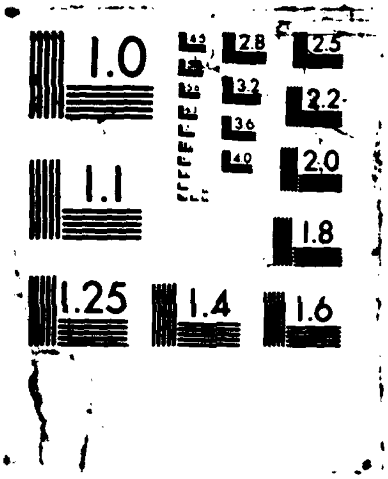
AD-A190 376 ECONOMIC EVALUATION OF AIR STRIPPING TO REMOVE VOLATILE 1/1
ORGANIC COMPOUNDS..(U) CONSTRUCTION ENGINEERING
RESEARCH LAB (ARMY) CHAMPAIGN IL H H ZAGHLOUL ET AL.
UNCLASSIFIED DEC 87 CERL-TR-N-87/23 F/G 24/4 NL


1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

US Army Corps of Engineers
Construction Engineering
Research Laboratory

AD-A190 376

USA-CERL TECHNICAL REPORT N-87/23
December 1987
Sanitary Landfill Leachate Control
at Military Installations

DTIC FILE COPY

②

Economic Evaluation of Air Stripping To Remove Volatile Organic Compounds From Water

by
Hany H. Zaghloul
Roy O. Ball
Stephen W. Maloney

DTIC
S ELECTE D
FEB 0 2 1988
D

This report documents the results of a study conducted to provide a basis for estimating the costs of installing and using air stripping to remove volatile organic compounds (VOCs) from water. The air-stripping technology was found to be a very economical and efficient method for contaminant removal. The technology is simple, relatively inexpensive to install, and has low labor and maintenance requirements. VOC removal rates range from 90 to 99.99 percent. Estimated costs, in terms of percentage of total production costs, were found to be 40 percent for capital costs, 50 percent for operational costs, and 10 percent for maintenance costs, according to literature sources. Results of a survey conducted during this study generally agree with these percentages, except that maintenance costs reported on the survey were lower due to the highly automated nature of new installations.

88 1 25 018

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

ADA190376

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704 0188
Exp Date Jun 30 1986

1a REPORT SECURITY CLASSIFICATION
Unclassified

1b RESTRICTIVE MARKINGS

2a SECURITY CLASSIFICATION AUTHORITY

2b DECLASSIFICATION/DOWNGRADING SCHEDULE

3 DISTRIBUTION/AVAILABILITY OF REPORT
Approved for public release; distribution unlimited.

4 PERFORMING ORGANIZATION REPORT NUMBER(S)
USA-CERL TR N-87/23

5 MONITORING ORGANIZATION REPORT NUMBER(S)

6a NAME OF PERFORMING ORGANIZATION
U.S. Army Construction Engr Research Laboratory

6b OFFICE SYMBOL (If applicable)

7a NAME OF MONITORING ORGANIZATION

6c ADDRESS (City, State, and ZIP Code)
P.O. Box 4005
Champaign, IL 61820-1305

7b ADDRESS (City, State, and ZIP Code)

8a NAME OF FUNDING/SPONSORING ORGANIZATION
USACE

8b OFFICE SYMBOL (If applicable)
CEEC-EG

9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c ADDRESS (City, State, and ZIP Code)
20 Massachusetts Ave., N.W.
Washington, DC 20314-1000

10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
4A162720	A896	A	033

11 TITLE (Include Security Classification)
Economic Evaluation of Air Stripping To Remove Volatile Organic Compounds From Water (Unclassified)

12 PERSONAL AUTHOR(S)
Zaghloul, Hany H.; Ball, Roy O.; Maloney, Stephen W.

13a TYPE OF REPORT
Final

13b TIME COVERED
FROM ______ TO ______

14 DATE OF REPORT (Year, Month, Day)
1987, September

15 PAGE COUNT
53

16 SUPPLEMENTARY NOTATION
Copies are available from the National Technical Information Service
Springfield VA 22161

17 COSATI CODES

FIELD	GROUP	SUB GROUP
24	04	

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
volatile organic compounds
air stripping
water

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This report documents the results of a study conducted to provide a basis for estimating the costs of installing and using air stripping to remove volatile organic compounds (VOCs) from water. The air-stripping technology was found to be a very economical and efficient method for contaminant removal. The technology is simple, relatively inexpensive to install, and has low labor and maintenance requirements. VOC removal rates range from 90 to 99.99 percent. Estimated costs, in terms of percentage of total production costs, were found to be 40 percent for capital costs, 50 percent for operational costs, and 10 percent for maintenance costs, according to literature sources. Results of a survey conducted during this study generally agree with these percentages, except that maintenance costs reported on the survey were lower due to the highly automated nature of new installations.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS

21 ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a NAME OF RESPONSIBLE INDIVIDUAL
Gloria Wienke

22b TELEPHONE (Include Area Code)
(217) 352-6511 x353

22c OFFICE SYMBOL
CECER-IMT-E

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

FOREWORD

This research was conducted for the Directorate of Engineering and Construction, Headquarters, U.S. Army Corps of Engineers (HQUSACE), under Project 4A162720A896, "Environmental Quality Technology"; Task A, "Installation Environmental Management"; Work Unit 033, "Sanitary Landfill Leachate Control at Military Installations." The work was performed by the Environmental Division (EN), U.S. Army Construction Engineering Research Laboratory (USA-CERL). The HQUSACE Technical Monitors were Mr. F. Bizzoco and Mr. R. Ross (CEEC-EG).

Dr. R. K. Jain is Chief of USA-CERL-EN. COL Norman C. Hintz is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

CONTENTS

CONTENTS (Cont'd)

FIGURES

TABLES

ECONOMIC EVALUATION OF AIR STRIPPING TO REMOVE VOLATILE ORGANIC COMPOUNDS FROM WATER

1 INTRODUCTION

Background

The more stringent water quality standards imposed by the Safe Drinking Water Act of 1974 have required the Army to implement new technology to reduce water pollutants. An example of potential health hazards associated with water pollutants is the contamination of ground and surface waters by toxic volatile organic compounds (VOCs).

The seven volatile organic compounds most commonly found in groundwater are: trichloroethylene (TCE) and tetrachloroethylene (PCE) (both are used as industrial solvents); methylene chloride (a paint stripper); 1,1,1-trichloroethane (1,1,1-TCA); cis-1,2-dichloroethylene (Cis 1,2-DCE); 1,2-dichloroethane (DCA); and 1,1-dichloroethylene (1,1-DCE).

Contamination by organic chemicals is generally associated with situations in which they are manufactured, spilled, used, or discarded. At Army installations, paint strippers are the most frequently used VOC. Their volatility eliminates any possibilities for their accumulation in surface waters or any well aerated environment. However, poor operation or storage practices may result in leakage of these compounds to the ground water reservoir.

New treatment methods for controlling VOCs have been applied. One such technology is air stripping--a method that involves removing contaminants from water by means of transfer to the air. A U.S. Environmental Protection Agency (USEPA) study[1] has indicated that air stripping is more economical for removing VOCs than diffused aeration in a basin or carbon adsorption. However, theoretical[2] cost estimates, which originated from either mathematical design models or laboratory and field-scale pilot plant studies, have differed so much from installed cost estimates[3] that it is difficult to generalize how much money must be allocated to install the technology in future construction. Thus, there is a need to determine the real cost of water treatment by air stripping. This will require obtaining data from operating facilities to provide full-scale performance and cost information that can be used to calculate a unit cost for this process.

---

[1] Environmental Science and Engineering, Inc., *Technologies and Costs for the Removal of Volatile Organic Chemicals from Potable Water Supplies* (U.S. Environmental Protection Agency [USEPA], May 1985).

[2] Robert M. Clark, et al., "VOC's in Drinking Water: Cost of Removal," *Journal of Environmental Engineering*, Vol 110, No. 6 (American Society of Civil Engineers [ASCE], December 1984), pp 1146-1162.

[3] David W. Hand, et al., "Design and Economic Evaluation of a Full Scale Air-Stripping Tower for Treatment of VOC's From a Contaminated Groundwater," manuscript submitted to the *Journal of the American Water Works Association* (1985).

Objective

The objective of this study was to provide a basis for Directorate of Engineering and Housing personnel to estimate VOC removal costs using air stripping.

Approach

First, current design practices used by consultants and manufacturers were reviewed to evaluate and distinguish the major effects of design elements on the cost of construction and operation. Next, a survey was used to collect field data from operating facilities currently using air-stripping techniques. The data used in this study were collected from several sources. In accordance with the guidelines set forth in ETL 1110-3-332,[4] the sources of data for this study are: technical consultants, manufacturers and literature, handbooks, and technical articles, among others. The data were then manipulated to arrive at the capital cost of using air stripping. The distribution of cost was examined and a final cost per unit of capacity (cents per thousand gallons) was derived from the sum of the amortized capital cost and the annual operating cost, divided by the annual capacity of the process. The result provided a unit cost for the pollution control service performed.

Scope

The survey was intended to present a general description of cost; however, the data collected were principally associated with trichloroethylene removal. For materials which are more difficult to air strip, the costs will be higher than determined here. Complex mixtures of compounds may also be more difficult to remove if the compounds interact with one another, and thus the cost may be higher than for single compounds.

Severe congestion at a construction site, or limitations on tower size due to proximity to airfields may also increase cost. No examples of this were encountered in the survey. Construction in areas of high air pollution may require methods to purify the air influent to the process, and restrictions on effluent air may also require some additional units to be added to remove contaminants from air. No data on these processes are presented here.

Severe weather conditions can also adversely affect the process. At cold temperatures, the process is less efficient. Extreme cold may require some type of heating to avoid ice buildup.

Mode of Technology Transfer

It is recommended that the information in this report be transferred through an Engineer Technical Letter. The data may also impact Army Technical Manual 5-813-3, *Water Supply, Water Treatment*.

---

[4] Engineer Technical Letter (ETL) 1110-3-332, *Engineering and Design Economic Studies* (Department of the Army [DA], 22 March 1982).

2 DESCRIPTION OF THE AIR-STRIPPING PROCESS

Physical Characteristics

The countercurrent air-stripping packed tower system is made up of a rigid container with a circular or square cross-section supported by an internal structure to form a tower-shaped structure. The construction material for a metal tower body is either aluminum or stainless steel. Other materials for the tower body construction may include multilayer fiberglass walls protected by various insulation or coating layers.

The space inside the tower body is filled with a synthetic packing medium consisting of small units formed into geometrical shapes such as saddles, rings, and balls. The packing material can be plastic, metal, or ceramic. However, most recent designs tend to use Tri-packs--a 2-in.*-diameter, ball-shaped plastic medium--because of its suitability for the water treatment application.

The installation pattern depends on the tower size and configuration. Small towers are suspended on a support structure resting on the ground, while the treated water effluent is connected to a separate storage tank. Larger towers are normally mounted on the thick structural concrete slab that tops a clear water well (Figure 1). A pump located at the contaminated wellhead delivers the water from the well to the top of the tower. In retrofit designs, where the air-stripping process is added to an existing treatment facility, upgrading the existing well pump or adding a new booster pump may be required to ensure delivery of the contaminated water to the top of the tower. Depending on the design, effluent from the tower may be gravity-fed into a treatment plant or collected in a clear well for distribution.

Operations

Treatment occurs as the contaminated water is pumped to the top of the column, distributed, and trickled down through a bed of packing material. The contaminated water is distributed by sprays or distribution trays while the air is blown upward through the tower by forced or induced draft. With water flowing down due to gravity and air being forced up, the gas forms a continuous and thorough contact with the liquid. The packing material provides a large surface area for mixing air and water, contact time for the VOC molecules to transfer from water to air, and a large void volume to reduce the air system's energy loss.

Removal of VOCs from water by aeration is based on transferring the compound from the liquid phase to the gaseous phase. A minimal thickness of water on the packing material promotes efficient mass transfer. It is economically desirable to operate packed columns with a maximum water flow rate and with the minimum volume of air needed to achieve the desired concentration of organics in the effluent. Air containing the VOCs is then released to the atmosphere at the top of the column. Due to the large volume of air being discharged, the concentration of VOCs in air is generally 1 to 5 parts per million (ppm) by volume.

Ideal operating conditions would produce a maximum treated water volume using a minimum amount of energy to blow low volumes of airflow through the column. The

---

*1 in. = 25.4 mm; 1 ft = 0.3 m; 1 cfm = 0.028 m^3/min; 1 gal = 3.8 m^3; 1 HP = 746 W.

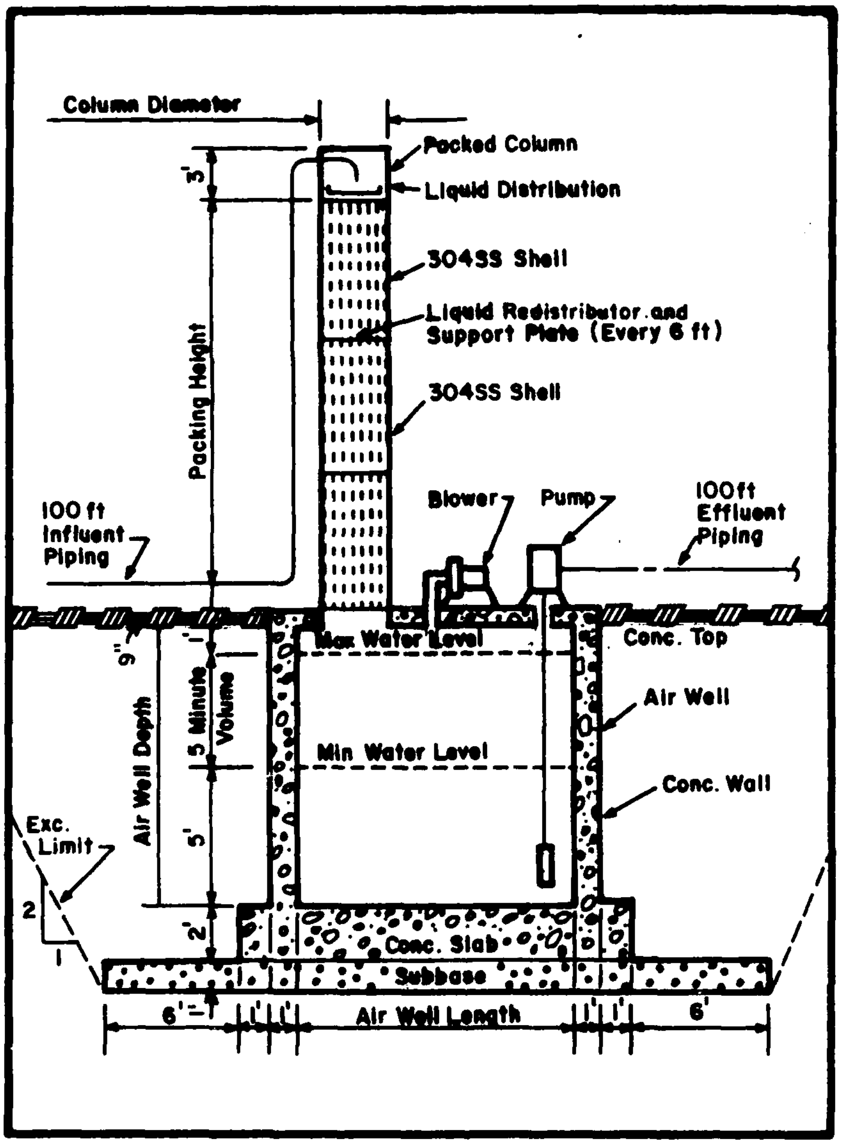


Figure 1. Packed-column air-stripping conceptual design. (Source: "Packed Column Air Stripping for Removal of Volatile Compounds," *Proceedings, ASCE Environmental Engineering Conference* [July 1982], p 577, by Michael O. Cummins and James J. Westrick. Used with permission.)

preliminary design and cost estimation procedures for a packed-tower air-stripping system are based on the removal efficiency desired in the design, the properties of the compound to be removed, flow requirements of the treated water, temperature of both air and treated water, and the properties of the packing material.

Temperature influences the solubility of the compound in water, the Henry's Law coefficient (which is a measure of the compound's tendency to be transferred from the water to the air), and the overall mass transfer efficiency of the system. Tower operation must be varied according to the temperature of the air and water. Two examples--ground water and surface water--illustrate the effect of temperature on air stripping. In a cold climate, surface water requires more airflow than normal due to the low air temperature, but for the ground water, a stable, moderate temperature may counterbalance the cold air effect. To maintain the efficiency of the process when the temperature of both the surface water and the air are quite low, the airflow must be heated to raise its temperature substantially prior to application.

Packing material properties directly affect the air pressure drop across the tower length, subsequently requiring larger blowers that increase power costs (Chapter 6). The areas of uncertainty in the design of this operation are the mass transfer coefficient and the Henry's Law coefficient of the compound at the trace levels encountered in water supplies (this coefficient may vary considerably for higher concentrations in the laboratory). The mass transfer coefficient is the main reason for adopting the pilot tower approach prior to full-scale application at any specific site. Determining this variable on-site is a crucial step in completing the design prior to construction.

Limitations

In certain cases, limitations can affect the use of the air-stripping tower. For example, precipitation or sedimentation cause the medium in a packed tower to become clogged. Here, spray and tray aerators must be considered, either for complete treatment or in combination with packed towers.

Each VOC has certain physical and chemical characteristics--such as molecular weight, density, Henry's Law coefficient, solubility, vapor pressure, and saturation condition--that affect the air-stripping process' removal efficiency potential. Generally, compounds with a *high molecular weight* and a low Henry's Law coefficient value may not be amenable to air stripping. Otherwise, tower aeration is by far the most cost-effective technology for removing VOCs from drinking water.[5]

---

[5] *Thomas Love, Jr.*, "Treatment of Drinking Water Containing Trichloroethylene and Related Industrial Solvents," *Journal of the American Water Works Association* (August 1982), pp 413-425.

3 AIR-STRIPPING DESIGN PRACTICES

A literature review of current air-stripping design practices indicated that most air-stripping design calculations provide for contaminant removal efficiencies of 90 to 99.99 percent. This target can be attained easily in pilot tower experiments that normally precede the final design stage for a given concentration of contaminants. An attractive design feature of this technology is its operational flexibility for a given range of contaminant concentrations. Both the air volume and the packing medium depth can be increased to accommodate future changes in the contaminants' profiles. Low concentrations of new contaminants in the well effluent or wide fluctuations in the main contaminant concentration are often encountered as the contaminant plume migrates slowly through the subsoil aquifer. In the former case, as stripping of the main contaminant occurs, lower concentrations of other contaminants could be readily stripped with the same amount of airflow. In the latter case, both the airflow volume and the tower length may be increased, with a subsequent increase to the packing medium depth, in response to increasing contaminant concentration.

The above alteration can be adopted easily for metal towers. Metal tower construction simply involves assembling metal rings of the required diameter into a tower of a designated height. The metal rings are normally produced in 5-ft*-tall segments. With this simple construction idea, unit costs drop with increasing design capacity. For a larger tower, the increase in cost would be directly related to the tower height increments. Auxiliary equipment (e.g., blowers, pumps, and controls) varies slightly with size.

The design parameters for packed tower air stripping are:

1. Henry's Law coefficient
2. Air-to-water ratio
3. Gas pressure drop
4. Type and size of packing medium.

Model calculations[6] were made to determine the trade-off between tower volume and air-to-water ratio for typical pressure drops across the tower. A minimum tower volume is obtained by maximizing the driving force for stripping while at the same time minimizing the overall mass transfer resistance.

A correlation regression equation was used to assess the performance of air-stripping towers with respect to their removal efficiency of different contaminants.[7] This allowed contaminants at various sites with differing raw water characteristics to be

---

[6] David W. Hand, et al.

[7] Robert M. Clark, et al.

compared. The response variable chosen was air-to-water ratio. The resulting relationship is:

$$AW = 74.6*(RM**12.44)*(SL**0.37)*(V**-0.45)*(ML**-0.18)*(0.33**S) \qquad \text{[Eq 1]}$$

where:

The correlation coefficient = 0.86

AW = air-to-water ratio (volume/volume)

RM = removal as a decimal percentage (i.e., 90 percent = 0.90)

V = vapor pressure in millimeters mercury

SL = solubility in micrograms per liter

ML = molecular weight

S = saturation state (1 for saturated compounds; 0 for unsaturated compounds).

Equation 1 can be used to estimate the removal efficiencies of systems if they are to remove contaminants other than those for which they were designed; estimates can be based on their initial air-to-water ratios. Thus, the equation can be used to transfer the removal efficiency of one contaminant into an estimated overall removal potential on a "unified" contaminant basis. The most common compound is TCE. The performance of systems stripping major contaminants other than TCE can be evaluated and compared to a *unified TCE base case* using Equation 1. Compounds requiring higher air-to-water ratios to achieve the same percentage removal would be more expensive to remove than TCE. This is an empirical equation that should only be used as a guide.

Another design effect that must be considered is that of transferring contaminants to the air, which increases pollutant concentrations in the air stream. The cost of air treatment may impose additional expense on the operation. None of the facilities surveyed in this study were treating air from tower outlets; nevertheless, future regulations may consider this problem due to the quick spread of this technology. A recent study[8] used the principle of the Threshold Limit Value/Time-Weighted Average (TLV-TWA) for each VOC. The TLV-TWA values are from industrial hygiene practice and are for 8-hour exposures for healthy male workers. The TLV-TWA values were exceeded in three of nine compounds studied: vinyl chloride, 1,1-dichloroethylene, and carbon tetrachloride. An air dispersion computer model (Industrial Source Complex [ISC]) was used to determine the VOC dispersion from the packed tower aeration system. Assumptions incorporated into the ISC dispersion model include a centerline wind direction, a mixing height of 1500 m, a temperature of 300 K, and an anemometer height of 7.0 m. Inspection of the resulting values indicated that the TLV-TWA value was exceeded only when the influent VOC concentration was greater than or equal to 200 µg/L.

---

[8] Environmental Science and Engineering, Inc.

One method of mitigating the effects of introducing contaminants into the air is by installing packed-tower aeration off-gas carbon adsorption equipment. Cost estimates for this equipment are not included in this study; however, system sizes requiring multiple packed towers for VOC removal would generally be assumed to install an off-gas adsorber unit for each column. The capital costs for such units include a carbon adsorber, an additional blower, a duct heater (for aeration towers with air flow rates greater than 1000 cfm), a concrete foundation, and all necessary duct work. Operation and maintenance costs include expenses for energy for blowers and duct heaters, operational labor, maintenance material, and carbon replacement. For a particular application, detailed designs and cost estimates should be developed based on pilot plant testing and site-specific considerations.

A possible secondary effect of air stripping is an increased potential for the effluent stream to corrode the distribution system. Aeration can increase the dissolved oxygen content of the treated water if it is below saturation, thus increasing the oxidation potential of the effluent water. This effect can increase maintenance costs and/or decrease life time of the distribution system.

Figure 2 is a conceptual diagram of the tower aeration system. The air and water flow in a countercurrent pattern. The air stream departs from an air outlet at the tower top end, while the treated water effluent flows under gravity through the bottom end of the tower.

Figure 3 shows a typical flow configuration with either aeration tower or diffused air aeration. The effluent stream from the treatment process is chlorinated, goes to a clear well, and then is distributed to the system.

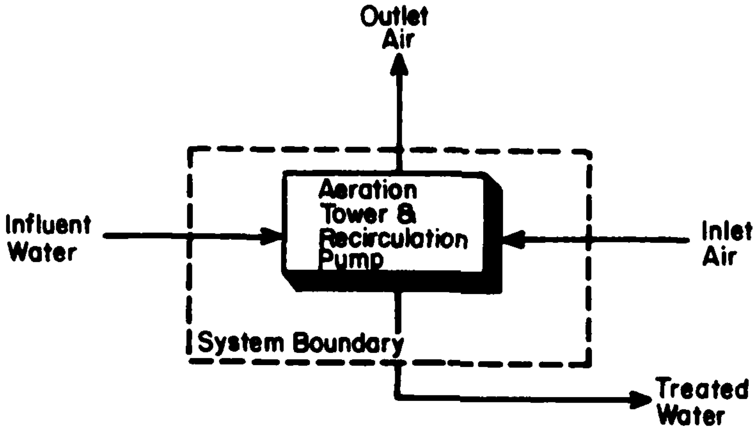


Figure 2. Tower aeration. (Source: *The Cost Digest: Cost Summaries of Selected Environmental Control Technologies*, EPA-600/8-84-010 [USEPA, October 1984], p 23.)

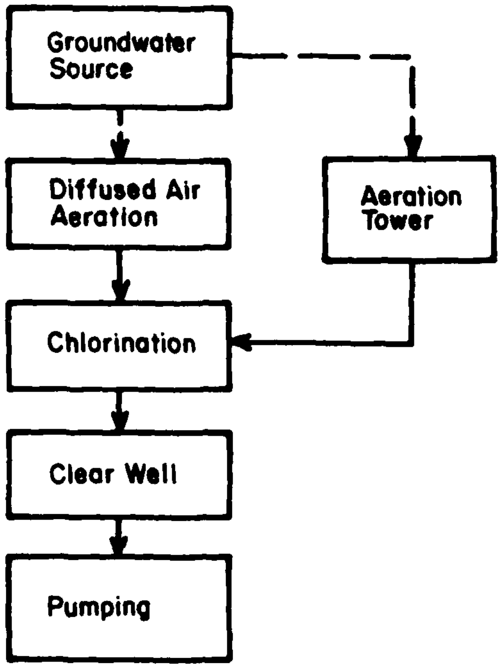


Figure 3. Assumed flow configuration for analysis. (Source: "VOC's in Drinking Water: Cost of Removal," *Journal of Environmental Engineering*, ASCE, Vol 110, No. 6 [December 1984], Fig. 3, p 1152, by Robert M. Clark, et al. Used with permission.)

4 DATA COLLECTION AND ANALYSIS METHODS

Data Collection

Operating facilities currently using air-stripping technology to remove VOCs from water were surveyed by telephone to provide a detailed data base that could be used as a basis for estimating capital and operating costs for this technology. Facilities were identified by contacting the American Water Works Association Research Foundation (AWWARF), the equipment manufacturer, or by reference from another utility. Basic information gathered during the survey included power costs, types of contaminants removed, average effluent concentrations, required effluent concentrations after VOC removal, average influent concentration, treated water flow rate, and compressed airflow rate. Also collected was information on the physical plant operating expenses and other miscellaneous site-specific data. Appendix A provides an outline of the survey used. The collected data were then used to arrive at a plant's capital cost using a procedure with a sound base of cost accounting. Thirteen facilities were surveyed in two different climate types. Facility size ranged from 225 to 8000 gallons per minute (gpm). Contaminant types removed were TCE, PCE, methyl tertiary butylether (MTBE), monochloroethane, and benzene.

Data Analysis

Cost Estimate Methodology

Two important considerations affect cost estimates for any system: design basis and accounting method (i.e., methodology). The two important design variables influencing the cost of packed-tower air stripping are the tower volume and the total operating power requirements. Tower volume has the largest impact on capital costs, while total operating power has the largest impact on the operational cost.

The methodology for estimating capital costs in this study is a series of factors applied to purchased equipment or installed equipment costs. The cost calculation in this study will be conducted using the Chilton factors method. Indirect cost elements included in operating expenses depend on the design, because they are typically computed as a percentage of both capital costs and direct operating expenses.

Cost Data Presentation

Data presented in this study consist of total capital investment, net annual operating expenses, and unit amortized cost. The data are presented in ranges as a function of plant capacity in millions of gallons per day (mgd) and concentration ranges of TCE (Appendix D). It should be noted that the data presented are primarily for TCE removal.

Life cycle is the basis on which cost data presentation was approached in this report. The estimation of life cycle for both mechanical and nonmechanical items in the project is based on long-established technical criteria, as required by ETL 1110-3-332. When the economic life of a facility is projected to be less than 25 years, the analysis period used for the life-cycle cost analysis (LCCA) should be the projected economic life. A recent version of TM 5-802-1, *Economic Studies for Military Construction*

Design—Applications[9] indicates that the analysis period should be the actual economic life or 25 years from beneficial occupancy date (BOD), whichever is less. *Economic life* is defined as the period of time during which the asset provides positive benefits to the Army. This definition is in accordance with U.S. Army Construction Engineering Research Laboratory (USA-CERL) Technical Report (TR) P-151, which states that "economic life should be taken as the *least* of the lifetimes listed below:

--The mission life, or period over which a need for the asset(s) is anticipated

--The physical life, or period over which the asset(s) may be expected to last physically.

--The technological life, or period before obsolescence requires that existing (or prospective) asset(s) be replaced."[10]

Consequently, the economic life chosen for mechanical parts was their physical life of 5 years, while the economic life chosen for nonmechanical parts was their technological life, which for this particular technology was estimated to be 20 years.

A discount rate of 10 percent was chosen in accordance with ETL 1110-3-332, USA-CERL TR P-151, and TM 5-802-1. ETL 1110-3-332 states that "the time value of money to be used in all LCCA's is 10 percent per year."[11] The rate of inflation was neglected in this study. ETL 1110-3-332 states that "in projecting future costs, no allowance should be made for cost increases that are likely to be in line with the cost growth experienced by the economy as a whole."[12] Finally, for the given cost data, simple annual compounding (one lump-sum of cash flow per year) was used as per TM-5-802-1.

The amortized capital cost and the annual operating costs are totaled to arrive at the total production cost. The capital costs are amortized at 10 percent over 5 years for mechanical items (a factor of 0.2638) and 20 years for nonmechanical items (a factor of 0.1175).

An explicit assumption in this method of deriving the production unit cost will be the actual operating capacity of the tower compared to its design capacity. Three ranges of the production capacity will be assumed: 50 percent, 70 percent, and 100 percent. Each range will result in a different number of operating hours per day, which will affect the variable production cost (i.e., the operating costs). On the other hand, fixed capital costs are constant every year because they are amortized over the same number of years. Thus, whether the tower is being operated at full capacity or not, the figure for the annual amortized capital cost will remain unchanged. Like all other production processes with higher annual production capacity, the fixed cost per unit of production will decrease, while the variable cost (the annual production cost) will remain unchanged. In other words, the variable cost for each unit of treated water produced will remain unchanged with either high or low annual production capacity. To find the final unit production cost (in this case, cents per 1000 gal), for this specific range of

---

[9] Technical Manual (TM) 5-802-1, *Economic Studies for Military Construction Design—Applications* (DA, 31 December 1986).

[10] Robert D. Neathammer, *Economic Analysis: Description and Methods*, USA-CERL TR P-151/ADA135280 (U.S. Army Construction Engineering Research Laboratory [USA-CERL], October 1983), p 3-2.

[11] p 4.

[12] p 6.

production, the total annual cost figure will be divided by the total water production capacity of the system working at a specific capacity range. For example, for a 100 percent capacity range (i.e., the tower is being operated 24 hours/day), the unit production cost will be lower compared to a 70 percent production capacity range for the same tower.

Other features of the analysis are as follows:

--Cost data are presented for the entire treatment system rather than for individual system components.

--Costs presented for air-stripping technology are for typical or representative designs and applications. Most of the surveyed facilities were designed and manufactured by Hydro-Group, Inc.

--All costs for new environmental control technology systems apply as if these systems were installed in new facilities during construction (i.e., no allowance is made for such expenses as demolition, site restoration, relocation costs, or plant rearrangement). If retrofit conditions are encountered, an additional allowance should be made by the user. The magnitude of the allowance will be system-specific and will depend on factors such as additional piping and valving required, construction site accessibility, space and height constraints, etc.

USA-CERL TR P-151 discusses use of a payback period in economic analysis. Payback period has not been used in this report because the goal of this study is to determine the cost of the air-stripping process. However, the information in TR P-151 can be used by Directorates of Engineering and Housing when considering alternative sources of water supply.

Site-Specific Considerations

Variations Among Individual Projects

The following factors, which may vary with individual projects, directly affect the final cost of the completed project and should be considered when using the cost factors provided in this report in a site-specific analysis:

1. Competition in contractor and material supplier markets (i.e., market climate) resulting in unusually high or low bids and prices

2. Variation in local material and labor costs

3. Timing of construction with regard to the season of the year, length of construction period, and interest rate (10 percent was used in this report)

4. Variation in conventional engineering design and construction practices

5. Special considerations imposed on normal design requirements by local regulatory agencies

6. Considerations given to cost control during design and construction

7. Physical and climatic variations in individual site conditions, such as soil-related problems, or active seismic or hurricane regions.

Additional Construction Activities

Large facilities (about 5 or more mgd) may require additional work. In such cases, allowance should be made for costs associated with these additional activities that result from the need to deviate from the use of prefabricated designs. The following contractor activities may be needed at large sites:

1. Earth-moving work
2. Trenches for pipe installation
3. Concrete for tower and fan base pads
4. Installation of effluent valving system in a buried vault
5. Tower erection
6. Installation of packing material
7. Mounting and connecting of fans, motors, and noise abatement equipment
8. Fabrication and installation of piping and valves
9. Installation of electrical controls and wiring.

Uncertainty and Sensitivity Analysis

In accordance with ETL 1110-3-332 and USA-CERL TR P-151, the effects of uncertainties on the results of the LCCA must be assessed. Costs resulting from the above site-specific considerations, including additional construction activities, generally can be estimated using construction manuals or consultants' experience. However, the factor with the most impact on cost estimation for the air-stripping process is the volumetric size of the process. The size of the process has a direct effect on both capital cost and energy cost, and consequently on the annual operation cost. A sensitivity analysis was conducted to examine the effect of changing the process size as an input variable to the Chilton factors method of estimating cost. The procedure and results of this sensitivity analysis test are explained on p 24 and shown in Figure 4.

5 CAPITAL COST ESTIMATION

The construction cost values have been developed using equipment cost data supplied by a manufacturer (Hydro-Group, Inc.), cost data from actual plant construction, unit takeoffs from actual and conceptual designs, and published data.

Direct Costs

Five major construction components were developed and then aggregated to provide direct construction costs:

1. Manufactured tower and support
2. Installation
3. Piping
4. Instrumentation
5. Building and site development.

Indirect Costs

The direct construction costs are not the final capital costs for the unit process. Allowance should be made for the many other indirect costs applicable at individual construction locations. Following are the most common indirect costs used in construction cost calculations. (Appendix B provides an example form for estimating these costs.)

1. Engineering and construction overhead
2. Miscellaneous
3. Contingency
4. Contractor's fee
5. Retrofit increment
6. Startup
7. Legal and finance fee.

Design Effects

A tower cost equation from the literature[13] was used, for comparison purposes, to approximate unit cost in dollars per 1000 gal. The formula considers the basic design parameters that have primary impact on the cost of stripping VOCs (i.e., system size and

---

[13] Robert M. Clark, et al.

air-to-water ratio). The following formula will be referred to as "Clark's regression formula." In the section on survey results (Chapter 7), the cost obtained using this formula will be compared against the cost obtained using the approach outlined in this report.

$$C = 0.17*(Q**-0.37)*(AW**0.06) \qquad \text{[Eq 2]}$$

where:

The correlation coefficient = 0.98

C = unit cost for packed tower aeration in dollars per 1000 gal

Q = system design capacity in mgd at 70 percent capacity

AW = air-to-water ratio required to remove a contaminant to a given level.

Note that the air-to-water ratio required to achieve a specific removal efficiency is also sensitive to temperature. Higher temperatures improve removal efficiency and provide lower air-to-water ratios.

Analysis

The capital investment cost estimate involves funds required to design, build, and bring the facility to acceptable operation. Working capital is also needed for facility operation. Both working capital and land requirements are nondepreciable expenses; that is, their value is expected to be fully recoverable by the end of the project life. The values for land and working capital used in this study are an approximate guide for capital investment planning purposes.

Except for land and working capital, the investment of all fixed capital is depreciated. Mechanical parts (e.g., pumps, and blowers) are depreciated over 5 years, while the remainder (tower and packing, piping, and instrumentation) is depreciated over 20 years. Based on the purchase price of the tower and its support equipment (pumps and blowers), an algorithm found in *The Cost Digest*[14] was developed for this study. As an initial cost for a process operation, the algorithm starts with the cost of purchased equipment, accessories for the equipment, and the field-fabricated process equipment. All other costs are derived from this basic figure using different multiplying factors that operate on certain subtotals obtained throughout the algorithm. The multiplying factors are selected ratios that allow for certain cost items. The cost items are grouped in subtotals such as total plant cost or total building cost; the subtotals are then multiplied by factors to arrive at the capital investment cost. The following sections clarify and explain the terms used for cost calculation factors given in Appendix B, and provide a basis for choosing the multiplication factors used on the data obtained in this study.

Tower and Support

The costs of critical structural components were obtained from Hydro-Group, Inc., and compared with actual experience of the facilities surveyed. These costs include the tower body, liquid distributor used to dispense the water at the top of the column, support plates on the column section to provide intermediate support of the medium and

---

[14] *The Cost Digest: Cost Summaries of Selected Environmental Control Technologies.*

to redistribute water and air flow, and a demister on top of the column to prevent water from splashing outside the column. Support equipment costs, such as for pumps and blowers, can be estimated from the literature according to their individual configurations.

The free on board (FOB) cost of the equipment is used to estimate the installation cost. Details of how the estimate is calculated are shown in Appendix B. First, the FOB price for the tower and its support or auxiliary equipment (i.e., pumps and blowers) is calculated from their configuration (size and/or capacity). Then, to allow for the cost of field installation, the FOB price for tower and support (T & S) is multiplied by a factor of 0.6 according to the Chilton factors method.

Bare Module Cost (BMC)

The cost given above for the tower and support, plus their installation, is called the Bare Module Cost (BMC). This includes the FOB equipment price as well as direct field material and field labor required for its installation. Based on the size of the plant (as indicated by the BMC figure), a group of direct and indirect costs has to be added to reach a cost for completing the project.

Piping

Multiplication factors for piping costs depend on the type of plant process used. The Chilton method allows for three different types of processes in chemical plants: (1) solid, for operations such as cement manufacturing, (2) solid/fluid, for operations that require handling both solids and fluids, such as canning and food processing industries, and (3) fluid, for operations that require continuous handling and processing of different types of fluids, such as oil refineries and wastewater processing. The following is a breakdown of multplication factors for the three main types of processes:[15]

1. Solid	0.07 to 0.10
2. Solid/fluid	0.10 to 0.30
3. Fluid	0.30 to 0.60.

Instrumentation

Factors for this item depend on the amount and degree of instrumentation to be used in the process. Data from detailed capital cost estimates of the air-stripping tower technology indicated an approximate multiplication factor of 0.10 of the BMC for the instrumentation in this specific process. The following are multiplication factors for the main types of process instrumentation categories:

1. None	0.03 to 0.05
2. Moderate	0.05 to 0.12
3. Extensive	0.12 to 0.20.

---

[15] V. W. Uhl, *Standard Procedure for Cost Analysis of Pollution Operations, Vol II. Appendices*, EPA-60018-79-018b (USEPA, Industrial Environmental Research Laboratory, June 1979).

Building and Site Development

This item allows for earth moving and trenching, vaults for valving, base pad concrete, etc. It may be necessary here to differentiate between treatment plant capacities by applying variable multiplication factors. An initial choice of factors for the building and site development allowance to be applied in this technology would be 0.1 of the BMC. However, in the following example taken from Uhl, these factors depend on the type of plant:

1. Outdoor	0.10 to 0.30
2. Outdoor/indoor	0.30 to 0.60
3. Indoor	0.60 to 1.00.

Contingency

This multiplication factor is added to cover two shortcomings of the estimation procedure. One is the failure to include items that are generally minor but cumulatively significant. The second is the inability to predict many factors that affect the final cost, such as business conditions, labor strikes, and legislation. The recommended range for this allowance is normally 8 to 10 percent of the Total Building Cost (TBC).

Retrofit Increments

Retrofit situations occur when there is an addition to an existing plant; here, the cost would be more than for adding to a new plant. As a rule of thumb, a retrofit cost should be increased from 25 to 40 percent over the amount for constructing a new facility. Factors contributing to the additional costs are plant age and available space. Retrofitting an old plant may require both structural modifications to the plant and process alterations. The limitation of available space may require removal and relocation of existing equipment, or custom-designing the new equipment to meet space limitations.

However, the simplicity of air-stripping tower construction limits the complexity of retrofit. Thus, the increases in capital costs most often confronted in retrofitting air-stripping towers are:[16]

1. Long duct runs	4 to 7 percent
2. Hilly terrains	0 to 10 percent
3. Tight space (sheltered towers)	1 to 18 percent.

Working Capital

The allowance for working capital is considered in accordance with USA-CERL TR P-151. The definition of working capital is: "Money tied up in liquid funds, or assets in hand or on order." This item covers expenses such as inventory of spare parts and cash needs for daily operations. It is assumed that this cost will be fully recovered at the end of operation.

---

[16] V. W. Uhl.

Also, when multiple units are built, the fixed capital cost is less than a simple multiple of the cost for installing one unit. Costs are reduced because of the common series of tasks used in the engineering, purchasing, supervising, and administering of the construction for the multiple-unit facility.

Summary

Several factors were applied to the BMC figure to arrive at a total plant cost. The total plant cost (TPC) resulting from these calculations is shown in Table D4, column 3 (Appendix D) as the calculated capital cost. The surveyed capital cost (Table D4, column 2) was obtained from plant operators. Since the operators generally did not include land or working capital in the surveyed capital cost, these items also were omitted from the calculated capital cost, to facilitate comparison between the two figures.

A correlation between the surveyed and calculated capital costs (using the Chilton factors method) is shown in Table D4 (columns 2 and 3, respectively), and graphed in Figure 4. The points on the graph are the values for surveyed cost on the horizontal axis and the calculated cost (using the Chilton factors method) on the vertical axis. A regression line for this relation (Capital Cost regression correlation) was drawn through these points. The correlation coefficient was found to be 0.96, and the slope of the line is very close to unity. This indicates that calculating the capital cost using the Chilton factors method suggested above produced a figure acceptably close to the capital cost figure obtained from actual plant operators.

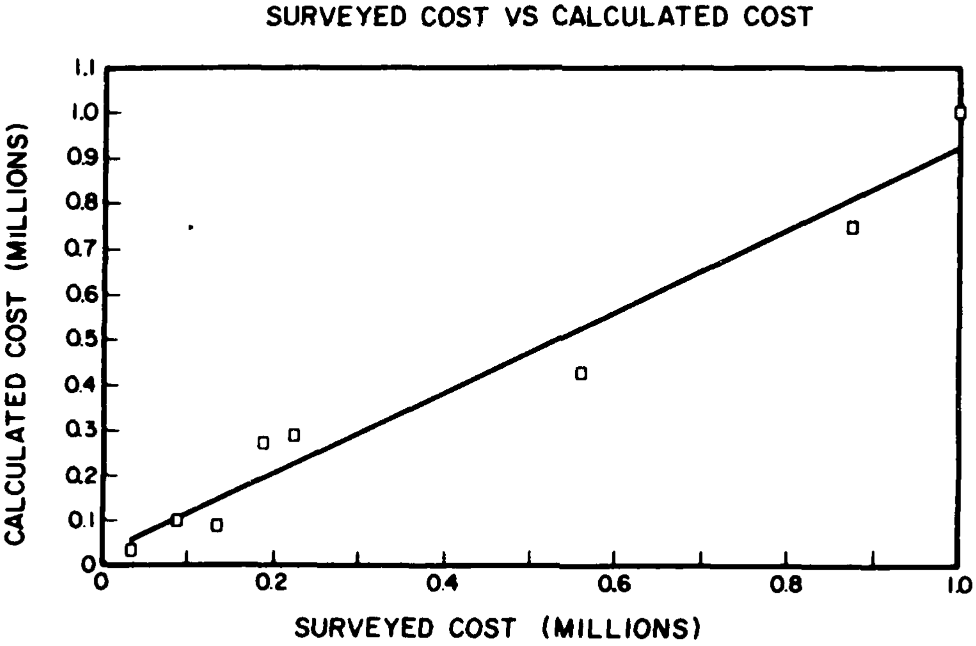


Figure 4. Capital cost regression correlation.

6 OPERATING COST ESTIMATION

The total annual expense is the basis for calculating the annual operating cost that will be incorporated into the estimate of the final cost per production unit. The total annual expense will include operating costs and general expenses. Since this process does not require any raw materials, the major component of the operating cost will be for electric power. Operating costs include direct costs such as power consumption, operating labor, and maintenance, and indirect costs such as overhead and insurance. The operating costs are either actual or those obtained by applying multiplication factors to the major components such as operating labor, utilities, and plant investment. However, values obtained by applying factors are suspect and may be greatly in error unless actual costs from working plants are available to calibrate the technique.

The remainder of this chapter discusses operating cost components and explains the basis of estimating or obtaining these figures (also shown in Appendix B).

Direct Costs

Power Cost

The operating cost for the pump and blower is obtained from operator records of power consumption or utility bills. One method of estimating this value is based on the air pressure drop across the tower and the air-to-water ratio if such data are available. Another method would consider the theoretical power requirement as determined from motor size-up and/or efficiency. In all cases, the local power cost variation will have the greatest impact on the calculation. Therefore, a separate question for the unit price of electricity (dollars/kWh) was included in the survey form (Appendix A).

Pump Power. Pumphead requirements are affected by the length of the tower and by hydraulic losses in valves, nozzles, and pipes. As long as the air-stripping operation was a recent addition to the facility (a situation encountered frequently during the survey), a booster pump had to be added to lift the treated water to the top of the air-stripping tower. In such cases, only the power consumed by this booster pump was considered, since a pump is necessary to deliver water from the well to the treatment operation, whether the air-stripping facility is in operation or not.

A direct method of calculating the power consumption can be applied if the brake horsepower data are available. A simple transformation from mechanical power (HP) to electric power (kW) is used. One HP equals 0.746 kW (for example, in the case of a 10-HP pump working for 1 hour, the electric power consumed will be 7.46 kWh). If such data are not available, the pump's mechanical power can be figured based on the treated water flow rate lifted to a head that is equal to the tower length. An additional value of water head (equal to one half the tower height) is added to the tower length to make up for hydraulic losses. When a value for the final pumphead is obtained, transformation to the equivalent electric power can be conducted similarly. However, when the operating cost for the pump and blower is estimated from the theoretical power requirement, it is factored up by 1.25 for motor size-up and 1.25 for motor efficiency (80 percent). An additional step in this latter process requires that the pump operating cost be increased by an additional factor of 1.25 for an assumed pump efficiency of 80 percent.

Blower Power. The blower brake power requirements are affected by the tower length, gas flow rate, and superficial mass loading of both air and water flows. The blower brake horsepower must drive a certain volume of air (usually in standard cubic feet/minute) through the tower cross-section and across the total length of packing medium in the tower. This generates an air pressure drop across the tower length. In the design process, a blower configuration is usually specified as cubic feet/minute against a pressure head of several inches of water. The vertical axes of Figures 5a and 5b show the pressure drop of air across 1 ft of packing media for a specified gas loading rate; this value is to be used with the set of water loading rates inside the graph. The medium

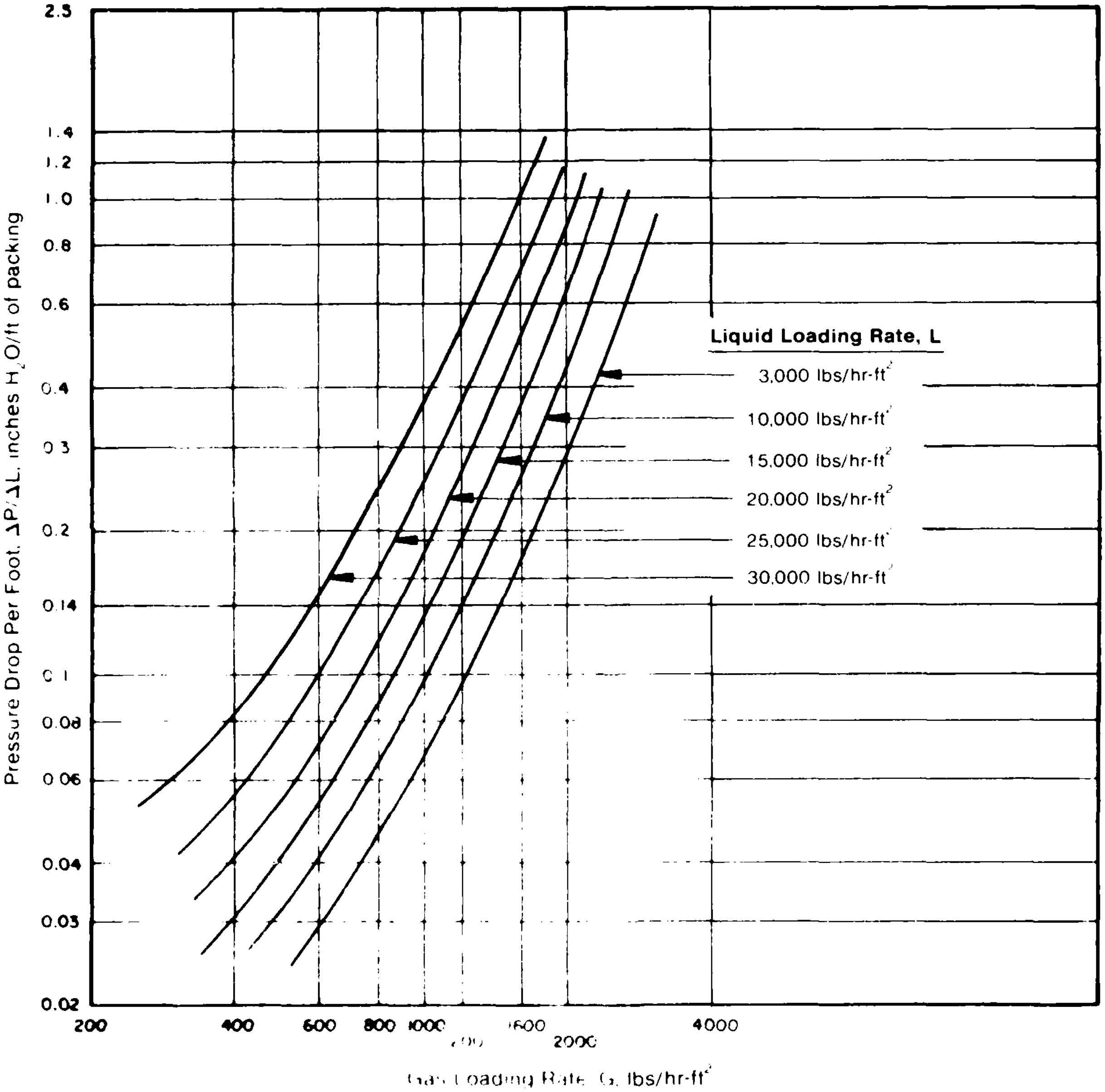


Figure 5a. **Pressure drop of 2-in. plastic Jaeger Tri-Packs®. (Source: Product Data PD-604 [Jaeger Tri-Packs, Inc.]. Used with permission.)**

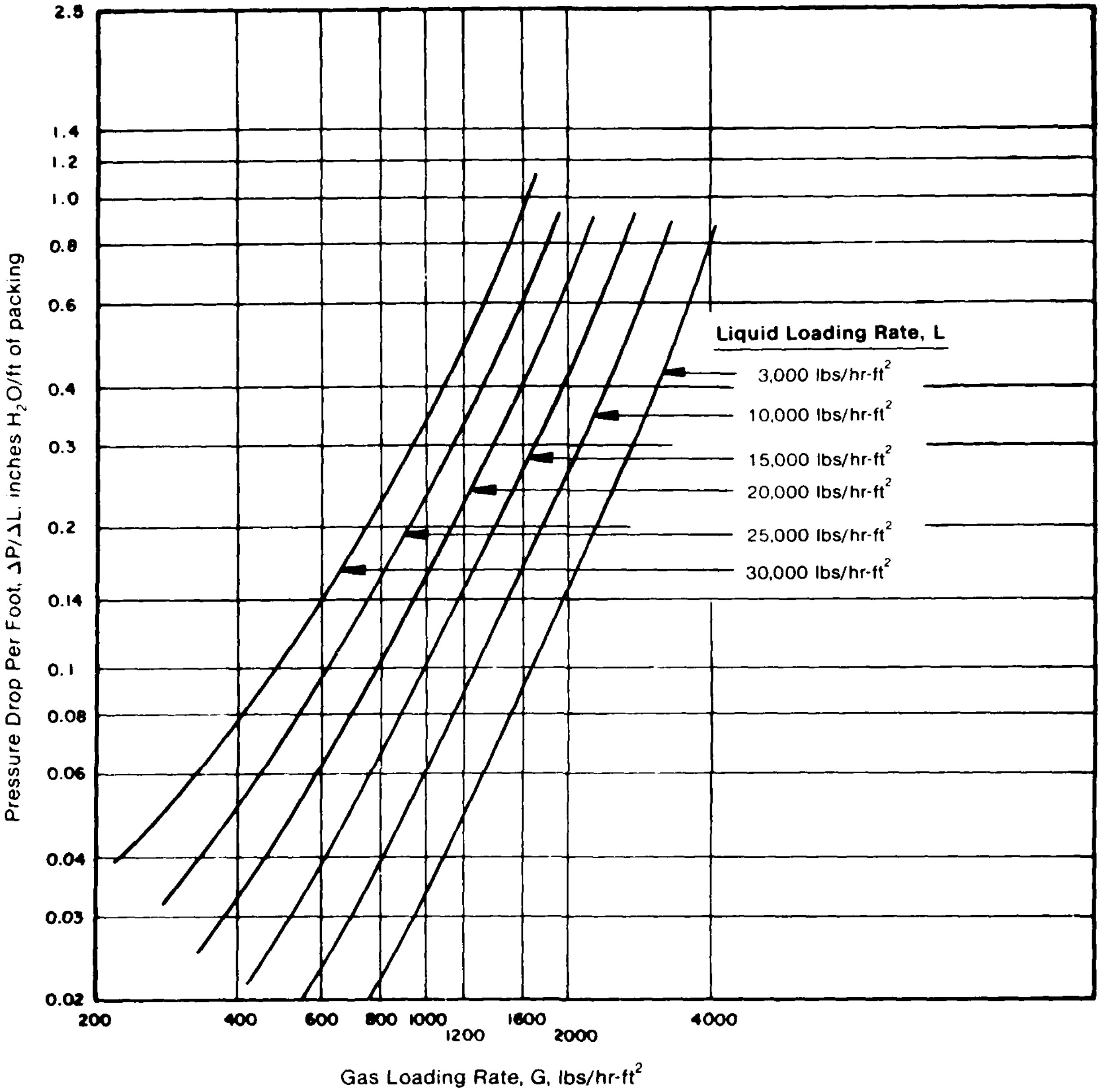


Figure 5b. **Pressure drop of 3-1/2-in. plastic Jaeger Tri-Packs®. (Source: Product Data PD-605 [Jaeger Tri-Packs, Inc.]. Used with permission.)**

represented in these figures is the plastic Tri-packs, sizes 2 and 3-1/2 in., respectively. (The 2-in. size was the most frequently chosen packing medium encountered in the survey.)

At low air-to-water ratios, the tower length generally has the greatest impact on blower brake power requirements; at higher air-to-water ratios, the gas flow rate has the largest impact. With low air-to-water ratios, the packing medium height inside the tower directly affects the pressure drop across the tower. To illustrate this relationship,

Figure 6 shows packing height plotted as a function of the air-to-water ratio.[17] The figure shows that an increase in the air-to-water ratio initially produces a significant reduction in the required packing height. However, beyond an air-to-water ratio of 20:1, the reduction in packing height becomes less significant. Based on these results, the minimum recommended air-to-water ratio needed to obtain consistent results varies between 20:1 and 30:1. Increases beyond 30:1 will increase blower horsepower requirements because of the higher pressure drop. However, it is important to design a system that operates far away from the "knee" of the curve, so that minor variations in air and/or water flow do not affect performance.

Higher concentrations of VOCs are usually removed by increasing the air-to-water ratio, which in turn increases the gas pressure drop. Accordingly, it is important to select a blower with excess capacity. Based on data taken from the survey, the blower's electricity consumption can be calculated directly from its horsepower. If the blower horsepower could not be obtained from the operator, an alternative was to use the configuration of the blower size based on the air and water loading rates given in Figures 5a and 5b. Once the pressure drop and the required air flow rate are known, the blower's configuration can be matched with values given in the literature to obtain its horsepower. Then, the horsepower of the matched blower can be transferred to its electric power equivalent, and the calculations would proceed as discussed above.

Operating Labor

The labor required for air stripping is expected to be minimal because of the high degree of automation associated with this process. The survey results in Table D3 of Appendix D show minimal or no allowance for this item. Thus, little or no allowance for operating labor was incorporated in the estimate of annual operating cost in Table D4.

Maintenance

A lump sum of maintenance costs can be obtained from the survey for general and heavy maintenance (Table D3 of Appendix D). A different approach for estimating maintenance costs (labor and material) is based on a multiplication factor of the plant's capital cost. The factors range from 4 to 10 percent for most environmental pollution control processes. As a rough estimate, a factor of 0.03 was chosen for this study because no raw material was used. Maintenance supervision is generally included in plant overhead.

Direct Supervision

This value is 10 to 25 percent of operating labor. The percentage depends on the operation's complexity and the personnel's technical ability.

Labor Burden

This is the amount set aside for pensions, vacation, social security, etc. It can be estimated as 25 to 30 percent of the operating labor cost.

---

[17] Robert F. Raczko, et al., "Air Stripping for Removal of Volatile Organics From Groundwater: From Pilot Studies to Full Scale Systems," *Proceedings, 1st Annual Hazardous Materials Conference* (Tower Conference Management Co., 1983).

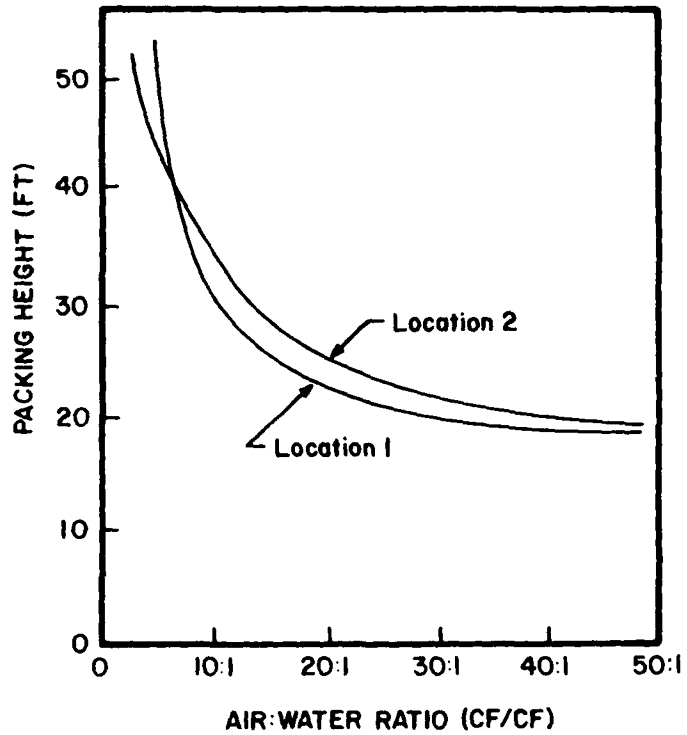


Figure 6. **Relationship between the packing height and the air-to-water ratio.** (Source: Raczco, Robert F., et al., "Air Stripping for Removal of Volatile Organics from Groundwater: From Pilot Studies to Full Scale Systems," *Proceedings, 1st Annual Hazardous Materials Conference* [Tower Conference Management Co., 1983]. Used with permission.)

Indirect Costs

Overhead

Generally, overhead is the cost of providing service functions required by the production personnel. This includes general supervision of maintenance, personnel, etc. This item may be estimated as a percentage of operating labor plus a percentage of maintenance charges.

General Expenses

This figure can be estimated as a percentage of depreciable investment. A good example in this process would be the effluent quality control assurance. Control laboratory costs depend on the nature of the process and on the difficulty of maintaining quality control. They can be obtained from the survey (Table D3 of Appendix D), and are based on actual number of samples, their analysis frequency, and length of laboratory time required to conduct the test.

Other methods of estimating general expenses were found in the literature.[18] One method is based on the operating labor cost figure, allowing 10 to 20 percent of this

---

[18] V. W. Uhl.

figure for general expenses. Another approach is based on the Total Depreciable Investment (TDI) figure. Two percent of this figure can be allowed for general expenses. Both methods are shown on the second page of Appendix C for guidance.

However, most of the plant operators surveyed were able to report an actual figure for the control lab cost (Table D3, column 8). The reported costs were substantially lower than those estimated using the methods above. Furthermore, the operators indicated that they kept no record of other general expenses (aside from control lab cost) associated with the air-stripping operation. Thus, the allowance for general expenses was found to be insignificant in the survey and was not included in the calculations for the production unit cost.

7 SURVEY RESULTS

Appendix D summarizes the data collected during this study; the data have been broken down into four sets of tables. These tables contain basic plant information, physical plant data, operating expenses information, and production costs for the air-stripping process.

Basic Plant Information

The basic plant information data summarize the survey data for types of contaminants, their influent and effluent concentration ranges, air and water flow rates, and the pattern of operation of each plant surveyed. The data indicate that TCE was the most commonly encountered contaminant. Other contaminants included PCE, MTBE, monochloroethane, and benzene. The influent averages ranged from a low of 10 parts per billion (ppb) to 2000 ppb. In one case, the contaminant varied from 100 to 2000 ppb, depending on which wells were operating, the location of the intake well, and the relative position of the intake well in the contaminant plume.

Effluent averages ranged from undetectable to 7 ppb of contaminant concentration in treated water except in one plant where the effluent was 25 ppb of TCE as required by the USEPA. Most of the plants surveyed achieved about 99 percent removal. In one plant under peak flow conditions, when the treated water concentration exceeded acceptable removal targets for the air stripper, the effluent water was mixed with large quantities of treated surface water in ground tanks. Surface water normally was used to dilute the ground water effluent after air stripping. Another plant with high ground water influent concentrations was designed to operate in two stages to achieve maximum removals. The first stage removed 99.4 percent of the influent contaminant concentrations, and the second stage removed 99.4 percent of the remaining contaminants; together, the two stages lowered the concentrations to less than 1 ppb.

The treated water flows varied with plant size; small towers treated 250 gpm, while large ones handled flows as high as 5000 gpm. Air-to-water ratios (volume/volume) varied according to the tower sizes and contaminant type. The ratios obtained in this survey were as low as 15:1 for large-diameter towers with low concentrations of TCE, and as high as 100:1 for small towers with several contaminants in a mixture. The design of this operation assumes continuous operation of the facility. Few of the plants surveyed used their air stripper less than 24 hr/day. However, some utilities operated their towers for one shift (8 to 10 hr/day), and one utility constructed a large facility of four towers with a capital investment of about $1 million as standby equipment for drought contingency conditions.

Physical Plant Information

The physical plant information in Table D2 of Appendix D summarizes the survey data for the tower configuration, packing medium, and support equipment such as blowers and pumps. All plants surveyed were built between 1983 and 1985. In fact, construction of two plants was still in progress during the early stages of this study. Most of the plants in the survey had only one tower, but depending on the size of the utility and the amount of water to be treated, some facilities had two or even four towers. Most of the air strippers surveyed in this report were constructed by Hydro-Group, Inc.; however, four plants constructed by other contractors also were surveyed.

The tower shell material was usually aluminum in the newer towers; older towers tended to use steel, a mixture of steel and aluminum, or in one case, fiberglass. Aluminum is preferred in the new designs because of its weather resistance, versatility, and capability for changing the tower length to accommodate varying conditions. Most of the towers surveyed had circular cross-sections. Most of the new construction comes in diameters that are multiples of three, (i.e., 6-, 9-, and 12-ft diameters). Tower sections typically come in rings of 5 ft high each, so most of the tower heights were in multiples of five. Heights of the towers surveyed ranged from 15 to 35 ft. In a few cases, the operators added the clearance underneath the tower to the surveyed tower height (resulting in tower heights that are not a multiple of five).

Packing material height inside the tower varied from 12 to 30 ft, depending on design requirements. In lower influent concentrations, less packing height is required, but space should be allowed for increasing the packing height in case contaminant concentrations change. Generally, the packing medium does not occupy the full length of the tower; room is allowed for the water distribution mechanism on the top (sprays or nozzles), as well as for the treated water collection device at the bottom (sump or drain). The size of the packing material varied according to the type of medium used, ranging from 1 to 3.5 in. In one case, the packing medium size changed across the tower, with a small size used on the top 85 percent and a larger size on the remainder. This maximized liquid withdrawal rates from the tower sump and prevented flooding during operation. The types of packing material surveyed included Pall Rings, Intalox Saddles, and Tri-packs. All the surveyed packing material was made of plastic or polypropylene. Most of the recent designs used a 2-in. Tri-packs medium.

Blower sizes in the surveyed plants varied widely according to the treatment capacity and the influent concentration. Blowers ranged from a low of 5 HP to a high of 60 HP (except in the case of Westwood, MA, where the tower was treating water for discharge into a surface stream using a 1 HP blower). Some operators did not know the size of the blowers in use or were unsure about their horsepower, so these data must be treated with caution.

Depending on the particular hydraulic conditions and mode of operation in each plant, the pump data varied widely. In most of the plants, the pumps and the stripping tower were supplied and installed by different contractors and, in many cases, under different contracts. Pumps were used mostly as boosters after towers or for lifting the effluents from the tower sump to the distribution network.

Operating Expense Information

The operating cost information in Table D3 of Appendix D summarizes the survey data for the power cost and consumption, as well as for the labor, maintenance, and control lab costs for each location surveyed. The values in this table were either obtained in the survey or were calculated using one of the methods explained in Chapter 6.

Power costs ranged between a low of $0.06/kWh to a high of $0.12/kWh depending on the plant's location. All the survey results indicated that the major operating cost component is power. It was observed that the power cost would vary, being governed by the rate of consumption. In one plant, the power cost varied according to location. In Hatboro, PA, the power cost for well #14 was 0.0933 $/kWh. A different location (well #17) had a different power supply network, resulting in a lower rate of 0.0896 $/kWh. The cost of power consumption per hour of operation in the surveyed plants varied according to the capacity of the pumps used to handle the water flows, regardless of the power requirement of the air-stripping process. In most cases, the cost of power consumption reported by the operator (in $/kWh) was largely the consumption of the treatment process as a whole and was read from one meter. A total figure for the electric bill of the air-stripping units was consistently obtained from the operator along with the volume of water treated by this amount of electricity. The well pump should be excluded from the operation, since it mainly lifts water from the well and contributes very little to the treatment process. A breakdown of the power cost can be implemented on the basis of the brake horsepower and on the efficiency of the blower and two pumps. Thus, the calculated values of the hourly cost of power consumption were used to arrive at a production unit cost.

Since the operation was automated, operating labor and supervision were normally too low or negligible to be used. In small plants, no labor costs were allocated for operations. One plant allocated 2 hr/week for regular maintenance. A manager of a large plant has allowed 24 hr/day for labor during full-scale operation, which has not yet occurred. Another manager of a large plant reported no labor cost, based on his experience with the operation for more than 1 year. Heavy maintenance costs had not yet occurred since most of the facilities were built within the past 3 years. General maintenance costs were minimal. In one case, the theoretical allowance for annual maintenance was reported to be 1 percent of the capital cost; however, operational plants reported as little as 2 hr/year for an electrician to oil blowers and change belts. Another plant reported no operating costs, but indicated maintenance requirements of 7 hr/week for a mechanic to check the system and 4 hr/month for an electrician to maintain the operations. Thus, no calculated values for the labor and maintenance cost were substantiated.

Laboratory testing was done monthly at a minimum cost of $30 to $65 per sample. However, for larger plants with multiple well intakes, the cost might increase, since one sample would be analyzed from each well. Daily sampling was done for 1 month at several sites at the beginning of the operation until the ground water concentrations approached a stable value. The range of the control lab monthly costs from the survey varied between $35/month for utilities running their own tests to $1200/month for utilities running more frequent tests at an outside lab.

Production Cost Information

The "cost of production" data in Table D4 of Appendix D summarizes the capital cost as an initial outlay of capital followed by its amortized annual cost. (The method for capital investment calculation is shown in Appendix B.) For the annual operating cost, three ranges of daily use were assumed: 50 percent, 70 percent, and 90 percent (Chapter 6). The final production unit cost was the sum of both the amortized cost and the operating cost per unit of production. Finally, a surveyed production unit cost was shown as reported by the operators after the unit had become operational.

To obtain cost estimates, representative data were collected on the size and capacity of the equipment. The level of detail was uneven due to the variance of knowledge among individuals responding to the questionnaire. For tower and support BMC, a manufacturer's list was obtained from Hydro-Group, Inc., to help estimate the cost. One of the largest packing medium manufacturers (Jaeger Tri-Packs, Inc.) provided an estimate of media price ranges for use as a guideline. Table 1 shows this information and provides a range of tower sizes and costs as reported by Hydro-Group, Inc. The most

Table 1

Tower Cost Estimate (Hydro-Group Database)

Tower Cost	Height (ft)	Diameter (ft)	Packing Height (ft)	Circumference (ft)	Metal Surface Area (ft)	Water Flow (gpm)
$29,000	25.00	6.00	15.00	37.70	943.00	500.00
$32,000	30.00	6.00	20.00	37.70	1131.00	500.00
$51,200	25.00	9.00	15.00	56.55	1414.00	1200.00
$48,300	30.00	9.00	20.00	56.55	1697.00	1200.00
$79,500	25.00	12.00	15.00	75.40	1885.00	2000.00
$84,500	30.00	12.00	20.00	75.40	2262.00	2000.00

significant impact on the capital cost was the tower size. Since the cost of the tower is crucial input to the calculation of the capital cost, as illustrated in Chapter 5, page 21, a careful estimate for the FOB cost of tower and support was vital to start the calculations. Towers are specifically designed and sized for a required water flow with a range of contaminant concentration. Since the structural pattern of a tower is standardized, the cost is governed mainly by its height and diameter. A straight-line regression model based on the data was used to predict the tower cost as a function of height and diameter. This regression model will be referred to as the "tower cost regression model." After an FOB cost for the tower was obtained from the tower cost regression model, this cost was projected into the capital cost estimate using the Chilton factors method (Chapter 4, Appendix B). Results of the capital cost calculations are shown in Table D4.

Two pumps are generally used to operate the system. A high-pressure pump lifts the water from the well and delivers it to the top of the tower, and a low-pressure pump lifts the treated water and provides pressure to the distribution network. This research has considered only the low-pressure pump in computing the capital cost, since the well pump always is needed whether VOCs are removed or not. Most cases indicated that the high-pressure pumps were used before the air stripper was installed, and continued use did not require any modifications.

Analysis

Packed-tower air stripping is a simple, flexible technology that can be used when effluent concentrations vary greatly. This makes air stripping a suitable treatment for groundwater contamination situations where the pollutant plume is continuously proceeding through the aquifer.

The effectiveness of a packed column depends on the water temperature, packing medium, surface loading, flow rate of the water, depth of packing, and volumetric ratio of airflow to water flow. This technology is currently very popular because of its simplicity and low labor requirements. The total production cost is very economical. A recent study[19] showed the following approximate relationship: in terms of percentage of the total production costs, the annual capital cost accounted for 42 percent, the operational cost 48 percent, and the maintenance cost only about 10 percent. This shows that operational cost is the largest portion of the annual total production cost. Operational costs in the air-stripping process are mainly for power. Maintenance costs are relatively low.

The telephone survey agreed with these estimates, especially at a 100 percent operating rate, when the facility is operated continuously 24 hr/day. As contaminant concentration increases, both capital and operating costs increase. The cost of production units was found to be sensitive to the initial concentration of the contaminant in the influent.

The comparison between cost of removal ($/1000 gal) using Clark's regression formula[20] (p 21) along with the Chilton factors method showed a different trend. Table 2 lists the removal cost as obtained from Clark's regression formula vs. the removal cost as calculated from the survey. Actual survey data were applied for the comparison in both cases. Using Clark's regression formula required input from Table D1 for the water flow rate and air-to-water ratio (columns 5 and 6, respectively). Data from Tables D1 through D4 were used to obtain the production unit cost ($/1000 gal) using the Chilton factors method for the same sites in comparison. Both water flow rate and air-to-water ratio are crucial inputs for Clark's regression formula. Thus, due to the absence of a surveyed air-to-water ratio, some utilities were not included in this comparison.

Removal cost estimates based on Clark's regression formula tended to be high for plant sizes ranging from 0.5 to 1 mgd. This trend seems to improve as the formula estimates converge closer to the survey costs at higher plant capacity. Clark's regression formula was originally applied to plant sizes ranging from 0.1 to 0.5 mgd. In the case of high air-to-water ratios within the 0.5 to 1 mgd range, the formula estimates were still high but closer to the survey cost. This indicated that Clark's regression formula shows better response with higher operational cost, as in the case of a high air-to-water ratio. However, the regression formula cost estimates were more sensitive to flow rate than to air-to-water ratio.

In summary, under conservative design conditions (low capital cost and moderate air-to-water ratios), Clark's regression formula tends to overestimate costs for plants with a medium flow range of 0.5 to 1 mgd. Due to lack of data in the survey, no testing was conducted on the behavior of the formula on lower flow ranges.

The calculated cost for VOC removals ($/1000 gal) in the survey indicated that cost and tower size increased as influent concentration increased. For low concentrations (<50 ppb), the cost of treatment varied between $0.03 and $0.08/1000 gal. Medium VOC concentrations (50 to 200 ppb) incurred a cost of treatment varying between $0.07 and $0.17/1000 gal, depending on the size of the operation (economy of scale) and the complexity of the pollutant mixture. Higher VOC concentrations (200 to 500 ppb and above) showed a cost of removal varying between $0.08 and $0.26/1000 gal, with the effect of tower size and pollutant complexity being similar to those given above for medium VOC concentrations.

---

[19] David W. Hand, et al.

[20] Robert M. Clark, et al.

Table 2

Comparison Between Cost of Removal ($/1000 gal) Using Clark's Regression Formula* and the Calculated Cost From Survey Data (Chilton Factors Method)

Location	Water Flow (mgd)**	Air-to-Water Ratio***	Formula Cost ($/1000 gal)‡	Calculated Cost ($/1000 gal)‡‡	Comments
Longdon, CA	5.04	15	0.11	0.03	High capacity
Acton, MA	0.42	50	0.30	0.11	
Baldwin, CA	1.008	40	0.21	0.12	Overestimation
Oakdale, NY	0.76	50	0.24	0.07	
Philadelphia, PA	5.24	15	0.11	0.09	High capacity
Great Neck, NY	1.01	98	0.22	0.20	High air-to-water ratio
Dedham, MA	0.42	100	0.31	0.23	
Williamsport, PA	8.1	75	0.10	0.10	Very high capacity

---

*Robert M. Clark, et al.

**Water flow is the capacity in million gallons per day at 70 percent of the design capacity.

***Air-to-water ratio (volume/volume) required to remove contaminant to the level reported on the survey. The air-to-water ratio is obtained from the survey data (Table D1, column 6).

‡Formula cost is the cost per production unit obtained using Clark's regression formula as shown on p 21 (Equation 2).

‡‡The calculated cost per production unit is the result of using the survey data and the Chilton factors method to arrive at a production unit cost. The range shown is for 70 percent capacity as obtained from Table D4, column 9.

8 SUMMARY

This report has documented the results of a study conducted to provide a basis for estimating the costs of using air stripping to remove volatile organic compounds from water. Data were collected through a literature survey and by a telephone survey of facilities that currently use air stripping. Data collected included basic plant information, physical plant data, operating expenses information, production costs, and design data. The data were then analyzed to estimate the costs of installing and using air stripping at Army facilities. Results indicated that air stripping is a very economical technology that is simple to install and has low labor requirements. Contaminant removal efficiencies are high, ranging from 90 to 99.99 percent. Estimated costs of using the technology, in terms of percentage of total production costs, are about 40 percent for capital costs, 50 percent for operational costs, and 10 percent for maintenance costs. Calculated costs for VOC removals depend on contaminant concentration and range from $0.03/1000 gal to $0.26/1000 gal.

CITED REFERENCES

Clark, Robert M., et al., "VOC's in Drinking Water: Cost of Removal," *Journal of Environmental Engineering*, Vol 110, No. 6 (American Society of Civil Engineers [ASCE], December 1984), pp 1146-1162.

The Cost Digest: Cost Summaries of Selected Environmental Control Technologies, EPA-600/8-84-010 (U. S. Environmental Protection Agency [USEPA], October 1984).

Cummins, Michael O., and James J. Westrick, "Packed Column Air Stripping for Removal of Volatile Compounds," *Proceedings, ASCE Environmental Engineering Conference* (July 1982), pp 571-585.

Engineer Technical Letter (ETL) 1110-3-332, *Engineering and Design Economic Studies* (Department of the Army [DA], 22 March 1982).

Environmental Science and Engineering, Inc., *Technologies and Costs for the Removal of Volatile Organic Chemicals from Potable Water Supplies*, (USEPA, May 1985).

Hand, David W., et al., "Design and Economic Evaluation of a Full Scale Air-Stripping Tower for Treatment of VOC's From a Contaminated Groundwater," manuscript submitted to the *Journal of the American Water Works Assocation* (1985).

Love, Thomas Jr., et al., "Treatment of Drinking Water Containing Trichloroethylene and Related Industrial Solvents," *Journal of the American Water Works Association* (August 1982), pp 413-425.

Neathammer, Robert D., *Economic Analysis: Description and Methods*, USA-CERL TR P-151/ADA135280 (U.S. Army Construction Engineering Research Laboratory [USA-CERL], October 1983)

Pressure Drop of 2" and 3-1/2" Tri-Packs®, Product Data PD604 and PD605 (Jaeger Tri-Packs, Inc., April 1987).

Raczko, Robert F., et al., "Air Stripping for Removal of Volatile Organics From Groundwater: From Pilot Studies to Full Scale Systems," *Proceedings, 1st Annual Hazardous Materials Conference* (Tower Conference Management Co., 1983).

Ruggiero, Dominick D., et al., *Removal of Organic Contaminants from Drinking Water Supply at Glen Cove, N.Y., Phase II*, EPA 600/2-82-027 (USEPA, March 1982).

Technical Manual (TM) 5-802-1, *Economic Studies for Military Construction Design—Applications* (DA, 31 December 1986).

Uhl, V. W., *Standard Procedure for Cost Analysis of Pollution Control Operations, Vol II. Appendices*, EPA-600/8-79-018b (USEPA, Industrial Environmental Research Laboratory, June 1979).

UNCITED REFERENCE

Clark, Robert M., "Cost Estimating for Conventional Water Treatment," *Journal of Environmental Engineering*, Vol 108, No. 9 (1983), pp 819-834.

APPENDIX A:

TELEPHONE SURVEY FORM

This appendix provides the telephone survey form used to collect data from plant operators. Major cost elements are included, along with background information about the surveyed plant. Changes to this form should be adopted according to the technique applied at a specific facility and its reflection on the cost structure.

Subject of Conversation: Survey of VOC removal cost via packed-tower air stripping

Incoming Call:	Person Calling	
	Address	
	Phone No. and Ext.	
	Person Called	
	Office	
	Phone No. and Ext.	
Outgoing Call:	Person Calling	Hany Zaghloul
	Office	USA-CERL/EN
	Phone No. and Ext.	(217) 373-6749
	Toll-Free No.	1-800-USA-CERL, Ext. 749 (Outside Illinois); 1-800-252-7122, Ext. 749 (Inside Illinois)
	Person Called	
	Address	
	Phone No. and Ext.	

Basic Information:

Facility name and location	
Power cost	$/kWh
Type of contaminant	
Effluent av. concentration	ppb
Effluent req. concentration	ppb
Influent av. concentration	ppb
Treated water flow rate	gpd
Compressed air flow rate	cu ft/sec

Physical Plant Information:

- Number of towers used
- Tower shell, material
  - Diameter
  - Height
- Tower packing, volume
  - Type
  - Size
- Blower size (HP)
  - Power Consumption (or % from source), kWh
- Pump size (HP)
- Power consumption (or % from source), kWh

Operating Expenses Information:

Labor costs	
Labor rate	$/year
Maintenance labor	$/year
Laboratory technician rate	$/year

Operating labor	man/year
General maintenance	hours/week
Heavy maintenance	weeks/year
Control laboratory	persons/year

Additional information:

Air pressure drop across tower length (pressure difference, if measured)?

Any related cost information?

Any possibility of contacting the project cost accountant?

Any other water treatment facilities in your vicinity using air-stripping towers (location, operator's name and phone number) ?

APPENDIX B:

COST ESTIMATES FORM

This appendix provides the cost estimation form used to calculate the various cost components and is based on the multiplication using the Chilton factors method.

COST ESTIMATE:

Capital Investment:

Tower and support (T&S) = $
Installation = T&S * 0.6 = $

Bare Module Cost (BMC) = $

Direct Costs:

Piping = BMC * 0.3 = $
Instrumentation - BMC * 0.1 = $
Bldg. and site development = BMC * 0.2 = $

Indirect Costs:

Eng. and const. overhead = BMC * 0.35 = $
Others (lines, paint, etc.) = BMC * 0.15 = $

Total Building Costs (TBC) = BMC + Direct + Indirect Costs = $

Contingency = TBC * (8 to 10%) = $
Contractor's fee = TBC * 0.03 = $
Retrofit increment = TBC * Fr = $

Total Plant Cost (TPC) = $

Startup = TPC * 0.05 = $
Others (legal and finance) = TPC * 0.01 = $

Total Depreciable Investment (TDI) = $

Land = TDI * 0.02 = $
Working capital - TDI * 0.03 = $

Total Capital Investment (TCI) = $

Operating Expenses:

Power consumption/day = $

Labor, operating labor (OL) = man/yr
Maint. labor: General maintenenace = hr/week
Heavy maintenance = week/yr
Total maint. labor cost (ML) = man/yr
Total maint. labor cost - (TPC) * 0.03 = $/yr
Direct supervision - (OL) * 0.10 = $/yr
Labor burden = (OL) * 0.30 = $/yr

Processing Expenses = $/yr

Overhead - (OL) * 0.50 + (ML) * 0.25 = $/yr
Insurance and taxes = (TCI) * 0.015 = $/yr

Net Operating Costs (NOC) = $/yr

General expenses = (TDI) * 0.02 = $/yr
Control lab. = man/yr
Control lab. = (OL) * 0.20 = $/yr

Net Annual Operating Expenses (NAOE) = $/yr

APPENDIX C:

VOC REMOVAL COST BY PACKED-TOWER AIR STRIPPING: SURVEY FORM

This appendix gives a spreadsheet example of the database analysis cited in the literature.[21] The capital cost estimate method used on the form is based on the data extracted from the physical plant information data for 1-, 2-, and 5-mgd plants.

COST ESTIMATE:	1 mgd*	2 mgd*	5 mgd*	2.16 mgd**
A--Capital Investment				
Tower and support (T&S)				
Installation				
1--Bare Module Cost (BMC)	$165,000	$206,000	$411,000	$49,994
Direct costs:				
Piping	$49,500	$61,800	$123,300	$14,998
Instrumentation	$16,500	$20,600	$41,100	$4,999
Bldg. and site development	$33,000	$41,200	$82,200	$9,999
Indirect costs:				
Eng. and const. overhead	$47,750	$72,100	$143,850	$17,498
Others (lines, paint, etc.)	$24,750	$30,900	$61,650	$7,499
2--Total Building Costs (TBC)	$346,500	$432,600	$863,100	$104,987
Contingency allowance: 8 to 10%	10	9	8	10
Contingency	$34,650	$38,934	$69,048	$10,299
Contractor's fee	$10,395	$12,978	$25,893	$3,150
Retrofit factor, %	0	0	0	
Retrofit increment	$0	$0	$0	$0
3--Total Plant Cost (TPC)	$39,545	$484,512	$958,041	$118,636
Startup	$19,577	$24,226	$47,902	$5,932
Others (legal and finance)	$3,915	$4,845	$9,580	$1,186
4--Total Depreciable Investment (TDI)	$415,038	$513,583	$1,015,523	$125,754
Land	$8,301	$10,272	$20,310	$2,515
Working capital	$12,451	$15,407	$30,466	$3,773
5--Total Capital Investment (TCI)	$435,790	$539,262	$1,066,300	$132,042

*Data from Dominick D. Ruggiero, et al., *Removal of Organic Contaminants From Drinking Water Supply at Glen Cove, N.Y., Phase II*, EPA 600/2-82-027 (USEPA, March 1982), p 81.

**Data from David W. Hand, et al., "Design and Economic Evaluation of a Full-Scale Air Stripping Tower for Treatment of VOC's From a Contaminated Groundwater," manuscript submitted to the *Journal of the American Water Works Association* (1985).

---

[21] Dominick D. Ruggiero, et al., *Removal of Organic Contaminants From Drinking Water Supply at Glen Cove, N. Y., Phase II*, EPA-600/2-82-027 (USEPA, 1982); David W. Hand, et al.

B--Operating Expenses:	1 mgd*	2 mgd*	5 mgd*	2.16 mgd**
Power consumption cost/year				
Labor				
6--Operating labor cost (OL)/year				
7--Total maint. labor cost (ML)/year				
Estimated ML	$11,746	$14,535	$28,741	$3,559
Direct supervision				
Labor burden				
8--Processing Expenses (PE)				
Overhead	$2,937	$3,634	$7,185	$890
Insurance and taxes	$6,537	$8,089	$15,994	$1,981
9--Net Operating Costs (NOC)	$9,473	$11,723	$23,180	$2,870
General expenses	$8,301	$10,272	$20,310	$2,515
Control lab. cost/year				
Estimated control lab. cost/year				
10--Net Annual Operating Expenses (NAOE)	$17,774	$21,994	$43,490	$5,385

APPENDIX D:

SUMMARY OF SURVEY DATA

This appendix summarizes the results of the study. The data have been broken into four sets of tables: basic plant information, physical plant information, operating expenses information, and production costs for the air-stripping process.

Table D1 presents basic plant information. The major type of contaminant removed by air stripping was found to be TCE. Thus, the influent average (ppb) for the contaminants consists mostly of TCE concentration. The surveyed water flows and air-to-water ratios are shown in columns 5 and 6, respectively.

Table D2 presents the physical plant information that was used to calculate the capital cost using the Chilton factors method. Tower size (diameter and length), as well as blower and pump sizes are shown in columns 7, 8, 13, and 15. This data was the input for the calculation process to arrive at a capital cost for the air-stripping operation at each of the sites surveyed.

Table D3 presents operating cost information. Power cost ($/kWh) and cost of power consumption ($/hr of operation) are shown in columns 2 through 5. The power cost was by far the major component of operating costs in this survey. Some labor, maintenance, and control lab cost statistics were also collected during the survey. These are shown in Table D3 for guidance; however, most operators attributed little or no labor and maintenance to their air strippers.

Table D4 presents the results of the calculations using the Chilton factors method based on the physical data from the surveyed sites. The capital cost is shown in columns 2 and 3. Column 2 shows the capital cost as reported by plant operators, which includes most of the work but often excludes separate small contracts, such as piping. Column 3 shows the calculated capital cost for the same facility using the survey data as an input for the Chilton factors method.

Table D1

Basic Plant Information

Plant/Location	VOC Type	Inf. Average (ppb)	Eff. Average (ppb)	Water Flow (gpm)	A/W Ratio	Daily Operation (hrs)	Comments
Longdon, Arcadia, CA	TCE	30	1.0	5000	15	24	
Wells 1 & 2, Acton, MA	TCE	160-25	1.0	417	50	24	
Alanti, Baldwin, CA	TCE, PCE, & Monochlorethane	500-300 combined	1.5 - 2.4	1000	40	24	1400 gpm design flow rate
Northport, Oakdale, NY	TCE	200-400	2.0 - 7.0	400-1100	65 - 32	2	
Upper Merion, Philadelphia, PA	TCE	20-10	--	5200	15	24	
Sta. #6, Garden City, NY	TCE	89-10	2.0	12000		24	Started June 1986
Great Neck, NY	TCE & Benzene	30-55 & 50	1.0	1000	98	24	Unit working on two wells
Rewack Well, Darien, CT	TCE	30	2.0	275		24	
Westwood, Dedham, MA	TCE	500	25.0	417	100		Small tower to meet USEPA discharge requirements
Well #14, Hatboro, PA	TCE & MTBE	230	1.0	250		8-10	
Well #17, Hatboro, PA	TCE & PCE	304	1.0	225		8-10	
Deering Well Field Norwalk, CT	TCE	160-10	<1.0	1736		--	Operated for only 3 days; tank leaked
3rd St. PS, Williamsport, PA	TCE	2000-100	1.0	8000	75	Standby	Four towers used in two stages; 3 mgd each stage

Notes:

TCE = Trichloroethylene
PCE = Tetrachloroethylene
MTBE = Methyltertiary butylether

Table D2

Physical Plant Information

Plant/Location	Year Const.	No. of Towers	Hydro-Group		Material	Tower Diam. (ft)	Shell Height (ft)	Packing Height (ft)	Media Size (in.)	Data Type	Blowers Data		Pump Data		
			Yes	No							No.	Size (HP)	No.	Size (HP)	Type
Longdon, Arcadia, CA		2		•	Aluminum	9 x 9 Sq	21	15	3.5	Pall Rings (Polypr.)	2	5.0	--	--	Existing well pumps
Wells 1 & 2, Acton, MA	1983	1	•		Aluminum	5.5	28	20	2.0	Tri-packs	1	15.0	2	--	Low-lift pumps
Alanti, Baldwin, CA		1		•	Steel	8.0	35	18	1.0	Intalox saddle	1	5.5	1	125	Semi-open impeller
Northport, Oakdale, NY	1984	1		•	Aluminum	6.0	27	17	2.0	Super Intalox saddle	1	8.33	1	60	
Upper Merion, Philadelphia, PA		2		•	Stainless Steel	12.0 12	30 30	14 14	1/2 2/3.5	Glitch saddle Tri-packs	4	40	--	--	Existing well pumps
Sta. #6, Garden City, NY	1985	1	•		Aluminum	9.0	30	20	2.0	Tri-packs	1	40	2	100	After tower booster
Great Neck, NY	1984	1	•		Steel & Aluminum	9.0	35	30	1.0	Tri-packs	2	10+15	1	125	Vertical turbine
Rewack Well, Darien, CT	1983	1	•		Aluminum				2.0		1	--	2	--	
Westwood, Dedham, MA	1985	1	•		Fiberglass	6.0	15	12	2.0	Tri-packs	1	1.0	--	--	Existing submersible
Well #14, Hatboro, PA	1985	1	•		Aluminum	6.0	35	30	3.5	Pall Rings (Polypr.)	1	15	1	40	Deep well turbine
Well #17, Hatboro, PA	1984	1	•		Aluminum	6.0	30	25	1.0	Pall Rings (Polypr.)	1	5.0	1	25	Deep well turbine
3rd St. PS, Williamsport, PA	1985	4	•		Aluminum	10.0	35	25	2 x 1.0 2 x 3.5	Tri-packs (2 first-stage towers) Tri-packs (2 second-stage towers)	4	60	2	50	Lift pumps for second stage

Table D3

Operating Cost Information

Plant/Location	Power Cost ($/kWh)		Cost of Power Consumption ($/hr)		Labor Cost--Surveyed ($/month)	Maintenance Cost--Surveyed ($/month)	Control Lab. ($/month)
	Surveyed	Assumed	Surveyed	Assumed			
Longdon, Arcadia, CA		0.07		4.582	None		
Wells 1 & 2, Acton, MA	0.06		3.47	1.058	Minimal		35
Alanti, Baldwin, CA	0.07			1.641			87
Northport, Oakdale, NY	0.11		24.48	2.714	None	527	1200
Upper Merion, Philadelphia, PA	0.065		13.36			None	
Sta. #6, Garden City, NY	0.12			5.968			200
Great Neck, NY		0.12		4.559			400
Rewack Well, Darien, CT	0.072		1.89				
Westwood, Dedham, MA		0.06		0.252			80
Well #14, Hatboro, PA	0.093		6.23	1.495	162 for both	100 for both	76 for both
Well #17, Harboro, PA	0.09		3.43	0.668			
Deering Well Field, Norwalk, CT							
3rd St. PS, Williamsport, PA	0.08		4.17	27.032	7200	833	417

Table D4

Cost of Production Unit

Plant/Location	Capital Cost ($)		Amortized Cost ($)	Annual Operating Cost ($)			Production Unit Cost (¢/gal)			Surveyed Cost (¢/1000 gal)
	Surveyed	Calculated		50%	70%	90%*	50%	70%	90%*	
Longdon, Arcadia, CA	189,000	273,044	33,545	20,069	28,097	40,138	4.0	3.4	2.8	5.0
Wells 1 & 2, Acton, MA	135,000	89,057	10,872	4,634	6,488	9,268	14.0	11.3	9.2	
Alanti, Baldwin, CA	225,000	290,843	35,698	7,187	10,063	14,375	16.3	12.4	7.4	
Northport, Oakdale, NY	89,000	100,720	12,273	11,887	16,642	23,774	8.4	7.1	6.2	
Upper Merion, Philadelphia, PA	875,000	749,780	90,439	58,517	81,924	117,034	10.9	9.0	7.6	6.0
Sta. #6, Garden City, NY	560,000	430,528	52,123	26,140	36,596	52,280	24.8	20.1	16.6	
Great Neck, NY		454,179	54,825	19,968	27,956	39,936	28.5	22.5	18.0	
Rewack well, Darien, CT	416,000									
Westwood, Dedham, MA	35,000	33,204	4,062	1,104	1,545	2,208	4.7	3.6	2.9	
Well #14, Hatboro, PA		170,692	20,752	6,548	9,167	13,096	41.6	32.5	25.8	
Well #17, Hatboro, PA		40,832	4,958	2,926	4,096	5,852	13.3	10.9	9.1	
Deering Well Field Norwalk, CT	869,740									
3rd St. PS, Williamsport, PA	1,000,000	1,002,297	127,398	118,400	165,760	236,800	11.7	10.0	8.7	

*Ranges for daily use. (p 33)

LIST OF ABBREVIATIONS

AWWARF	American Water Works Association Research Foundation
BMC	Bare Module Cost
BOD	Beneficial Occupancy Date
DA	Department of the Army
DCA	dichloroethane
DCE	dichloroethylene
ETL	Engineer Technical Letter
FOB	free on board
gpm	gallons per minute
LCCA	life cycle cost analysis
mgd	million gallons per day
ML	maintenance labor cost
MTBE	methyl tertiary butylether
NAOE	Net Annual Operating Expenses
NOC	Net Operating Costs
OL	operating labor cost
PCE	tetrachloroethylene (a.k.a. perchloroethylene)
PE	processing expenses
ppb	parts per billion
ppm	parts per million
TBC	Total Building Cost
TCA	trichloroethane
TCE	trichloroethylene
TCI	Total Capital Investment
TDI	Total Depreciable Investment
TLV-TWA	Threshold Limit Value/Time-Weighted Average
TM	Technical Manual
TPC	Total Plant Cost
TR	Technical Report
USA-CERL	U.S. Army Construction Engineering Research Laboratory
USEPA	U.S. Environmental Protection Agency
VOC	volatile organic compound

USA-CERL DISTRIBUTION

Chief of Engineers
ATTN: Tech Monitor
ATTN: CEIM-SL (2)
ATTN: CECC-P
ATTN: CECW
ATTN: CECW-0
ATTN: CECW-P
ATTN: CEEC
ATTN: CEEC-C
ATTN: CEEC-E
ATTN: CERD
ATTN: CERD-C
ATTN: CERD-M
ATTN: CERM
ATTN: DAEN-ZCE
ATTN: DAEN-ZCF
ATTN: DAEN-ZCI
ATTN: DAEN-ZCM
ATTN: DAEN-ZCZ

FESA, ATTN: Library 22060
ATTN: DET III 79906

US Army Engineer Districts
ATTN: Library (41)

US Army Engineer Divisions
ATTN: Library (14)

US Army Europe
AEAEN-ODCS/Engr 09403
ISAE 09081
V Corps
ATTN: DEH (11)
VII Corps
ATTN: DEH (15)
21st Support Command
ATTN: DEH (12)
USA Berlin
ATTN: DEH (11)
USASETAF
ATTN: DEH (10)
Allied Command Europe (ACE)
ATTN: DEH (3)

8th USA, Korea (19)

ROK/US Combined Forces Command 96301
ATTN: EUSA-HHC-CFC/Engr

USA Japan (USARJ)
ATTN: AJEN-DEH 96343
ATTN: DEH-Honshu 96343
ATTN: DEH-Okinawa 96331

416th Engineer Command 60623
ATTN: Facilities Engineer

US Military Academy 10966
ATTN: Facilities Engineer
ATTN: Dept of Geography &
Computer Science
ATTN: DSCPER/MAEN-A

AMMRC, ATTN DRXMR-WE 02172

USA AMCCOM 61299-6000
ATTN: AMSMC-RI
ATTN: AMSMC-IS

AMC - Dir., Inst., & Servc
ATTN: DEH (23)
ATTN: AMCEN-A

DLA ATTN: DLA WI 22314

DNA ATTN: NADS 20305

FORSCOM
FORSCOM Engr, ATTN: AFEN-DEH
ATTN: DEH (23)

HSC
ATTN: HSLO-F 78234
ATTN: Facilities Engineer
Fitzsimons AMC 80240
Walter Reed AMC 20012

TRADOC
HQ, TRADOC, ATTN: ATEN-DEH
ATTN: DEH (19)

TSARCOM, ATTN: STSAS-F 63120

USACC, ATTN: Facilities Engr (2)

WESTCOM
ATTN: DEH, Ft. Shafter 96858
ATTN: APEN-IM

SHAPE 09055
ATTN: Surv. Section, CCB-OPS
Infrastructure Branch, LANDA

HQ USEUCOM 09128
ATTN: ECJ 4/7-LOE

FORT BELVOIR, VA 22060 (7)
ATTN: Canadian Liaison Officer
ATTN: British Liaison Officer
ATTN: Australian Liaison Officer
ATTN: French Liaison Officer
ATTN: German Liaison Officer
ATTN: Water Resources Support Ctr
ATTN: Engr Studies Center
ATTN: Engr Topographic Lab.
ATTN: ATZA-DTE-SU
ATTN: ATZA-DTE-EM
ATTN: R&D Command

CRREL, ATTN: Library 03755

WES, ATTN: Library 39180

HQ, XVIII Airborn Corps
and Fort Bragg
ATTN: AFZA-FE-EE 28307

Area Engineer, AEDC-Area Office
Arnold Air Force Station, TN 37389

Chanute AFB, IL 61868
3345 CES/DE, Stop 27

Norton AFB, CA 92409
ATTN: AFRCE-MX/DEE

AFESC, Tyndall AFB, FL 32403

NAVFAC
ATTN: Engineering Command (7)
ATTN: Division Offices (6)
ATTN: Naval Public Works Center (9)
ATTN: Naval Civil Engr Lab. (3)

NCEL
ATTN: Library, Code L08A 93043

Defense Technical Info. Center 22314
ATTN: DDA (2)

SETAF Engineer Design Office 09019

Engr Societies Library, NY 10017

Natl Guard Bureau Instl. Div 20310

US Govt Print Office 22304
Receiving Sect/Depository Copies (2)

US Army Env. Hygiene Agency
ATTN: HSHB-E 21010

National Bureau of Standards 20899

310
06/87

USA-CERL DISTRIBUTION

Fort Buchanan 00934
ATTN: AFZK-B-FE

Fort Devens 01433-5100
ATTN: AFZD-DE

U.S. Army Troop Support Command 01760
ATTN: STRNC-DF

HISA Facility Engineer Division 07703
ATTN: SELHI-DEH

Picatinny Arsenal 07801-5001
ATTN: SMCAR-PSE

Fort Dix 08640-5500
ATTN: ATZD-EHZ

Fort Hamilton 11252-6000
ATTN: DEH

Watervliet Arsenal 12189-5000
ATTN: SMCWV-EH

10th Mountain Div (LI) & Ft Drum 13602-5097
ATTN: AFZS-EH

Seneca Army Depot 14541
ATTN: SDSSE-AD

Hays Army Ammo Plant 15207-1969
ATTN: SMCHA-CA

Fort Indiantown Gap 17003
ATTN: AFZQ-DE

Carlisle Barracks 17013
ATTN: ATZE-DE

New Cumberland Army Depot 17070
ATTN: SDSNC-AF

Letterkenny Army Depot 17201
ATTN: SDSLE-SF

HQDESCOM Letterkenny Army Depot 17201
ATTN: AMSDS-RM-EF

Tobyhanna Army Depot 18466
ATTN: SDSTO-AF

Scranton Army Ammo Plant 18505-1138
ATTN: SMCSC-EN

Fort George G. Meade 20755-5155
ATTN: Director, DEH (AFZI-EH)

HQ, First U.S. Army 20755-7000
ATTN: AFKA-EN

U.S. Army/LABCOM/ISA 20783-1197
ATTN: SLCIS-FE

Aberdeen Proving Ground 21005
ATTN: STEAP-FE

U.S. Army Engr Ctr and Ft Belvoir 22060-5113
ATTN: ATTN: ATZA-DEH

Defense Logistics Agency 22304-6100
ATTN: DLA W

U.S. Army Materiel Command 22333
ATTN: DCS, Engineer

Fort A. P. Hill 22427
ATTN: ATZM-FHE

Fort Story 23459
ATTN: ATZF-FE

Fort Eustis 23604
ATTN: ATZF-EH

Fort Monroe 23651
ATTN: ATZG-EH

U.S. Army Qtrmaster Ctr and Ft Lee 23801-5200
ATTN: ATZM-E

Fort Pickett 23824
ATTN: ATZM-FPE

Radford Army Ammo Plant 24141
ATTN: SMCRA-EN

Fort Bragg 28307
ATTN: AFZA-DE

Fort Jackson 29207-5650
ATTN: ATZJ-EH

Fort Gillem 30050
ATTN: AFZK-G-FE

Fort McPherson 30330
ATTN: AFZK-EH

Directorate of Installation Support
USASC&FG 30905-5060
ATTN: Chief, Facilities Division

HQ, 24th Inf Div (Mech) and Ft Stewart 31314
ATTN: Director, Engineering & Housing

Fort Benning 31905
ATTN: ATZB-EH

193d Inf Brigade (Panama) APO Miami 34004-5000
ATTN: AFZU-EH

U.S. Army Armament, Munitions, and
Chemical Command 35044-0368
ATTN: SMCAL

U.S. Army Missile Command 35898-5340
ATTN: AMSMI-RA-FE

Anniston Army Depot 36201
ATTN: SCSAN-DAS-FE

Fort McClellan 36205-5000
ATTN: ATZN-FE

Fort Rucker 36362
ATTN: ATZQ-EH

Volunteer Army Ammo Plant 37422-2607
ATTN: SMCVO-CO

Holston Army Ammo Plant 37660-9982
ATTN: SMCHO-EN

Mississippi Army Ammunition Plant 39529-7000
ATTN: SMCMS-EN

Fort Knox 40121
ATTN: ATZK-EH

Lex-BG-Depot Activity 40511
ATTN: SDSAN-LAF

Fort Campbell 42223
ATTN: FZB-DEH

Defense Construction Supply Center 43216-5000
ATTN: DCSC-WI

Ravenna Army Ammo Plant 44266-9297
ATTN: SMCRV-O

Lima Army Tank Center 45804
ATTN: AMSTA-XY

Fort Benjamin Harrison 46216
ATTN: ATZI-FE

Jefferson Proving Ground 47280
ATTN: STEJP-LD-F

USA-CERL DISTRIBUTION (Cont'd)

Crane Army Ammo Activity 47522-5099
ATTN: SMCCN-EF

Newport Army Ammo Plant 47966-0121
ATTN: SMCNE-EN

TACOM Support Activity 48055
ATTN: AMSTA-XYN

U.S. Army Tank Automotive Cmd Fac Div 48090
ATTN: AMSTA-XE

U.S. Army Tank Automotive Command
Facility Division, Detroit Arsenal 48397
ATTN: AMSTA-XE

Badger Army Ammo Plant 53913-5000
ATTN: SMCBA-OR

Fort McCoy 54656-5000
ATTN: AFZR-FE

Twin Cities Army Ammo Plant 55112-5000
ATTN: SMCTC-CO

Ft. Sheridan 60037
ATTN: AFKE-EN

Joliet Army Ammo Plant 60436-5000
ATTN: SMCJO-EN

Savanna Depot Activity 61074
ATTN: SDSLE-VAE

Rock Island Arsenal 61299-5000
ATTN: SMCRI-FE

Rock Island, Illinois 61299-7190
ATTN: AMXEN-I

St. Louis Area Support Center 62040
ATTN: SAVAS-ZF

St. Louis Army Ammo Plant 63120-1584
ATTN: SMCSL-FE

U.S. Army Aviation Systems Cmd 63120-1798
ATTN: SAVAI-F

Lake City Army Ammo Plant 64050-0330
ATTN: SMCLC-EN

Fort Leonard Wood 65473
ATTN: ATZT-DEH

Sunflower Army Ammo Plant 66018-0640
ATTN: SMCSU-O

Fort Leavenworth 66027
ATTN: ATZL-TEH

1st Inf Div (M) and Ft Riley 66442-6000
ATTN: AFZN-DE

Kansas Army Ammunition Plant 67357-9017
ATTN: SMCKA-OR

Cornhusker Army Ammo Plant 68801-2041
ATTN: SMCCO-E

Louisiana Army Ammo Plant 71130-5000
ATTN: SMCLA-EN

Fort Polk 71459
ATTN: AFZX-EH

Pine Bluff Arsenal 71602-9500
ATTN: SMCPB-FA

USAG Fort Chaffee 72905-5000
ATTN: ATZR-ZF

Fort Sill 73503
ATTN: ATZR-E

McAlester Army Ammo Plant 74501-5000
ATTN: SMCMC-ISF

Red River Army Depot 75501
ATTN: SDSRR-AF

Lone Star Army Ammunition Plant 75505-9101
ATTN: SMCLS-EN (2)

Longhorn Army Ammo Plant 75670-1059
ATTN: SMCLO-EN

III Corps and Fort Hood 76544-5057
ATTN: AFZP-DE-CMD

Fort Hood 76544
ATTN: AFZF-DE

Fort Sam Houston, Texas 78234
ATTN: AFZG-DE

Corpus Christi Army Depot 78419
ATTN: SDSCC-EF

Fort Bliss, Texas 79916
ATTN: ATZC-DEH

Rocky Mountain Arsenal, Colorado 80022-2180
ATTN: SMCPM-ISF

Pueblo Depot Activity 81001
ATTN: SDSTE-PUA-F

U.S. Army Dugway Proving Ground 84022
ATTN: STEDP-FS

Tooele Army Depot 84074-5008
ATTN: SDSTE-ASF

U.S. Army Yuma Proving Ground 85365-9102
ATTN: STEYP-FE-D

Ft. Juachuca, Arizona 85613-6000
ATTN: ASH-FE

White Sands Missile Range 88002
ATTN: STEWS-IS

Fort MacArthur 90731

Natl Training Ctr and Fort Irwin 92310-5000
ATTN: AFZJ-EH

Fort Ord, California 93941
ATTN: AFZW-EH

Presidio of San Francisco 94129
ATTN: AFZM-FE

Sixth US Army 94129-7000
ATTN: AFKC-EN

Sharpe Army Depot 95331-5230
ATTN: SDSSH-AFE-C

Riverbank Army Ammunition Plant 95367-0678
ATTN: SMCRB-EC

Sierra Army Depot 96113-5171
ATTN: SDSSI-FE

Sacramento Army Depot 96813
ATTN: PANAM

Fort Lewis 98433
ATTN: AFZH-FE

Vancouver Barracks 98660
ATTN: AFZH-V

Fort Greely 98733
ATTN: AFZT-FE

6th Inf Div (L) & U.S. Army Garrison 99505-5500
ATTN: AFVR-DE

Fort Wainwright 99703-5500
ATTN: AFVR-FW-DE

END
DATE
FILMED
5-88
DTIC