost Calculations for Five Contaminants at Various Plant Sizes

Treatment Cost- Conventional A/S, Chemical: Xylene
[Inf conc = 1000 µg/L, Eff conc = 50 µg/L, H=350 atm]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ftT	PAC. COST PER Yr. $	A.TREAT COST $ in 88	T.COST 1000 GALS $ in 88
0.10	1.02	85.03	138	15	12	368	43	7260	0.1989
0.25	1.59	87.48	345	15	30	893	105	10923	0.1197
0.50	2.25	87.37	689	15	60	1788	210	15455	0.0847
1.00	3.18	87.48	1011	17	135	4049	476	22553	0.0618
2.50	5.31	78.44	2527	16	354	10624	1248	38194	0.0419
5.00	8.53	60.79	5055	15	857	25703	3019	58476	0.0320
10.00	14.27	43.44	10110	15	2398	71933	8449	91299	0.0250
15.00	19.52	34.83	15164	14	4188	125626	14756	119525	0.0218
25.00	28.87	26.53	25274	13	8506	255169	29972	169288	0.0186
50.00	50.20	17.55	50548	12	23739	712163	83650	275430	0.0151

Treatment Cost- Cascade A/S, Chemical: Xylene
[Inf conc = 1000 µg/L, Eff conc = 50 µg/L, H=350 atm]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2
0.10	1.02	85.03	237	13.75	11	337	40	1036	1268
0.25	1.59	87.48	619	13.58	27	809	95	2705	1363
0.50	2.25	87.37	1267	13.55	54	1615	190	5536	1393
1.00	3.18	87.48	1765	14.89	118	3547	417	7712	972
2.50	5.31	78.44	4234	14.8	328	9825	1154	18500	836
5.00	8.53	60.79	8853	13.68	781	23443	2754	38683	677
10.00	14.27	43.44	16373	12.93	2066	61989	7281	71542	448
15.00	19.52	34.83	25548	12.17	3641	109221	12829	111632	373
25.00	28.87	26.53	39321	11.48	7513	225389	26474	171813	263
50.00	50.20	17.55	82887	10.2	20184	605534	71126	362175	183

CONST. COST $/yr	PUMP 60% EFF HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST/YR $	PUMP COST-73 $	PUMP COST-88 $	PUMP COST / Yr $	PUMP COST-90 $	PUMP COST / Yr $
6140	0.5	1	1	681	450	646	76	669	79
9333	1	1	2	1047	600	861	101	892	105
12523	2	2	4	2094	725	1040	122	1078	127
18279	4	2	6	3141	900	1291	152	1339	157
26867	11	6	17	8899	1500	2152	253	2231	262
38936	20	9	29	15181	1950	2797	329	2900	341
60546	37	15	52	20416	2700	3873	455	4016	472
73900	53	20	73	28661	3100	4447	522	4611	542
92309	83	29	112	43974	4000	5738	674	5949	699
109570	150	49	199	78132	7200	10328	1213	10709	1258

LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O	P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $
34783	42589	1.7	23	0.24	0.4	1	1	1	535
86958	43817	2.1	29	1	1	3	2	3	1554
173917	43763	1.4	19	1	2	4	3	5	2444
347833	43817	0.8	12	3	4	3	2	7	3509
869583	39287	0.8	12	6	11	8	6	16	8591
1739167	30449	0.5	7	12	20	10	7	27	14003
3478333	21760	0.4	5	23	38	13	9	47	24715
5217500	17443	0.4	5	32	53	20	14	67	30791
8695833	13291	0.32	4	50	84	23	16	100	45793
17391667	8792	0.3	3	89	149	40	28	178	69621

BLOW COST-73 $	BLOW COST- 88 $	BLOW COST / Yr $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST-90 $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
1900	2726	320	2826	332	8563	9016	9697	0.2657
2000	2869	337	2975	349	13015	13574	14621	0.1602
3000	4304	505	4462	524	17464	18325	20419	0.1119
3000	4304	505	4462	524	25491	26647	29788	0.0816
5500	7890	927	8180	961	37466	39937	48837	0.0535
6000	8607	1011	8924	1048	65977	70385	85566	0.0469
8500	12193	1432	12642	1485	102596	113001	133418	0.0366
10000	14345	1685	19873	2334	125224	142856	171517	0.0313
14000	20083	2359	20822	2446	179541	212658	256632	0.0281
17000	24387	2864	25284	2970	219085	306963	385095	0.0211

PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COSTin-90 $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
500	741	87	2800	4150	488	6304	6918	7453	0.2042
650	964	113	4500	6670	784	9165	10157	11711	0.1283
800	1186	139	4500	6670	784	11805	12918	15362	0.0842
1050	1556	183	3000	4447	522	19318	20440	23949	0.0656
1400	2075	244	5700	8449	992	29854	32244	40835	0.0448
1900	2816	331	6000	8894	1045	40258	44387	58390	0.0320
2500	3706	435	6500	9635	1132	52041	60889	85604	0.0235
3000	4447	522	7000	10376	1219	66473	81043	111835	0.0204
3700	5485	644	7200	10673	1254	83237	111608	157402	0.0172
4800	7115	836	7500	11117	1306	94625	167892	237513	0.0130

Treatment Cost- Conventional A/S, Chemical: Chlorobenzene
[Inf conc = 600 μg/L, Eff conc = 6 μg/L, H=264 atm]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL CU FT	PAC.COST $30/CU FT	PAC. COST PER Yr.	A.TREAT COST $	T.COST 1000 GALS
0.10	1.01	86.72	193	25	20	601	71	10723	0.2938
0.25	1.59	87.48	482	25	50	1488	175	16837	0.1845
0.50	2.25	87.37	965	25	99	2981	350	24543	0.1345
1.00	3.18	87.48	1470	28	222	6668	783	36653	0.1004
2.50	5.66	69.04	3676	26	654	19615	2304	63353	0.0694
5.00	9.19	52.37	7325	24	1591	47735	5607	97933	0.0537
10.00	14.27	43.44	14705	23	3677	110298	12956	154055	0.0422
15.00	19.69	34.23	22057	22	6696	200865	23594	202235	0.0369
25.00	29.04	26.22	36762	20	13240	397204	46655	283740	0.0311
50.00	50.52	17.33	73524	18	36064	1081907	127080	469413	0.0257

Treatment Cost- Cascade A/S, Chemical: Chlorobenzene
[Inf conc = 600 μg/L, Eff conc = 6 μg/L, H=264 atm]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2
0.10	1.01	86.72	336	22.74	18	546	64	1468	1833
0.25	1.59	87.48	834	22.83	45	1359	160	3644	1836
0.50	2.25	87.37	1642	22.93	91	2734	321	7175	1805
1.00	3.18	87.48	2571	24.9	198	5930	697	11234	1415
2.50	5.66	69.04	6403	23.33	587	17598	2067	27978	1113
5.00	9.19	52.37	12586	22.28	1477	44307	5204	54995	830
10.00	14.27	43.44	25396	21.16	3383	101480	11920	110968	694
15.00	19.69	34.23	37814	20.31	6181	185418	21779	165228	543
25.00	29.04	26.22	62203	19.03	12597	377913	44390	271796	411
50.00	50.52	17.33	125513	16.96	33983	1019502	119750	548429	274

CONST. COST-88 $	PUMP 60% EFF HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $	PUMP COST-73 $	PUMP COST-88 $	PUMP COST / Yr $	PUMP COST-90 $	PUMP COST / Yr $
9334	0.7	1	2	889	550	789	93	818	96
14487	1	2	3	1568	600	861	101	892	105
19029	3	5	8	4182	825	1183	139	1227	144
27953	7	6	13	6796	1150	1650	194	1710	201
44270	17	12	29	15161	1800	2582	303	2677	314
62900	32	20	52	27185	2300	3299	388	3421	402
86790	62	36	98	51234	3250	4662	548	4834	568
104972	87	47	134	70055	4200	6025	708	6247	734
126247	136	68	204	106651	5100	7316	859	7585	891
147790	247	114	361	188730	8000	11476	1348	11898	1398

LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O	P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $
34783	43437	0.7	15.92	0.4	1	1	1	1	578
86958	43817	0.75	17.13	1	2	2	2	3	1496
173917	43763	0.7	16.05	2	3	4	3	6	2885
347833	43817	0.45	11.21	4	7	5	3	11	4807
869583	34579	0.42	9.8	10	17	10	7	24	11015
1739167	26233	0.37	8.24	20	33	16	12	44	20214
3478333	21760	0.32	6.77	37	62	27	19	81	37115
5217500	17144	0.28	5.69	53	89	34	24	113	51759
8695833	13136	0.25	4.76	83	139	46	33	172	78783
17391667	8681	0.25	4.24	149	248	84	60	308	140836

BLOW COST-73 $	BLOW COST- 88 $	BLOW COST / Yr $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
2000	2869	337	2975	349	11150	11666	12554	0.3440
3000	4304	505	4462	524	17305	18109	19677	0.2156
5000	7173	842	7437	873	22730	24098	28280	0.1550
5500	7890	927	8180	961	33390	35335	42131	0.1154
7800	11189	1314	11601	1363	52881	56862	72023	0.0789
11000	15780	1853	16360	1922	75134	83064	110249	0.0604
15000	21518	2527	22310	2620	103671	119815	171049	0.0469
17250	24745	2907	25656	3014	125390	152730	222785	0.0407
19750	28331	3328	29374	3450	150802	201799	308449	0.0338
26500	38014	4465	39413	4629	176535	309642	498372	0.0273

PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
400	593	70	2400	3558	418	9756	10308	10886	0.2684
650	964	113	4500	6670	784	14118	15174	16670	0.1644
900	1334	157	4500	6670	784	18637	19898	22784	0.1124
1250	1853	218	4500	6670	784	26566	28264	33071	0.0815
1800	2668	313	5000	7412	871	42558	45809	56824	0.0560
2300	3409	400	6500	9635	1132	62758	69494	89708	0.0442
3300	4892	575	8200	12155	1428	86506	100428	137543	0.0339
4200	6226	731	14250	21123	2481	106502	131494	183252	0.0301
5100	7560	888	15000	22235	2612	132638	180527	259310	0.0256
7500	11117	1306	17500	25940	3047	160791	284894	425730	0.0212

Treatment Cost- Conventional A/S, Chemical: 1,2-dichloropropane
[Inf conc = 100 µg/L, Eff conc = 5 µg/L, H=162 atm]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	A.TREAT COST $	T.COST 1000 GALS $
0.10	1.01	86.72	303	16.00	13	384	45	8306	0.2276
0.25	1.59	87.48	551	16.00	32	953	112	12055	0.1321
0.50	2.25	87.37	1103	18.00	72	2146	252	18173	0.0996
1.00	3.18	87.48	2114	17.00	135	4048	476	26949	0.0738
2.50	6.47	52.83	5514	15.00	493	14787	1737	46119	0.0505
5.00	10.07	43.62	11029	15.00	1194	35821	4208	71666	0.0393
10.00	15.91	34.95	22057	14.00	2782	83456	9803	112670	0.0309
15.00	22.47	26.28	33086	13.00	5153	154575	18156	149973	0.0274
25.00	35.60	17.45	55143	11.00	10944	328310	38563	214090	0.0235
50.00	50.36	17.44	110286	12.00	23890	716710	84185	347160	0.0190

Treatment Cost- Cascade A/S, Chemical: 1,2-dichloropropane
[Inf conc = 100 µg/L, Eff conc = 5 µg/L, H=162 atm]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2
0.10	1.01	86.72	537	14.10	11	339	40	2346	2930
0.25	1.59	87.48	738	15.29	30	910	107	3225	1625
0.50	2.25	87.37	1825	15.35	61	1830	215	7974	2007
1.00	3.18	87.48	3725	15.09	120	3594	422	16276	2050
2.50	6.47	52.83	9641	13.78	453	13585	1596	42126	1282
5.00	10.07	43.62	18380	13.35	1063	31881	3745	80311	1009
10.00	15.91	34.95	36934	12.64	2512	75349	8850	161383	812
15.00	22.47	26.28	53780	12.20	4835	145063	17039	234992	593
25.00	35.60	17.45	94608	10.63	10576	317266	37266	413390	416
50.00	50.36	17.44	186241	10.53	20964	628913	73872	813780	409

CONST. COST-88 $	PUMP 60% EFF HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $	PUMP COST-73 $	PUMP COST-88 $	PUMP COST / Yr $	PUMP COST-90 $	PUMP COST / Yr $
6846	0.9	1	2	993	500	717	84	744	87
9768	1	2	3	1568	600	861	101	892	105
14545	2	3	5	2614	725	1040	122	1078	127
20774	4	5	9	4705	900	1291	152	1339	157
32511	10	10	20	10456	1400	2008	236	2082	245
46110	19	18	37	19343	1900	2726	320	2826	332
63896	37	32	69	36073	2700	3873	455	4016	472
78764	52	43	95	49666	3100	4447	522	4611	542
98468	79	61	140	73192	3950	5666	666	5875	690
113739	158	117	275	143769	5700	8177	960	8478	996

LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O	P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $
34783	43437	2.10	29.61	0.2	0.41	2	2	2	1369
86958	43817	1.50	22.94	1	1	3	2	3	1776
173917	43763	1.10	16.89	1	2	5	3	6	3332
347833	43817	0.75	11.32	3	4	7	5	9	5189
869583	26463	0.50	6.89	6	10	10	7	18	9645
1739167	21848	0.40	5.34	12	20	15	11	31	16430
3478333	17505	0.35	4.42	22	37	26	18	55	29453
5217500	13164	0.33	4.03	32	53	34	24	78	41161
8695833	8741	0.30	3.19	47	78	47	34	112	58833
17391667	8736	0.30	3.16	92	154	92	66	220	115865

BLOW COST-73 $	BLOW COST- 88 $	BLOW COST / Yr $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
2000	2869	337	2975	349	9547	10029	11022	0.3020
3000	4304	505	4462	524	13622	14362	15931	0.1746
3800	5451	640	5652	664	20282	21325	23939	0.1312
5000	7173	842	7437	873	28970	30476	35181	0.0964
7000	10042	1179	10411	1223	45336	48541	58997	0.0647
10000	14345	1685	14873	1747	64300	70587	89930	0.0493
14500	20800	2443	21566	2533	89103	101911	137984	0.0378
17000	24387	2864	25284	2970	109837	131504	181170	0.0331
19000	27256	3201	28259	3319	137314	179887	253078	0.0277
26750	38373	4507	39785	4673	158609	248462	392231	0.0215

PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
400	595	70	4500	6670	784	6220	7113	8482	0.2324
625	930	109	4500	6670	784	9512	10512	12288	0.1347
775	1153	135	4500	6670	784	12904	14038	17370	0.0952
1050	1562	183	5000	7412	871	17429	18905	24095	0.0660
1500	2231	262	5700	8449	992	24681	27531	37176	0.0407
1950	2900	341	6400	9487	1114	37140	42340	58770	0.0322
2800	4164	489	8100	12007	1410	53277	64027	93480	0.0256
3100	4611	542	14250	21123	2481	66728	86790	127950	0.0234
4050	6024	708	15250	22605	2655	77467	118096	176929	0.0194
5700	8478	996	18750	27793	3265	89707	167839	283705	0.0155

Treatment Cost- Conventional A/S, Chemical: EDB
[Inf conc = 50 µg/L, Eff conc = 5 µg/L, H=37 atm]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr.	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2
0.10	1.48	40.60	1200	10.33	18	530	62	5243	3064
0.25	2.53	34.60	3000	10.83	54	1627	191	13109	2617
0.50	3.87	29.50	6000	10.83	127	3821	449	26217	2228
1.00	5.97	24.80	12000	10.50	294	8815	1035	52434	1873
2.50	9.84	22.80	30000	9.84	748	22454	2637	131085	1724
5.00	15.09	19.40	60000	9.68	1730	51912	6098	262170	1466
10.00	22.80	17.00	110000	9.45	3856	115689	13589	480645	1178
15.00	29.86	14.90	160000	9.84	6887	206602	24267	699120	999
25.00	38.39	15.00	275000	10.01	11574	347218	40784	1201613	1039
50.00	54.30	15.00	550000	9.94	23006	690190	81069	2403225	1038

Treatment Cost- Cascade A/S, Chemical: EDB
[Inf conc = 50 µg/L, Eff conc = 5 µg/L, H=37 atm]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr.	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2
0.10	1.48	40.60	1750	8.92	15	458	54	7647	4469
0.25	2.53	34.60	4100	8.63	43	1297	152	17915	3576
0.50	3.87	29.50	9000	8.53	100	3011	354	39326	3343
1.00	5.97	24.80	17000	8.14	228	6832	802	74282	2654
2.50	9.84	22.80	46000	7.35	559	16766	1969	200997	2643
5.00	15.09	19.40	90000	7.05	1261	37834	4444	393255	2200
10.00	22.80	17.00	185000	7.87	3214	96408	11324	808358	1981
15.00	29.86	14.90	265000	7.97	5578	167348	19657	1157918	1655
25.00	38.39	15.00	430000	7.87	9107	273220	32092	1878885	1624
50.00	54.30	15.00	810000	8.01	18527	555797	65284	3539295	1529

LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O	P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $
34783	20329	2.40	25	0.2	0.3	5	7	7	3648
86958	17358	1.70	18	0.5	1	9	12	13	6888
173917	14783	1.20	13	0.9	2	12	17	19	9967
347833	12428	0.80	8	1.8	3	16	23	26	13422
869583	11435	0.65	6	4.3	7	30	43	50	26264
1739167	9727	0.55	5	8.5	14	50	72	86	44844
3478333	8523	0.50	5	16.6	28	82	117	144	75373
5217500	7457	0.35	3	25.9	43	87	124	167	87187
8695833	7518	0.24	2	43.9	73	104	148	221	115663
17391667	7515	0.17	2	87.2	145	146	208	354	184933

LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O	P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $
34783	20329	1.80	16	0.2	0.26	2	3	3	1784
86958	17358	1.00	9	0.4	1	3	4	5	2404
173917	14783	0.75	6	0.7	1	5	6	8	4027
347833	12428	0.55	4	1.4	2	6	9	11	5703
869583	11435	0.44	3	3.2	5	12	17	22	11528
1739167	9727	0.40	3	6.2	10	20	28	39	20277
3478333	8523	0.30	2	13.8	23	34	49	72	37652
5217500	7457	0.20	2	21	35	33	47	82	43045
8695833	7518	0.10	1	34.5	58	27	38	96	49929
17391667	7515	0.05	0	70.2	117	25	36	153	80167

PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER in 90 $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
600	892	105	3700	5503	646	8384	9197	12845	0.3519
800	1190	140	4500	6693	786	15029	16146	23034	0.2524
1000	1487	175	5000	7437	873	23032	24529	34496	0.1890
1100	1636	192	6500	9667	1136	34447	36810	50232	0.1376
1300	1933	227	10000	14873	1747	53232	57843	84107	0.0922
1400	2082	245	14250	21194	2489	80261	89093	133937	0.0734
2200	3272	384	17000	25284	2970	118387	135330	210703	0.0577
2850	4239	498	18000	26771	3145	161469	189379	276566	0.0505
3800	5652	664	19000	28259	3319	211063	255831	371494	0.0407
5400	8031	943	24500	36439	4280	296598	382891	567824	0.0311

PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER in 90 $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
450	669	79	3900	5800	681	7240	8053	9838	0.2695
575	855	100	5400	8031	943	11978	13174	15578	0.1707
625	930	109	6100	9073	1066	18146	19675	23702	0.1299
650	967	114	8100	12047	1415	26696	29027	34731	0.0952
1050	1562	183	14250	21194	2489	39746	44388	55916	0.0613
1400	2082	245	16500	24540	2883	58496	66067	86343	0.0473
2000	2975	349	19300	28705	3372	98656	113701	151353	0.0415
2300	3421	402	19000	28259	3319	130790	154168	197213	0.0360
3000	4462	524	17100	25433	2987	166083	201686	251615	0.0276
4100	6098	716	17200	25582	3005	238844	307849	388016	0.0213

Treatment Cost- Conventional A/S, Chemical: DBCP
[Inf conc = 20 µg/L, Eff conc = 2 µg/L, H=7 atm]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr.	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2
0.10	1.49	40.00	2368	20.60	36	1073	126	10347	5960
0.25	2.44	37.00	5789	24.25	114	3413	401	25295	5391
0.50	3.66	33.00	11786	20.96	221	6618	777	51499	4894
1.00	5.43	30.00	24765	17.98	416	12485	1467	108211	4675
2.50	9.05	27.00	68172	16.11	1036	31074	3650	297878	4633
5.00	11.24	35.00	100000	21.23	2106	63175	7421	436950	4404
10.00	20.05	22.00	258586	15.72	4961	148817	17480	1129892	3579
15.00	25.76	20.00	398936	16.34	8510	255287	29986	1743151	3347
25.00	35.05	18.00	688637	17.22	16613	498385	58540	3008999	3120
50.00	52.58	16.00	1254181	15.91	34531	1035930	121680	5480144	2525

Treatment Cost- Cascade A/S, Chemical: DBCP
[Inf conc = 20 µg/L, Eff conc = 2 µg/L, H=7 atm]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr.	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2
0.10	1.49	40.00	3600	16.73	29	871	102	15730	9061
0.25	2.44	37.00	8100	17.03	80	2397	282	35393	7543
0.50	3.66	33.00	18850	16.80	177	5302	623	82365	7828
1.00	5.43	30.00	42050	16.04	371	11141	1309	183737	7937
2.50	9.05	27.00	120000	16.31	1048	31454	3695	524340	8155
5.00	11.24	35.00	186000	15.81	1569	47064	5528	812727	8192
10.00	20.05	22.00	215000	14.04	4432	132972	15619	939443	2976
15.00	25.76	20.00	720000	14.27	7433	222992	26193	3146040	6040
25.00	35.05	18.00	1200000	13.71	13227	396810	46609	5243400	5436
50.00	52.58	16.00	2250000	14.21	30829	924861	108634	9831375	4530

LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O	P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $
34783	20035	2.50	51.51	0.4	1	19	27	28	12790
86958	18533	2.40	58.19	1	2	53	76	77	35371
173917	16529	2.30	48.22	2	3	89	127	131	59708
347833	15026	2.10	37.76	3	5	147	210	215	98335
869583	13524	2.00	32.22	7	12	345	493	504	230725
1739167	17531	1.90	40.33	19	31	633	905	936	427980
3478333	11019	1.30	20.43	28	46	829	1185	1231	643451
5217500	10018	1.10	17.97	43	72	1126	1608	1680	878145
8695833	9016	1.00	17.22	76	126	1862	2660	2786	1456594
17391667	8014	0.73	11.62	140	233	2287	3267	3500	2172850

LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O	P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $
34783	20035	2.10	35.14	0.3	0	20	28	29	13202
86958	18533	1.30	22.14	1	1	28	40	41	18965
173917	16529	1.10	18.48	2	2	55	78	81	36858
347833	15026	1.00	16.04	3	5	106	151	156	71359
869583	13524	0.90	14.68	7	12	276	395	407	186127
1739167	17531	0.70	11.07	14	23	323	462	485	221813
3478333	11019	0.70	9.83	25	41	332	474	515	319737
5217500	10018	0.50	7.14	38	63	807	1152	1215	555747
8695833	9016	0.50	6.86	60	100	1292	1845	1946	890047
17391667	8014	0.39	5.54	125	208	1957	2796	3003	1373928

PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
600	892	105	7500	11155	1310	16837	18378	31168	0.8539
750	1115	131	14000	20822	2446	32572	35550	70921	0.7772
850	1264	148	17000	25284	2970	42176	46071	105779	0.5796
1000	1487	175	22000	32721	3843	53648	59132	157467	0.4314
1500	2231	262	38000	56517	6639	80113	90663	321388	0.3522
2200	3272	384	57000	84776	9958	131125	148888	576868	0.3161
2800	4164	489	61000	90725	10657	173163	201789	845240	0.2316
3700	5503	646	71000	105598	12404	231255	274291	1152436	0.2105
5800	8626	1013	100000	148730	17470	331760	408783	1865378	0.2044
7200	11429	1342	100000	158730	18644	512265	653932	2826782	0.1549

PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
400	595	70	5000	7437	873	13283	14328	27530	0.7543
500	744	87	8500	12642	1485	22222	24076	43041	0.4717
700	1041	122	13500	20079	2358	32828	35931	72789	0.3988
900	1339	157	17500	26028	3057	46504	51027	122387	0.3353
1200	1785	210	30000	44619	5241	78775	87920	274047	0.3003
1650	2454	288	35000	52056	6114	94894	106825	328638	0.1801
2200	3272	384	48000	76190	8949	163568	188520	508257	0.1392
2900	4313	507	60000	89238	10482	196229	233410	789157	0.1441
3800	5652	664	70000	104111	12229	256597	316099	1206146	0.1322
6000	8924	1048	105000	156167	18343	398708	526733	1900661	0.1041

APPENDIX F

Cost Calculations for Five Contaminants at Various Removal Efficiencies

Treatment Cost at various removal efficiencies- Conventional A/S
[Chemical: Xylene, H = 350 atm, Plant Size = 5 mgd]

WATER TREAT gal/day	WATER TREAT gpm	WATER TREAT cu m/s	INFL. CONC ug / L	EFFL. CONC ug / L	REMOVAL EFF. %	DIA m	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm
5	3472	0.2191	1000	250.0	75	2.81	9.22	52.03	5054
5	3472	0.2191	1000	200.0	80	2.81	9.22	52.03	5054
5	3472	0.2191	1000	150.0	85	2.62	8.58	60.08	5054
5	3472	0.2191	1000	100.0	90	2.62	8.58	60.08	5054
5	3472	0.2191	1000	50.0	95	2.62	8.58	60.08	5054
5	3472	0.2191	1000	10.0	99	2.62	8.58	60.08	5054
5	3472	0.2191	1000	0.1	99.9	3.09	10.14	43.02	6982

Treatment Cost at various removal efficiencies- Cascade A/S
[Chemical: Xylene, H = 350 atm, Plant Size = 5 mgd]

WATER TREAT gal/day	WATER TREAT gpm	WATER TREAT cu m/s	INFL.T CONC ug / L	EFFL. CONC ug / L	REMOVAL EFF. %	DIA m	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm
5	3472	0.2191	1000	250.0	75	2.81	9.22	52.03	7500
5	3472	0.2191	1000	200.0	80	2.81	9.22	52.03	7650
5	3472	0.2191	1000	150.0	85	2.62	8.58	60.08	7600
5	3472	0.2191	1000	100.0	90	2.62	8.58	60.08	7600
5	3472	0.2191	1000	50.0	95	2.62	8.58	60.08	7800
5	3472	0.2191	1000	10.0	99	2.62	8.58	60.08	7800
5	3472	0.2191	1000	0.1	99.9	3.09	10.14	43.02	11000

DEPTH m	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	ANNUAL TREAT. $	T.COST PER $	CONST. COST $	PUMP 60% EFF HP	BLOWER 70% EFF HP
1.84	6.05	404	12112	1423	28617	0.0157	20736	8	3
2.21	7.25	484	14514	1705	32470	0.0178	23227	9	4
2.73	8.95	517	15516	1823	37643	0.0206	26040	12	5
3.29	10.80	624	18724	2199	45167	0.0247	30523	15	7
4.33	14.22	822	24653	2896	58533	0.0321	39516	20	9
7.18	23.55	1361	40828	4796	91190	0.0500	60222	33	15
9.30	30.50	2462	73853	8675	138825	0.0761	85394	41	41

DEPTH m	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2	LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O
1.62	5.30	354	10610	1246	32771	491	1739167	26062	0.25
1.89	6.21	414	12432	1460	33427	501	1739167	26062	0.28
2.41	7.90	457	13696	1609	33208	575	1739167	30095	0.30
2.73	8.95	517	15516	1823	33208	575	1739167	30095	0.35
3.32	10.90	630	18897	2220	34082	590	1739167	30095	0.50
6.00	19.68	1137	34119	4008	34082	590	1739167	30095	0.60
7.83	25.70	2074	62230	7310	48065	595	1739167	21547	0.90

TOTAL HP	OPER COST / Yr $	PUMP COST-73 $	PUMP COST-88 $	PUMP COST / Yr $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 88 $	BLOW COST / Yr $
11	5751	1200	1721	202	1785	210	3000	4304	505
13	6796	1400	2008	236	2082	245	3000	4304	505
17	8888	1500	2152	253	2231	262	3800	5451	640
22	11502	1800	2582	303	2677	314	3800	5451	640
29	15161	1900	2726	320	2826	332	3800	5451	640
48	25094	2400	3443	404	3570	419	4000	5738	674
82	42869	2700	3873	455	4016	472	8500	12193	1432

P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $	PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $
1.33	5	8	2	1	9	4632	1200	1785	210
1.74	5	9	2	1	11	5524	1400	2082	245
2.37	7	12	3	2	14	7092	1500	2231	262
3.13	8	13	4	3	16	8234	1500	2231	262
5.45	10	16	7	5	21	10820	1800	2677	314
11.81	17	29	14	10	39	20435	2100	3123	367
23.13	23	38	40	29	66	34552	2400	3570	419

BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
4462	524	28916	31073	36823	0.0202
4462	524	32391	34864	41661	0.0228
5652	664	36313	39061	47949	0.0263
5652	664	42564	45741	57243	0.0314
5652	664	55105	58996	74157	0.0406
5949	699	83979	89893	114987	0.0630
12642	1485	119082	129713	172582	0.0946

BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
2000	2965	348	25332	27136	31768	0.0174
2000	2965	348	27744	29797	35322	0.0194
2500	3706	435	32052	34359	41450	0.0227
3000	4447	522	35273	37880	46113	0.0253
3000	4447	522	42239	45296	56116	0.0307
3500	5188	609	70179	75163	95598	0.0524
7000	10376	1219	100341	109288	143840	0.0788

Treatment Cost at various removal efficiencies- Conventional A/S
[Chemical: Chlorobenzene, H = 264 atm, Plant Size = 5 mgd]

WATER TREAT MGD	WATER TREAT gpm	WATER TREAT cu m/s	INFL.T CONC ug / L	EFFL. CONC ug / L	REMOVAL EFF. %	DIA m	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm
5	3472	0.2191	600	150	75	2.60	8.52	60.93	5054
5	3472	0.2191	600	120	80	2.60	8.52	60.95	5054
5	3472	0.2191	600	90	85	3.09	10.14	43.02	7352
5	3472	0.2191	600	60	90	2.81	9.22	52.03	7352
5	3472	0.2191	600	30	95	2.81	9.22	52.03	7352
5	3472	0.2191	600	6	99	2.81	9.22	52.03	7352
5	3472	0.2191	600	0.6	99.9	2.81	9.22	52.03	7352

Treatment Cost at various removal efficiencies- Cascade A/S
[Chemical: Chlorobenzene, H = 264 atm, Plant Size = 5 mgd]

WATER TREAT MGD	WATER TREAT gpm	WATER TREAT cu m/s	INFL.T CONC ug / L	EFFL. CONC ug / L	REMOVAL EFF. %	DIA m	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm
5	3472	0.2191	600	150	75	2.60	8.52	60.93	7000
5	3472	0.2191	600	120	80	2.60	8.52	60.95	7000
5	3472	0.2191	600	90	85	3.09	10.14	43.02	11000
5	3472	0.2191	600	60	90	2.81	9.22	52.03	11000
5	3472	0.2191	600	30	95	2.81	9.22	52.03	11500
5	3472	0.2191	600	6	99	2.81	9.22	52.03	11500
5	3472	0.2191	600	0.6	99.9	2.81	9.22	52.03	11500

DEPTH m	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	ANNUAL TREAT. $	T.COST PER $	CONST. COST $	PUMP 60% EFF HP	BLOWER 70% EFF HP
2.15	7.05	402	12052	1416	31415	0.0172	22462	10	3
2.77	9.10	518	15553	1827	36170	0.0198	25743	12	3
2.41	7.90	638	19129	2247	41689	0.0228	29139	11	7
3.47	11.40	761	22822	2681	49723	0.0272	33012	15	10
5.03	16.50	1101	33032	3880	63974	0.0351	41864	20	13
8.26	27.10	1808	54253	6373	98633	0.054	63112	32	21
11.70	38.40	2562	76875	9030	149853	0.0821	96016	49	33

DEPTH m	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2	LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O
1.86	6.10	348	10428	1225	30587	537	1739167	30521	0.27
2.45	8.05	459	13758	1616	30587	537	1739167	30528	0.30
1.98	6.50	525	15739	1849	48065	595	1739167	21547	0.35
3.00	9.85	657	19719	2316	48065	720	1739167	26062	0.45
3.95	12.95	864	25925	3045	50249	753	1739167	26062	0.50
7.15	23.45	1565	46946	5514	50249	753	1739167	26062	0.55
10.09	33.10	2209	66264	7783	50249	753	1739167	26062	0.55

TOTAL HP	OPER COST / Yr $	PUMP COST-73 $	PUMP COST-88 $	PUMP COST / Yr $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 88 $	BLOW COST / Yr $
13	6796	1400	2008	236	2082	245	3000	4304	505
15	7842	1500	2152	253	2231	262	3000	4304	505
18	9410	1500	2152	253	2231	262	3800	5451	640
25	13070	1700	2439	286	2528	297	4000	5738	674
33	17252	1800	2582	303	2677	314	4000	5738	674
53	27708	2300	3299	388	3421	402	6250	8966	1053
82	42869	3000	4304	505	4462	524	8500	12193	1432

P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $	PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $
1.65	5	9	2	1	10	5336	1300	1933	227
2.42	7	12	3	2	14	7141	1500	2231	262
2.28	6	9	4	3	12	6433	1300	1933	227
4.43	9	14	8	5	20	10384	1500	2231	262
6.48	11	19	12	8	27	14259	1800	2677	314
12.90	21	34	23	17	51	26612	2400	3570	419
18.21	29	48	33	23	72	37563	2900	4313	507

BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
4462	524	31323	33507	40303	0.0221
4462	524	35899	38512	46354	0.0254
5652	664	40634	43807	53217	0.0292
5949	699	46035	49712	62782	0.0344
5949	699	58380	63273	80526	0.0441
9296	1092	88009	95875	123584	0.0677
12642	1485	133895	144933	187803	0.1029

BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST $
2000	2965	348	27102	28902	34238	0.0188
2000	2965	348	31756	33983	41124	0.0225
2500	3706	435	33433	35944	42377	0.0232
3000	4447	522	39776	42877	53261	0.0292
3000	4447	522	45819	49701	63961	0.0350
3500	5188	609	76156	82698	109310	0.0599
7000	10376 -	1219	115414	124923	162486	0.0890

Treatment Cost at various removal efficiencies- Conventional A/S
[Chemical: 1,2-dichloropropane, H = 162 atm, Plant Size = 5 mgd]

WATER TREAT MGD	WATER TREAT gpm	WATER TREAT cu m/s	INFL.T CONC ug / L	EFFL. CONC ug / L	REMOVAL EFF. %	DIA m	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm
5	3472	0.2191	100	25	75	2.80	9.19	52.37	7352
5	3472	0.2191	100	20	80	2.80	9.19	52.37	7352
5	3472	0.2191	100	15	85	2.80	9.19	52.37	7352
5	3472	0.2191	100	10	90	3.07	10.07	43.62	11029
5	3472	0.2191	100	5	95	3.07	10.07	43.62	11029
5	3472	0.2191	100	1	99	3.07	10.07	43.62	11029
5	3472	0.2191	100	0.1	99.9	3.07	10.07	43.62	11029

Treatment Cost at various removal efficiencies- Cascade A/S
[Chemical: 1,2-dichloropropane, H = 162 atm, Plant Size = 5 mgd]

WATER TREAT MGD	WATER TREAT gpm	WATER TREAT cu m/s	INFL.T CONC ug / L	EFFL. CONC ug / L	REMOVAL EFF. %	DIA m	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm
5	3472	0.2191	100	25	75	2.80	9.19	52.37	11400
5	3472	0.2191	100	20	80	2.80	9.19	52.37	11500
5	3472	0.2191	100	15	85	2.80	9.19	52.37	11500
5	3472	0.2191	100	10	90	3.07	10.07	43.62	16250
5	3472	0.2191	100	5	95	3.07	10.07	43.62	16400
5	3472	0.2191	100	1	99	3.07	10.07	43.62	17500
5	3472	0.2191	100	0.1	99.9	3.07	10.07	43.62	18250

DEPTH m	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	ANNUAL TREAT. $	T.COST PER $	CONST. COST $	PUMP 60% EFF HP	BLOWER 70% EFF HP
2.37	7.78	516	15474	1818	35342	0.0194	25447	10	4
2.59	8.50	564	16906	1986	40477	0.0222	29351	12	4
3.00	9.85	653	19591	2301	47422	0.0260	33721	15	5
3.26	10.68	850	25505	2996	56837	0.0311	38242	14	14
4.57	15.00	1194	35821	4208	72254	0.0396	46933	19	19
6.76	22.19	1766	52992	6224	110624	0.0606	70352	31	31
10.70	35.10	2794	83822	9846	167306	0.0917	105351	49	47

DEPTH m	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2	LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O
2.00	6.56	435	13047	1533	49812	751	1739167	26233	0.12
2.18	7.15	474	14221	1670	50249	758	1739167	26233	0.12
2.65	8.69	576	17284	2030	50249	758	1739167	26233	0.12
2.46	8.08	643	19296	2266	71004	892	1739167	21848	0.18
3.96	13.00	1035	31045	3647	71660	900	1739167	21848	0.20
6.10	20.01	1593	47786	5613	76466	961	1739167	21848	0.21
9.17	30.10	2396	71881	8443	79743	1002	1739167	21848	0.22

TOTAL HP	OPER COST / Yr $	PUMP COST-73 $	PUMP COST-88 $	PUMP COST / Yr $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 88 $	BLOW COST / Yr $
14	7319	1500	2152	253	2231	262	3000	4304	505
16	8365	1600	2295	270	2380	280	3000	4304	505
20	10456	1800	2582	303	2677	314	3800	5451	640
28	14638	1700	2439	286	2528	297	4000	5738	674
38	19866	1900	2726	320	2826	332	5500	7890	927
62	32413	2200	3156	371	3272	384	7500	10759	1264
96	50188	2900	4160	489	4313	507	8500	12193	1432

P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $	PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $
0.79	5.8	10	1	1	11	5538	1500	2231	262
0.86	6.3	10	2	1	12	6041	1500	2231	262
1.04	7.6	13	2	1	14	7342	1800	2677	314
1.45	7.1	12	4	3	14	7559	1600	2380	280
2.6	11.4	19	7	5	24	12432	1900	2826	332
4.2	17.5	29	12	8	37	19599	2100	3123	367
6.62	26.4	44	19	14	58	30082	2600	3867	454

BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
4462	524	35486	38090	45409	0.0200
4462	524	40931	43720	52085	0.0300
5652	664	47024	50304	60760	0.0300
5949	699	53329	57321	71959	0.0400
8180	961	65448	70949	90815	0.0500
11155	1310	98106	106025	138438	0.0800
12642	1485	146912	158749	208938	0.1100

BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
1500	2223	261	29921	31977	37515	0.0206
1500	2223	261	34430	36623	42664	0.0234
1500	2223	261	41486	44092	51435	0.0282
2500	3706	435	40346	43328	50886	0.0279
3800	5633	662	56722	61362	73794	0.0404
3900	5781	679	88467	95126	114725	0.0629
4000	5929	696	125984	135578	165660	0.0908

Treatment Cost at various removal efficiencies- Conventional A/S
[Chemical: EDB, H = 37 atm, Plant Size = 5 mgd]

WATER TREAT MGD	WATER TREAT gpm	WATER TREAT cu m/s	INFL.T CONC ug / L	EFFL. CONC ug / L	REMOVAL EFF. %	DIA m	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm
5	3472	0.2191	50	12.5	75	3.70	12.14	30.01	35000
5	3472	0.2191	50	10.0	80	3.70	12.14	30.01	35000
5	3472	0.2191	50	7.5	85	3.70	12.14	30.01	35000
5	3472	0.2191	50	5.0	90	4.05	13.29	25.04	40000
5	3472	0.2191	50	2.5	95	4.05	13.29	25.04	40000
5	3472	0.2191	50	0.5	99	4.54	14.88	19.98	45000
5	3472	0.2191	50	0.1	99.9	6.40	21.00	10.03	50000

Treatment Cost at various removal efficiencies- Cascade A/S
[Chemical: EDB, H = 37 atm, Plant Size = 5 mgd]

WATER TREAT MGD	WATER TREAT gpm	WATER TREAT cu m/s	INFL.T CONC ug / L	EFFL. CONC ug / L	REMOVAL EFF. %	DIA m	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm
5	3472	0.2191	50	12.5	75	3.70	12.14	30.01	50000
5	3472	0.2191	50	10.0	80	3.70	12.14	30.01	54000
5	3472	0.2191	50	7.5	85	3.70	12.14	30.01	54000
5	3472	0.2191	50	5.0	90	4.05	13.29	25.04	58000
5	3472	0.2191	50	2.5	95	4.05	13.29	25.04	58000
5	3472	0.2191	50	0.5	99	4.54	14.88	19.98	65000
5	3472	0.2191	50	0.1	99.9	6.40	21.00	10.03	73000

DEPTH m	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2	LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O
2.45	8.04	930	27898	3277	152933	1322	1739167	15033	0.30
2.84	9.32	1078	32339	3799	152933	1322	1739167	15033	0.30
3.29	10.79	1249	37463	4400	152933	1322	1739167	15033	0.30
3.59	11.78	1633	48991	5754	174780	1261	1739167	12544	0.27
4.73	15.52	2152	64548	7582	174780	1261	1739167	12544	0.26
6.40	21.00	3650	109485	12860	196628	1131	1739167	10006	0.18
8.70	28.54	9881	296434	34819	218475	631	1739167	5024	0.13

DEPTH m	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2	LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O
1.95	6.40	740	22205	2608	218475	1888	1739167	15033	0.55
2.28	7.48	865	25962	3050	235953	2039	1739167	15033	0.50
2.49	8.17	945	28354	3330	235953	2039	1739167	15033	0.50
3.00	9.84	1365	40939	4809	253431	1828	1739167	12544	0.35
3.80	12.47	1729	51857	6091	253431	1828	1739167	12544	0.35
5.10	16.73	2908	87246	10248	284018	1634	1739167	10006	0.25
7.20	23.62	8177	245325	28816	318974	921	1739167	5024	0.17

P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $	PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $
2.41	7	12	13	19	31	13068	1500	2231	262
2.80	8	14	15	22	36	15149	1600	2380	280
3.24	10	16	18	25	41	17549	1700	2528	297
3.18	10	17	20	29	46	19439	1700	2528	297
4.03	14	23	25	36	59	25103	2000	2975	349
3.78	18	31	27	38	69	30002	2200	3272	384
3.71	25	42	29	42	83	37035	2700	4016	472

P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $	PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $
3.52	6	9	28	20	29	15202	1400	2082	245
3.74	7	11	32	23	34	17556	1400	2082	245
4.08	7	12	35	25	37	19173	1500	2231	262
3.44	9	14	31	22	37	19234	1600	2380	280
4.36	11	18	40	28	47	24362	1800	2677	314
4.18	15	24	43	30	55	28724	2000	2975	349
4.02	21	35	46	33	67	35234	2300	3421	402

BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
6500	9635	1132	53621	58291	71360	0.0391
6800	10080	1184	62156	67418	82567	0.0452
6800	10080	1184	72005	77886	95435	0.0523
7500	11117	1306	86014	93371	112810	0.0618
8750	12970	1523	113327	122782	147884	0.0810
8750	12970	1523	171684	186452	216454	0.1186
9500	14082	1654	329371	366316	403351	0.2210

BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
6500	9635	1132	42678	46662	61864	0.0339
6800	10080	1184	49900	54378	71934	0.0394
6800	10080	1184	54496	59273	78445	0.0430
6800	10080	1184	71878	78150	97383	0.0534
7500	11117	1306	91045	98756	123119	0.0675
7500	11117	1306	136811	148714	177438	0.0972
7500	11117	1306	272583	303107	338340	0.1854

Treatment Cost at various removal efficiencies- Conventional A/S
[Chemical: DBCP, H = 7 atm, Plant Size = 5 mgd]

WATER TREAT MGD	WATER TREAT gpm	WATER TREAT cu m/s	INFL CONC ug / L	EFFL. CONC ug / L	REMOVAL EFF. %	DIA m	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm
5	3472	0.2191	20	5	75.0	4.54	14.88	19.98	130000
5	3472	0.2191	20	4	80.0	4.54	14.88	19.98	130000
5	3472	0.2191	20	3	85.0	6.40	21.00	10.03	150000
5	3472	0.2191	20	2	90.0	6.40	21.00	10.03	150000
5	3472	0.2191	20	1	95.0	6.40	21.00	10.03	150000
5	3472	0.2191	20	0.2	99.0	7.40	24.28	7.50	220000
5	3472	0.2191	20	0.02	99.9	9.05	29.69	5.00	300000

Treatment Cost at various removal efficiencies- Cascade A/S
[Chemical: DBCP, H = 7 atm, Plant Size = 5 mgd]

WATER TREAT MGD	WATER TREAT gpm	WATER TREAT cu m/s	INFL.T CONC ug / L	EFFL. CONC ug / L	REMOVAL EFF. %	DIA m	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm
5	3472	0.2191	20	5	75.0	4.54	14.88	19.98	200000
5	3472	0.2191	20	4	80.0	4.54	14.88	19.98	200000
5	3472	0.2191	20	3	85.0	6.40	21.00	10.03	225000
5	3472	0.2191	20	2	90.0	6.40	21.00	10.03	230000
5	3472	0.2191	20	1	95.0	6.40	21.00	10.03	240000
5	3472	0.2191	20	0.2	99.0	7.40	24.28	7.50	340000
5	3472	0.2191	20	0.02	99.9	9.05	29.69	5.00	480000

DEPTH m	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2	LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O
3.15	10.33	1796	53876.00	6328.25	568035	3269	1739167	10008	0.70
3.80	12.47	2166	64993.27	7634.08	568035	3269	1739167	10008	0.70
3.90	12.80	4428	132847.91	15604.27	655425	1894	1739167	5025	0.60
4.80	15.75	5450	163505.12	19205.25	655425	1894	1739167	5025	0.60
6.70	21.98	7608	228225.90	26807.33	655425	1894	1739167	5025	0.60
7.30	23.95	11081	332442.45	39048.57	961290	2078	1739167	3759	0.40
8.90	29.20	20207	606201.97	71204.26	1310850	1894	1739167	2513	0.25

DEPTH m	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2	LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O
2.40	7.87	1368	41048.38	4821.53	873900	5029	1739167	10008	1.00
2.90	9.51	1653	49600.12	5826.01	873900	5029	1739167	10008	1.00
3.10	10.17	3520	105597.06	12403.39	983138	2841	1739167	5025	0.85
4.20	13.78	4769	143066.98	16804.59	1004985	2904	1739167	5025	0.80
5.05	16.57	5734	172021.02	20205.52	1048680	3030	1739167	5025	0.70
6.45	21.16	9791	293733.40	34501.82	1485630	3211	1739167	3759	0.44
8.10	26.57	18390	551711.91	64803.87	2097360	3031	1739167	2513	0.30

P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $	PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $
7.23	9	15	148	211	226	118168	1600	2380	280
8.73	11	18	178	254	273	142552	1700	2528	297
7.68	11	19	181	258	277	144803	1800	2677	314
9.45	14	23	223	318	341	178219	1950	2900	341
13.19	19	32	311	444	476	248764	2200	3272	384
9.58	21	35	331	473	508	265424	2300	3421	402
7.30	26	43	344	491	534	279091	2900	4313	507

P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $	PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $
7.87	7	12	247	177	188	98342	1200	1785	210
9.51	8	14	299	213	227	118830	1400	2082	245
8.64	9	15	305	218	233	121808	1600	2380	280
11.02	12	20	398	284	304	159173	1900	2826	332
11.60	15	24	437	312	336	175845	2000	2975	349
9.31	19	31	497	355	386	201766	2200	3272	384
7.97	23	39	601	429	468	244656	2700	4016	472

BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
22000	32611	3830	84492	94930	213098	0.1168
25000	37058	4353	101927	114211	256762	0.1407
25000	37058	4353	147629	167901	312703	0.1713
29000	42987	5049	181697	206292	384511	0.2107
35000	51881	6094	253619	286905	535668	0.2935
37000	54845	6442	319508	365400	630825	0.3457
39000	57810	6790	476393	554895	833985	0.4570

BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST/Yr $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
19000	28164	3308	64375	72714	171056	0.0937
22000	32611	3830	77786	87687	206517	0.1132
22000	32611	3830	117346	133859	255667	0.1401
27000	40022	4701	158985	180823	339995	0.1863
29000	42987	5049	191161	216765	392610	0.2151
31000	45951	5397	282305	322589	524355	0.2873
33000	48916	5746	433572	504593	749249	0.4105

APPENDIX G

Cost Calculations for Sensitivity Analysis for Ethylenedibromide

Treatment Cost at various water loadings- Con A/S, [Chemical: EDB, H = 37 atm, Plant Size = 5 mgd]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2
5.00	9.41	50.00	60000	11.15	775	23239	2730	262170	3775
5.00	9.91	45.00	60000	10.99	848	25441	2988	262170	3398
5.00	10.52	40.00	60000	10.40	903	27084	3181	262170	3020
5.00	11.24	35.00	60000	9.94	986	29586	3475	262170	2643
5.00	12.14	30.00	60000	9.68	1120	33605	3947	262170	2265
5.00	13.30	25.00	60000	9.51	1321	39643	4656	262170	1888
5.00	14.87	20.00	60000	8.99	1561	46820	5499	262170	1510
5.00	17.17	15.00	60000	8.53	1975	59237	6958	262170	1133
5.00	21.03	10.00	60000	7.71	2677	80311	9433	262170	755
5.00	29.74	5.00	60000	7.38	5126	153788	18064	262170	378

Treatment Cost at various water loadings- Cascade A/S, [Chemical: EDB, H = 37 atm, Plant Size = 5 mgd]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2
5.00	9.41	50.00	90000	9.19	638	19138	2248	393255	5663
5.00	9.91	45.00	90000	9.02	696	20885	2453	393255	5097
5.00	10.52	40.00	90000	8.86	769	23068	2710	393255	4530
5.00	11.24	35.00	90000	8.53	846	25387	2982	393255	3964
5.00	12.14	30.00	90000	8.01	927	27796	3265	393255	3398
5.00	13.30	25.00	90000	7.58	1053	31578	3709	393255	2831
5.00	14.87	20.00	90000	7.05	1225	36738	4315	393255	2265
5.00	17.17	15.00	90000	6.99	1618	48529	5700	393255	1699
5.00	21.03	10.00	90000	6.33	2199	65958	7747	393255	1133
5.00	29.74	5.00	90000	6.53	4534	136017	15976	393255	566

LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O	P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $
1739167	25044	3.00	33	10	16	315	225	241	173325
1739167	22540	2.70	30	10	16	280	200	216	154538
1739167	20035	2.50	26	9	15	245	175	190	135991
1739167	17531	1.60	16	9	15	150	107	122	85924
1739167	15026	1.00	10	8	14	91	65	79	55058
1739167	12522	0.70	7	8	14	63	45	59	40068
1739167	10018	0.50	4	8	13	42	30	43	29003
1739167	7513	0.30	3	7	12	24	17	30	22704
1739167	5009	0.10	1	7	11	7	5	16	11504
1739167	2504	0.07	1	6	11	5	3	14	8184

LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O	P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $
1739167	25044	2.50	23	8	13	162	232	245	91843
1739167	22540	2.20	20	8	13	140	200	214	80206
1739167	20035	2.00	18	8	13	125	179	192	72204
1739167	17531	1.40	12	7	12	84	121	133	50626
1739167	15026	1.10	9	7	12	62	89	101	38640
1739167	12522	0.80	6	7	11	43	61	72	28184
1739167	10018	0.40	3	6	10	20	28	39	15810
1739167	7513	0.20	1	6	10	10	14	24	10501
1739167	5009	0.15	1	6	9	7	10	19	8346
1739167	2504	0.10	1	6	10	5	7	16	7399

PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST / Yr'9 $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
1800	2677	314	23000	29440	3458	52710	59212	232537	0.1270
1800	2677	314	22000	28160	3308	54744	61355	215892	0.1180
1600	2380	280	20000	25600	3007	54945	61413	197403	0.1080
1600	2380	280	18000	23040	2706	56144	62605	148530	0.0810
1500	2231	262	12000	15360	1804	59042	65055	120113	0.0660
1500	2231	262	11500	14720	1729	63581	70228	110296	0.0600
1400	2082	245	8250	10560	1240	67164	74148	103151	0.0570
1400	2082	245	6000	7680	902	73591	81696	104400	0.0570
1400	2082	245	2000	2560	301	81464	91443	102946	0.0560
1400	2082	245	2000	2560	301	110305	128914	137099	0.0750

PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST / Yr'9 $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
1500	2231	262	27000	34560	4059	43408	49978	141821	0.0780
1500	2231	262	22000	28160	3308	44939	50962	131168	0.0720
1400	2082	245	19500	24960	2932	46799	52684	124888	0.0680
1400	2082	245	14000	17920	2105	48177	53508	104134	0.0570
1400	2082	245	12000	15360	1804	48835	54148	92788	0.0510
1400	2082	245	9500	12160	1428	50645	56027	84211	0.0460
1400	2082	245	8000	10240	1203	52701	58464	74274	0.0410
1150	1710	201	6000	7680	902	60288	67091	77592	0.0430
1150	1710	201	3500	4480	526	66905	75379	83725	0.0460
1150	1710	201	2000	2560	301	97559	114037	121436	0.0670

APPENDIX H

Cost Calculations for Sensitivity Analysis for Dibromochloropropane

Treatment Cost at various water loadings- Con A/S, [Chemical: DBCP, H = 7 atm, Plant Size = 5 mgd]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2
5.00	8.97	55.00	125000	25.26	1595	47845	5620	546188	8652
5.00	9.91	45.00	125000	24.61	1899	56958	6690	546188	7079
5.00	11.24	35.00	125000	23.79	2360	70791	8315	546188	5506
5.00	12.14	30.00	125000	22.64	2620	78603	9233	546188	4719
5.00	13.30	25.00	125000	22.31	3099	92956	10919	546188	3933
5.00	14.87	20.00	125000	21.82	3788	113632	13347	546188	3146
5.00	17.17	15.00	125000	20.67	4785	143535	16860	546188	2360
5.00	18.81	12.50	125000	19.85	5514	165407	19429	546188	1966
5.00	21.03	10.00	125000	19.36	6721	201633	23684	546188	1573
5.00	24.29	7.50	125000	19.03	8810	264287	31043	546188	1180
5.00	29.74	5.00	125000	19.68	13670	410100	48170	546188	787
5.00	42.06	2.50	125000	20.01	27796	833870	97946	546188	393

Treatment Cost at various water loadings- Cascade A/S, [Chemical: DBCP, H = 7 atm, Plant Size = 5 mgd]

WATER TREAT MGD	DIA ft	WATER LOADING gpm/ft2	AIR FLOW R = 3-5 cfm	DEPTH ft	PAC.VOL cu ft	PAC.COST $30/cu ft	PAC. COST PER Yr. $	BLOWER CAP. lb/hr.	GAS LOADING lb/hr/ft2
5.00	8.97	55.00	186000	18.70	1181	35418	4160	812727	12874
5.00	9.91	45.00	186000	17.39	1342	40251	4728	812727	10533
5.00	11.24	35.00	186000	15.94	1582	47454	5574	812727	8192
5.00	12.14	30.00	186000	14.86	1720	51604	6061	812727	7022
5.00	13.30	25.00	186000	14.14	1964	58918	6920	812727	5852
5.00	14.87	20.00	186000	13.58	2358	70742	8309	812727	4681
5.00	17.17	15.00	186000	12.47	2886	86577	10169	812727	3511
5.00	18.81	12.50	186000	16.40	4557	136700	16057	812727	2926
5.00	21.03	10.00	186000	18.04	6265	187963	22078	812727	2341
5.00	24.29	7.50	186000	19.03	8810	264287	31043	812727	1755
5.00	29.74	5.00	186000	20.34	14126	423770	49776	812727	1170
5.00	42.06	2.50	186000	21.00	29163	874880	102763	812727	585

LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O	P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $
1739167	27548	1.70	43	22	37	843	602	639	459918
1739167	22540	1.35	33	22	36	652	466	502	359613
1739167	17531	1.10	26	21	35	513	367	402	286616
1739167	15026	1.05	24	20	33	466	333	366	261166
1739167	12522	0.90	20	20	33	394	281	314	223048
1739167	10018	0.75	16	19	32	321	229	261	184551
1739167	7513	0.70	14	18	30	284	203	233	164235
1739167	6261	0.60	12	17	29	234	167	196	137353
1739167	5009	0.50	10	17	28	190	136	164	114087
1739167	3757	0.40	8	17	28	149	107	135	92631
1739167	2504	0.15	3	17	29	58	41	70	45334
1739167	1252	0.10	2	18	29	39	28	57	35823

LIQUID CAP. lb/hr	LIQUID LOADING lb/hr/ft2	P/ Z in H2O	P in	PUMP HP	PUMP 60% EFF HP	BLOWER HP	BLOWER 70% EFF HP	TOTAL HP	OPER COST / Yr $
1739167	27548	1.80	34	16	27	983	702	729	501771
1739167	22540	1.50	26	15	25	762	544	569	390903
1739167	17531	1.25	20	14	23	582	416	439	300637
1739167	15026	1.10	16	13	22	477	341	363	247891
1739167	12522	0.90	13	12	21	372	265	286	194836
1739167	10018	0.80	11	12	20	317	227	246	167452
1739167	7513	0.75	9	11	18	273	195	213	144659
1739167	6261	0.70	11	14	24	335	240	263	178445
1739167	5009	0.60	11	16	26	316	226	252	170119
1739167	3757	0.40	8	17	28	222	159	187	124203
1739167	2504	0.20	4	18	30	119	85	115	73766
1739167	1252	0.11	2	18	31	67	48	79	48738

PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST / Yr'9 $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
2800	4164	489	43000	55040	6465	128044	140618	600536	0.3291
2800	4164	489	37000	47360	5563	122561	135304	494917	0.2712
2500	3718	437	32000	40960	4811	134339	147902	434518	0.2381
2500	3718	437	30000	38400	4510	138098	152278	413444	0.2265
2400	3570	419	28000	35840	4210	149086	164634	387681	0.2124
2400	3570	419	23000	29440	3458	163007	180231	364782	0.1999
2100	3123	367	22000	28160	3308	178317	198851	363086	0.1990
1900	2826	332	19000	24320	2857	187585	215585	352938	0.1934
1800	2677	314	16000	20480	2406	204527	230931	345018	0.1891
1800	2677	314	14000	17920	2105	232164	243543	333889	0.1830
1900	2826	332	8250	10560	1240	294147	343890	389223	0.2133
1900	2826	332	8000	10240	1203	422920	522401	558224	0.3059

PUMP COST-73 $	PUMP COST-90 $	PUMP COST / Yr $	BLOW COST-73 $	BLOW COST- 90 $	BLOW COST / Yr $	TOWER COST / Yr'9 $	TOTAL CAP.COST $	ANNUAL COST $	T. COST 1000 GALS $
2200	3272	384	49000	62720	7367	84254	96166	597937	0.3276
2000	2975	349	40000	51200	6014	86610	97701	488604	0.2677
1650	2454	288	35000	44800	5262	90053	101178	401815	0.2202
1550	2305	271	31000	39680	4661	90664	101657	349549	0.1915
1500	2231	262	27000	34560	4059	94494	105736	300572	0.1647
1450	2157	253	22500	28800	3383	101481	113426	280878	0.1539
1300	1933	227	21000	26880	3157	107556	121110	265769	0.1456
2000	2975	349	25000	32000	3759	155029	175194	353639	0.1938
2200	3272	384	24000	30720	3608	190661	216731	386851	0.2120
2200	3272	384	18000	23040	2706	232164	266298	390501	0.2140
2700	4016	472	15500	19840	2330	303952	356530	430296	0.2358
3200	4759	559	9000	11520	1353	443719	548395	597132	0.3272