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# Project Summary

# Design Scale-Up Suitability for Air-Stripping Columns

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**An investigation was conducted to determine the suitability of a design scale-up from pilot-scale to full-scale air-stripping columns used in the removal of volatile organic compounds from contaminated water supplies.**

**Forty-eight experimental runs were made in packed columns of four different diameters (6, 12, 24, and 57 in.) at air-to-water ratios ranging from 5:1 to 50:1. Water was used from the Village of Brewster, New York, well fields; this water was contaminated with tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene. Various packing types (½-in., 1-in., and 3-in. saddles and 2-in. TRI-PACKS*) were used in the experimental runs.**

**The mass transfer coefficients generally increased with column diameter — that is, mass transfer coefficients obtained from a pilot column tend to be conservative. Thus a full-scale column designed from pilot data would tend to be overdesigned. Such was the case even when the pilot column had a column diameter-to-packing size ratio of 12:1 or 24:1.**

**The experimental mass transfer coefficients were compared with values calculated from the Onda mass transfer coefficient model. Generally, the two values were in reasonably good agreement. Based on these results, it appears that the Onda model tends to give a conservative design for a full-scale system. Using a cost model developed by the U. S. Environmental Protection Agency (EPA), the 2-in. plastic TRI-PACKS (of the packing types tested) gave the most cost-effective design for a full-scale system. No operational problems were encountered during subfreezing weather other than rupture of some sample lines.**

***This Project Summary was developed by EPA's Water Engineering Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).***

## Introduction

The Village of Brewster, New York, has a serious groundwater contamination problem — namely, their well fields are badly contaminated with industrial chlorinated solvents (tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene). A continuing program has been under way to evaluate various approaches of providing a potable water supply, such as decontamination of water from the existing well fields by air-stripping or location of a new water supply source. Air-stripping was selected as the most cost-effective approach.

In 1982, a packed column pilot plant (12-in.-diameter with 18 ft of 1-in. packing) was erected at the Village well fields, and an air-stripping test program was conducted. This pilot column was designed for 99% removal of tetrachloroethylene at the average annual temperature at Brewster using a design procedure described in the technical literature and augmented by EPA's Technical Support Division (EPA-TSD). Test results were very encouraging; the removal of tetrachloroethylene exceeded 99% (with 1-in. ceramic saddles at an air-to-water ratio of 20:1).

EPA-TSD, which had developed a computer program based on theory

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similar to the technical literature, undertook a cooperative study with this pilot plant, and the data were analyzed using their program. More recently, EPA-TSD tested a larger packed column pilot plant (2-ft-diameter) at the Village well fields.

Based on the various studies conducted by the Village's consulting engineer, a decision was made to design and construct a full-scale air-stripping column for the Village's water supply. Since air-stripping columns of three different sizes would now be available (two pilot-scale and one full-scale column), a proposal for a cooperative research agreement was made to EPA's Drinking Water Research Division (EPA-DWRD) to conduct tests in these columns with various packing materials. At the request of EPA-DWRD, a fourth column diameter (6-in.) was added.

The principal objective of this cooperative research agreement was to investigate and confirm the scale-up capability of an air-stripping packed column from pilot-scale to full-scale module (design capacity of 0.5 mgd). Secondary objectives were as follows:

1. Develop engineering design guidelines by evaluating mass transfer coefficients and Henry's coefficients in full-scale and pilot-scale packed columns;

2. Evaluate the effect of cold weather operation on the full-scale module (i.e., the effect of sub-freezing air temperatures on operability and the effect of low water temperatures on Henry's coefficient);

3. Evaluate the limiting ratios of column diameter-to-packing size for pilot columns (i.e., are ratios of less than 12:1 feasible?);

4. Evaluate by means of a computer program the economics of different packing sizes and operating conditions (i.e., the optimum range for air-to-water ratio and other conditions to give minimum life cycle cost); and

5. Document the installed equipment cost of the air-stripping technique in a full-scale module.

## Description of Equipment

### General Arrangement

Water can be supplied to the packed columns from two old well fields (Well Fields 1 and 2), two old gravel pack wells (SG 1 and 2), two new gravel pack wells (SG 3 and 4), and/or a rock well (Deep Well 2). All of these Village wells are contaminated with the synthetic chlorinated organics to some degree, with Well Field 1 having the highest contamination levels.

The study included three pilot-scale columns and one full-scale air-stripping column. Three of the columns (6-in., 12-in., and 57-in. diameters) are hard-piped installations; the EPA-TSD column (24-in. diameter) was set up on a temporary basis for its scheduled tests. A description of the column construction is provided below. A sketch showing a typical air-stripping packed column is presented in Figure 1.

### Pilot-Scale and Full-Scale Packed Columns

Each of the packed columns has similar internal components:

(a) a liquid distributor above the packing at the top of the column, (b) wall collectors (within the packing) to remove water from the column wall and redistribute it onto the packing, (c) a packing support plate near the bottom of the column, and (d) an air inlet below the packing support plate. Sample tubes are provided within the packing at 2-ft intervals. In addition, sample taps are provided for the water entering and leaving the column. Instrumentation is provided for measuring the air and water flows and the air and water temperatures.

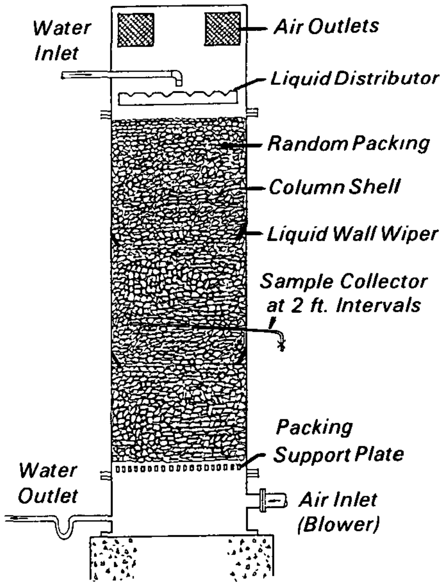

Figure 1. Cross section of a typical air-stripping packed column, Village of Brewster, New York

The packing height in each of the pilot columns is 18 ft. The full-scale column has a packing height of 17 ft 9 in. and was designed for 99% removal of tetrachloroethylene at an air-to-water ratio of 33:1 (with 1-in. plastic saddles).

## Cost of Full-Scale Air-Stripping Facility

The actual construction costs of the full-scale column (57-in. diameter) are tabulated in Table 1. These include costs for the building (housing the air blowers, pumps, and electrical controls), ancillary equipment, sitework, and contractor's overhead and profit. This air-stripping facility has a nominal capacity of 600 gpm (0.86 MGD). Note that there are many items and features (such as building, large clearwell, backup blowers and pumps, chemical feed system, etc.) that may not be needed for locations with different system operating conditions and less severe weather conditions.

## Outline of Test Runs

The packing materials tested were ½-in. ceramic saddles, 1-in. and 3-in. plastic saddles, and 2-in. plastic TRI-PACKS. The planned experimental conditions were selected to allow evaluation of: (a) different column diameters with the same packing material (at the same air and water velocities), and (b) different ratios of column diameter to packing size (i.e., minimum ratio of column diameter to packing size).

An outline of the planned test conditions is presented in Table 2. Because of budgetary considerations, the experimental plan had to be limited to fit the available funding level. In the case of some of the test runs, the 5:1 and 10:1 air-to-water ratios could not be run because of water flow limitations that were due either to insufficient pumping capacity from the Village's well fields or to excessive pressure drop in a column or water feed line.

The air and water flow conditions (loadings) used for the various packing materials are shown in Table 3. These flow conditions were selected to give a calculated air pressure drop gradient of 1/16 in. water column per foot of column packing.

## Operating Conditions and Sample Results

### Operating Conditions

Forty-eight experimental runs were made in the four packed columns with

**Table 1.** *Construction Cost Of Full-Scale Air-Stripping Facility (1983 Dollars)**

| *Item* | *Construction Cost (including installation)* |
|---|---|
| *Process equipment* | |
| *Column shell* | *$40,775.* |
| *Column internals* | |
| *Plastic saddle packing* | |
| *Air blowers (two)* | *4,620.* |
| *High service pumps (two)* | *18,980.* |
| *Total process equipment* | *$64,375.* |
| *Air well (also building foundation)* | *$46,818.* |
| *Piping, valves, and appurtenances* | *25,000.* |
| *Air ductwork and appurtenances* | *7,260.* |
| *Chemical feed equipment* | *7,000.* |
| *Instrumentation* | *1,320.* |
| *Electrical* | *49,103.* |
| *Building superstructure and sitework* | *72,971.* |
| *Subtotal* | *$273,847* |
| *Additional support equipment, piping, valves and appurtenances for research operations* | *9,792.* |
| *Total construction cost* | *$283,639* |

**Contractor's overhead and profit included.*

**Table 2.** *Outline of Experimental Plan*

| | *Column Diameter (in.)* | | | |
|---|---|---|---|---|
| *Item* | *6* | *12* | *24* | *57* |
| *Packing types:* | | | | |
| *Saddles (in.)* | *1/2 & 1* | *1 & 3* | *1* | *1 & 3* |
| *TRI-PACKS (in.)* | *2* | *2* | *2* | *—* |
| *Packing height (ft)* | *18* | *18* | *18* | *17.8* |
| *Air-to-water ratios* | *5:1* | *5:1* | *5:1* | *—* |
| | *10:1* | *10:1* | *10:1* | *10:1* |
| | *20:1* | *20:1* | *20:1* | *20:1* |
| | *35:1* | *35:1* | *35:1* | *35:1* |
| | *50:1* | *50:1* | *50:1* | *50:1* |

various packings and at various air-to-water ratios. For purposes of data evaluation, the runs were assigned an analysis number (Table 4). All runs with the same column and same packing material were collectively referred to as a data group.

## *Water Sample Results*

As noted previously, water samples were collected for each run at the column inlet, at approximately 2-ft intervals within the packing, and at the column outlet. Approximately 430 water samples were collected and analyzed for these experimental runs.

The results of these water analyses for tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene were plotted as concentration profiles for each run. A typical set of concentration profiles for one run is shown in Figure 2.

## Data Analysis and Discussion

## *Mass Transfer Coefficients*

One set of mass transfer coefficients resulting from analysis of the experimental data is summarized in Table 5 for tetrachloroethylene. Values for air-to-water ratios of 20:1, 35:1, and 50:1 are shown, since such ratios are typically used for air-stripping of these volatile organic compounds (VOC's). Similar results were obtained for trichloroethylene and cis-1,2 dichloroethylene.

The mass transfer coefficients generally increase as the column diameter increases (with the same packing material). This result is to be expected, since the wall effect (i.e., channeling of water on the inside of the column wall) is greater with a smaller-diameter column. Of special note, however, is the observation that the mass transfer coefficient continued to increase as the column diameter-to-packing size ratio was increased from 12:1 and also from 24:1 (for the 1-in. saddles). Thus these results indicate that using pilot-plant data to design a full-scale column will result in a conservative design.

## *Full-Scale System Designs*

In designing a full-scale packed column system for a specific requirement (say, 99% removal of tetrachloroethylene), a number of design parameters (such as packing type, packing size, and air-to-water ratio) can be varied to achieve the same result. To select the cost-optimized design parameters, a cost model has been developed that estimates both the capital and operating costs. With the data obtained from the four different-diameter columns, cost-optimized designs were developed. The design criteria used were as follows:

99% removal of tetrachloroethylene
350 gpm (0.5 MGD) design flow
9°C water temperature
5.8 ¢/kWh power cost
10% interest rate
1.2 safety factor for Henry's coefficient
1.2 safety factor for mass transfer coefficient

The data in Table 6 summarize the results for the 1-in. plastic saddles and air-to-water ratios of 20:1 to 50:1.

From these results, the cost-optimized parameters in Table 7 would probably be selected. Thus once again, a full-scale system designed from pilot-plant data will probably result in a conservative design.

Note that the actual construction costs for the 57-in. packed column system (Table 1) are significantly higher than the estimated capital costs predicted by the cost model. This result is to be expected, since there are many site-specific items and features that are not included in the cost model.

## *Onda Mass Transfer Coefficients*

The mass transfer coefficients predicted by the Onda correlation were compared with the best fit experimentally derived results for tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene. The two values were generally, but not always, in reasonably good agreement.

**Table 3.** *Air and Water Flow Conditions for Plastic and Ceramic Saddles and TRI-PACKS*

| *Air: Water Ratio (volume basis)* | *Liquid Loading (gpm/ft$^2$)* | *Air Loading (scfm/ft$^2$)* |
|---|---|---|
| *Flow conditions for:* | | |
| *1-in. plastic saddles* | | |
| *5* | *45* | *30* |
| *10* | *38* | *50* |
| *20* | *24* | *65* |
| *35* | *16* | *78* |
| *50* | *13* | *87* |
| *3-in. plastic saddles and 2-in. TRI-PACK* | | |
| *5* | *75* | *50* |
| *10* | *58* | *77* |
| *20* | *37* | *100* |
| *35* | *25* | *120* |
| *50* | *20* | *130* |
| *1/2 in. ceramic saddles* | | |
| *5* | *20.0* | *13.4* |
| *10* | *14.9* | *20.0* |
| *20* | *9.64* | *25.8* |
| *35* | *6.59* | *30.8* |
| *50* | *5.10* | *34.1* |

**Table 4.** *Operating Data Arranged for Data Analysis*

| *Data Group* | *Analysis Number* | *Packing Size (in.)* | *Column Diameter (in.)* | *Air: Water Ratio* | *Loading Rate* Air | Water $(m^3 m^{-2} sec^{-1})$ | *Run Number* |
|---|---|---|---|---|---|---|---|
| *1* | *1* | *0.5* | *6* | *50.* | *0.17* | *0.0034* | *13* |
| | *2* | *0.5* | *6* | *34.* | *0.16* | *0.0046* | *9* |
| | *3* | *0.5* | *6* | *20.* | *0.13* | *0.0067* | *8* |
| | *4* | *0.5* | *6* | *10.* | *0.10* | *0.0098* | *7* |
| | *5* | *0.5* | *6* | *5.0* | *0.067* | *0.014* | *6* |
| | *6* | *0.5* | *6* | *5.0* | *0.067* | *0.013* | *12* |
| | *7* | *0.5* | *6* | *49.* | *0.17* | *0.0035* | *10* |
| *2* | *8* | *1.* | *6* | *50.* | *0.44* | *0.0089* | *46* |
| | *9* | *1.* | *6* | *36.* | *0.40* | *0.011* | *45* |
| | *10* | *1.* | *6* | *21.* | *0.33* | *0.016* | *44* |
| | *11* | *1.* | *6* | *9.8* | *0.25* | *0.026* | *48* |
| | *12* | *1.* | *6* | *5.0* | *0.15* | *0.031* | *47* |
| *3* | *13* | *1.* | *12* | *50.* | *0.44* | *0.0088* | *43* |
| | *14* | *1.* | *12* | *36.* | *0.39* | *0.011* | *42* |
| | *15* | *1.* | *12* | *21.* | *0.33* | *0.016* | *41* |
| | *16* | *1.* | *12* | *9.9* | *0.25* | *0.026* | *40* |
| | *17* | *1.* | *12* | *5.0* | *0.15* | *0.031* | *39* |
| *4* | *18* | *1.* | *24* | *49.* | *0.44* | *0.0089* | *35* |
| | *19* | *1.* | *24* | *36.* | *0.39* | *0.011* | *34* |
| | *20* | *1.* | *24* | *20.* | *0.32* | *0.017* | *33* |
| | *21* | *1.* | *24* | *10.* | *0.26* | *0.026* | *32* |
| | *22* | *1.* | *24* | *5.0* | *0.15* | *0.030* | *31* |
| *5* | *23* | *1.* | *57* | *53.* | *0.47* | *0.0088* | *38* |
| | *24* | *1.* | *57* | *37.* | *0.40* | *0.011* | *37* |
| | *25* | *1.* | *57* | *22.* | *0.34* | *0.016* | *36* |
| *6* | *26* | *2.* | *6* | *47.* | *0.65* | *0.014* | *18* |
| | *27* | *2.* | *6* | *35.* | *0.61* | *0.017* | *20* |
| | *28* | *2.* | *6* | *20.* | *0.51* | *0.025* | *22* |
| | *29* | *2.* | *6* | *9.9* | *0.39* | *0.039* | *24* |
| | *30* | *2.* | *6* | *5.1* | *0.26* | *0.051* | *26* |

These results indicate that the Onda correlation tends to give a conservative design for a full-scale system.

## *Effect of Temperature on Operability*

Even though the experimental runs were made during both winter and summer months, the water temperature stayed within a fairly narrow range. The water temperature entering the packed columns ranged from approximately 9° to 12° C over the course of all the runs. This relatively constant temperature was due, of course, to the consistency of the groundwater temperature. In addition, the ambient air temperature did not significantly affect the water temperature within the column.

The 57-in. column was run continuously through periods of subfreezing weather, and the low air temperatures did not interfere with the operation of the packed column. The only problem encountered with low temperatures was with the copper tubing sample lines. Some of these lines split open at night, even though the sample valves were left partly open. For any future designs, such sample lines should be insulated to prevent freezing.

## *Henry's Coefficient*

Henry's coefficient, a physical-chemical property that expresses the volatility of a particular VOC, depends on the temperature and the molecular properties of the VOC. For each of the experimental runs, Henry's coefficient was determined.

An attempt was made to correlate Henry's coefficient with temperature, but it was unsuccessful because of scatter in the data. Instead, a best-fit Henry's coefficient was determined, and these values were 0.30, 0.21, and 0.094 atmosphere for tetrachloroethylene, trichloroethylene, and cis-1,2 dichloroethylene, respectively. The inability to arrive at any satisfactory correlation for Henry's coefficient may be partly due to the relatively narrow range of temperatures encountered, as discussed above.

## Conclusions and Recommendations

1. The mass transfer coefficients generally increased as the column diameter increased. There did not appear to be any cut-off point (i.e., the trend continued beyond column diameter-to-packing size ratios of 12:1). This trend is attributed to a so-called wall effect, which

**Table 4.** *(continued)*

| Data Group | Analysis Number | Packing Size (in.) | Column Diameter (in.) | Air: Water Ratio | Loading Rate Air $(m^3 m^{-2} sec^{-1})$ | Loading Rate Water $(m^3 m^{-2} sec^{-1})$ | Run Number |
|---|---|---|---|---|---|---|---|
| 7 | 31 | 2. | 12 | 51. | 0.66 | 0.013 | 17 |
| | 32 | 2. | 12 | 34. | 0.61 | 0.018 | 19 |
| | 33 | 2. | 12 | 20. | 0.51 | 0.026 | 21 |
| | 34 | 2. | 12 | 10. | 0.39 | 0.039 | 23 |
| | 35 | 2. | 12 | 5.0 | 0.25 | 0.051 | 25 |
| 8 | 36 | 2. | 24 | 49. | 0.66 | 0.014 | 30 |
| | 37 | 2. | 24 | 36. | 0.61 | 0.017 | 29 |
| | 38 | 2. | 24 | 19. | 0.50 | 0.026 | 28 |
| | 39 | 2. | 24 | 9.9 | 0.39 | 0.039 | 27 |
| 9 | 40 | 3. | 12 | 48. | 0.66 | 0.014 | 2 |
| | 41 | 3. | 12 | 35. | 0.61 | 0.017 | 4 |
| | 42 | 3. | 12 | 20. | 0.51 | 0.026 | 5 |
| | 43 | 3. | 12 | 48. | 0.65 | 0.014 | 15 |
| | 44 | 3. | 12 | 37. | 0.60 | 0.016 | 16 |
| 10 | 45 | 3. | 57 | 49. | 0.66 | 0.014 | 14 |
| | 46 | 3. | 57 | 36. | 0.61 | 0.017 | 3 |
| | 47 | 3. | 57 | 20. | 0.51 | 0.025 | 11 |

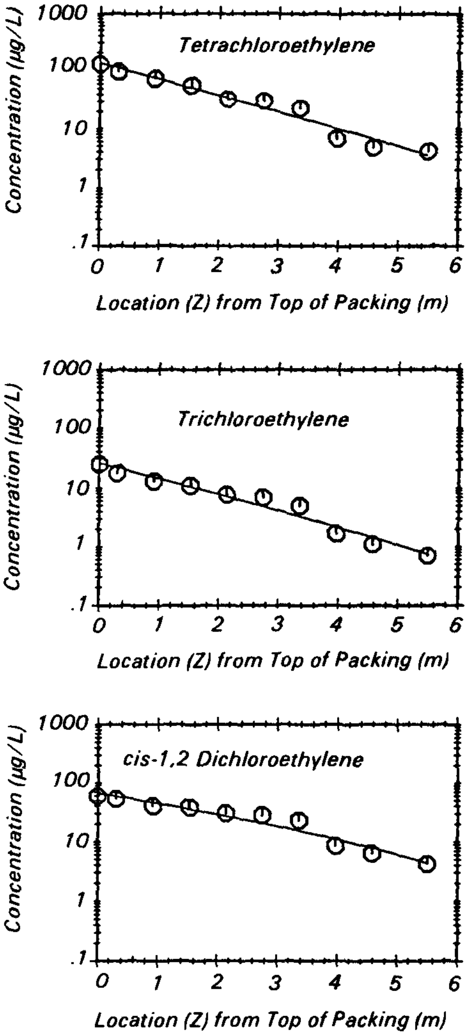

**Figure 2.** Typical concentration profiles (12-inch column, 1-inch saddles, and an air-to-water ratio of 21).

**Table 5.** Mass Transfer Coefficients for Tetrachloroethylene

| Column Diameter (in.) | Packing Type | Column Diameter-to-Packing Size Ratio | Mass Transfer Coefficients $(sec.^{-1})$ for Air-to-Water Ratios 20 | 35 | 50 |
|---|---|---|---|---|---|
| 6 | 1" Saddles | 6:1 | 0.0086 | 0.0065 | 0.0064 |
| 12 | 1" Saddles | 12:1 | 0.0012 | 0.012 | 0.0078 |
| 24 | 1" Saddles | 24:1 | 0.0015 | 0.012 | 0.0099 |
| 57 | 1" Saddles | 57:1 | 0.035 | 0.017 | 0.014 |
| 6 | 2" TRI-PACKS | 3:1 | 0.015 | 0.012 | 0.010 |
| 12 | 2" TRI-PACKS | 6:1 | 0.016 | 0.014 | 0.010 |
| 24 | 2" TRI-PACKS | 12:1 | 0.013 | 0.016 | 0.028 |
| 12 | 3" Saddles | 4:1 | 0.0091 | 0.0064 | 0.0066 |
| 57 | 3" Saddles | 19:1 | 0.015 | 0.010 | 0.0086 |

would be more pronounced in a small-diameter column.

2. Because of the trend noted above, it appears that using pilot-plant data to design a full-scale column will result in a conservative design.

3. Reasonably good agreement was obtained between the experimentally derived mass transfer coefficients and those calculated from the Onda model. These results indicate that the Onda correlation tends to give a conservative design for a full-scale system.

4. The 57-in. column was run continuously through periods of subfreezing weather, and no operational problems were encountered other than rupture of some sample lines (even though the sample valves were left open). In future designs, such sample lines should be insulated.

The full report was submitted in fulfillment of Cooperative Agreement CR810247 by the Village of Brewster, New York, and Nathan L. Jacobson & Associates under the sponsorship of the U. S. Environmental Protection Agency.

**Table 6.** *Design Parameters and Cost Estimates Resulting from Cost Model for 1-in. Plastic Saddles*

| Column Diameter (in.) | Air-to-Water Ratio | Diameter (in.) | Packing Height (ft) | Cost Estimate (1982 Dollars) Capital (K$) | Operating (K$/year) | Production (¢/1000 gal) |
|---|---|---|---|---|---|---|
| 6 | 50. | 70. | 27. | 140. | 7.2 | 13. |
| 6 | 36. | 63. | 34. | 140. | 7.4 | 13. |
| 6 | 21. | 52. | 40. | 130. | 7.2 | 12. |
| 12 | 50. | 70. | 22. | 120. | 6.6 | 12. |
| 12 | 36. | 63. | 18. | 110. | 5.6 | 9.9 |
| 12 | 21. | 52. | 28. | 110. | 6.0 | 10. |
| 24 | 49. | 70. | 17. | 110. | 6.1 | 11. |
| 24 | 36. | 63. | 18. | 110. | 5.7 | 10. |
| 24 | 20. | 51. | 24. | 100. | 5.5 | 9.6 |
| 57 | 53. | 70. | 12. | 98. | 5.4 | 9.2 |
| 57 | 37. | 63. | 13. | 94. | 5.0 | 8.8 |
| 57 | 22. | 53. | 9.6 | 80. | 4.1 | 7.4 |

**Table 7.** *Cost-Optimized Parameters for 1-in. Plastic Saddles*

| Test Column Diameter (in.) | Air-to-Water Ratio | Full-Scale Design Column Diameter (in.) | Packing Height (ft.) | Est. Production Cost (¢/1000 gal) |
|---|---|---|---|---|
| 6 | 20:1 | 52 | 40 | 12 |
| 12 | 20:1 | 52 | 28 | 10 |
| 24 | 20:1 | 51 | 24 | 9.6 |
| 57 | 20:1 | 53 | 9.6 | 7.4 |

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*The complete report, entitled "Design Scale-Up Suitability for Air-Stripping Columns," (Order No. PB 86-154 176/AS; Cost: $16.95, subject to change) will be available only from:*

*National Technical Information Service*
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