

A Compilation of Field-Collected Cost and Treatment Effectiveness Data for the Removal of Dissolved Gasoline Components from Groundwater

**HEALTH AND ENVIRONMENTAL SCIENCES DEPARTMENT
API PUBLICATION NUMBER 4525
NOVEMBER 1990**

**American Petroleum Institute
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Health and Environmental Sciences Department

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**PREPARED UNDER CONTRACT BY:
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EXECUTIVE SUMMARY

This study was conducted to document, summarize and evaluate cost and treatment effectiveness data for air stripping and carbon adsorption systems designed to remove dissolved petroleum hydrocarbons from groundwater. The compounds of primary interest were benzene, toluene, ethylbenzene and xylene isomers (BTEX) as well as the oxygenates methyl-tertiary-butyl-ether (MTBE) and isopropyl ether (IPE). The availability of comprehensive effectiveness and capital and operational maintenance costs for these treatment systems will assist API member companies in planning pump-and-treat remediation systems for removal of BTEX and oxygenates from groundwater.

Operating data were gathered from 57 field sites throughout the United States. Treatment system profiles including capital investment, operating and maintenance costs, influent and effluent contaminant concentrations, and operating parameters (e.g., flow rates, fouling characteristics) were generated for each site. While rigorous statistical analyses did not provide meaningful correlative data for system comparisons, a variety of summary statistics were useful for estimating costs and treatment effectiveness.

Median investment costs and operating and maintenance costs for air stripping systems operating at flow rates from 10 to 50 gallons per minute (gpm) were \$1,627 per gpm and \$2.80 per thousand gallons, respectively. Median costs for systems operating below 10 gpm were substantially greater. Median operating costs were approximately 40% greater than design costs, a difference at least partially attributable to operating flow rates that were lower than design flow rates.

The air stripping systems studied generally achieved benzene removal effectiveness of 99% or more. IPE removal effectiveness was similarly high (>98%; 3 sites), while MTBE removal effectiveness ranged from approximately 56% to 99% with a median removal effectiveness of greater than 91% (15 sites). Where design removal efficiencies were not met, biological or precipitated metal salt fouling were believed to be responsible. Fouling was found to be a common problem with air stripping systems, although fouling prevention and/or treatment efforts were generally successful.

Limited carbon adsorption system data indicated treatment costs similar to air stripping system costs operating at similarly low flow rates (<2 gpm). Carbon adsorption treatment effectiveness ranged from approximately 85% to 99.9% for benzene. Removal effectiveness for MTBE and IPE were 87% and 50%, respectively.

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INTRODUCTION

Air stripping and liquid-phase activated carbon adsorption systems are two of the most commonly implemented water treatment technologies for removing dissolved gasoline components from groundwater. This study was undertaken to compile cost and treatment effectiveness data from installed and operating remediation systems throughout representative regions of the United States. The fuel components of particular interest included benzene, toluene, ethylbenzene and xylenes (BTEX) as well as the oxygenates methyl-tertiary-butyl-ether (MTBE) and isopropyl ether (IPE).

Relevant data were collected and analyzed from 57 anonymous remediation sites under the supervision of Groundwater Technology, Inc (GTI). Selected site visits were conducted in order to verify engineering descriptions and to gather influent and effluent water quality samples. Water quality and cost data were used to document actual treatment effectiveness and capital and operating/maintenance costs in comparison to design parameters.

Pertinent summary data are presented and discussed in the brief narrative section of this report. All relevant site-specific data and a variety of tabular summaries are provided in the various appendices.

METHODS AND DATA COMPILATION

Site Selection

GTI initially selected 50 sites from a list of 138 remediation sites that met at least three of the following criteria:

- o sites contaminated with dissolved gasoline components,
- o sites where air stripping or activated carbon adsorption systems were used for groundwater treatment,
- o sites with systems achieving and/or designed to achieve less than one part per billion (1 ppb) effluent benzene,
- o sites contaminated with dissolved fuel additives such as MTBE and IPE.

The list was expanded to 57 sites by the American Petroleum Institute (API) based on the following additional criteria:

- o availability of system descriptions and cost data,
- o a balanced regional geographic distribution of sites throughout the United States, and
- o operating pretreatment systems. (Fouling of groundwater treatment equipment is a common remediation problem. Sites which satisfied other criteria and had antifouling systems were of special interest in this study.)

For the purposes of this study, each site was assigned a regional but otherwise anonymous identification number. The regions and site numbers representing the original 138 sites are presented here.

<u>Region</u>	<u>Sites</u>
Mid-Atlantic	MA-1 through MA-17
Midwest	MW-1 through MW-16
Northeast	NE-1 through NE-25
South Central	SC-1 through SC-5
Southeast	SE-1 through SE-36
West	W-1 through W-39

Operating data from each of the 57 final study sites are presented in Appendices B and C and arranged by technology (air stripping, carbon adsorption) and region (in alphabetical and numerical order). Three of the sites maintained multiple, independent systems treating groundwater from a single contaminant plume. In such cases, the site identification number included a treatment system number in parentheses (e.g., MA-10[1]; SE-33[2]). Of the 57 sites investigated, 62 individual treatment systems were studied.

Data Collection and Compilation

Site data were gathered during the site visits from project files and project personnel files. A thorough review of project files provided engineering design, capital and operating costs, and miscellaneous site-specific data. This information was reviewed for anomalies or data omissions. Data gaps and discrepancies were resolved through project personnel interviews, where possible. Site visits were conducted to verify data and to collect influent/effluent water samples for analysis.

For individual sites, the following data were gathered from project files through formal correspondence requests and during site visits:

Design Data:

Design tower height and diameter
 Design packing type and height
 Design water and air temperatures
 Design water and air flow rates
 Design tank size and retention time
 (for carbon adsorption systems)
 Design & achieved rate of contaminant
 removal

Cost Data:**A. Capital Costs**

(These costs are presented separately
 and as combined "Total Initial Cost"
 in Appendices B and C)

Engineering design cost
 Permitting cost
 Equipment cost
 Piping cost
 Site preparation cost
 Electrical installation cost
 Pretreatment system cost

**B. Annual Operating and Maintenance Costs
(O&M)**

(These costs are presented separately
 and as combined "Total Annual Costs" in
 Appendices B and C)

Treatment system operating cost
 Pretreatment system operating cost
 Monitoring cost
 Maintenance cost

Miscellaneous Data: Initial date of operation
 Sampling frequency
 Site-specific comments

Site visits were also used to verify the integrity of the data collected from project files and project staff. The variables to be verified for air stripping systems included: air flow rate, water flow rate, air temperature, water temperature, tower height, packing height and tower diameter. The packing type was noted. For carbon adsorption systems, the tank size and system configuration were noted. Air flow rates were measured using either a Dwyer Pitot Tube or a Kurz Air Velocity Meter, Model 443. Five replicate readings were obtained and an average was calculated. Similarly, water flow rates were measured with either a flow meter or on a timed basis using a retention tank. The water and air temperatures were measured with a scientific thermometer. Three replicate readings were taken and an average was calculated. The tower height, packing height and tower diameter were measured with a tape measure, and the packing was inspected to verify design specifications. Influent and effluent water samples were collected in duplicate from the air stripping towers or carbon tanks. The water samples were obtained from the sampling ports on the influent and effluent lines and collected in 40-ml sampling vials. These samples were then sent to Groundwater Technology Environmental Laboratories (GTEL) and analyzed for benzene, toluene, ethylbenzene, total xylenes, MTBE, and IPE. Results of these analyses can be found in Appendix D. Standard water sampling procedures for volatile organic compounds were used by GTI personnel. These procedures can be found in Appendix E, which also contains the GTEL QA/QC procedures for laboratory sampling and analysis.

Once the samples were received by the laboratory, the condition of each sample was carefully checked and recorded. Each container was inspected and any anomalies noted. The freight

bill and chain-of-custody documents were reviewed and matched to the labeled contents of each shipping container. Any labeling errors were noted and corrected once the project engineer had been notified of the error. All samples were logged in and assigned a number for ease of location throughout the process. The samples were maintained at 4°C until analyzed.

Distilled water blanks were prepared in the same manner as water samples at each site. The standard procedure for the preparation of field blanks is described in Appendix E. Field blanks served as indicators of sample contamination throughout the entire sampling and sample transport process.

All influent samples were analyzed using EPA Method 624. Since effluent concentrations for benzene were likely to be less than 1 ppb, and the detection limit for benzene using EPA Method 624 is 1.7 ppb, it was decided that effluent samples would be analyzed by EPA Method 524.1, for which the benzene detection limit is 0.2 ppb. Detection limits for relevant contaminants for each of these EPA methods are presented in Appendix E.

Laboratory QA/QC procedures followed for this study dictated that GTEL analyze duplicate samples and matrix spiked samples at a rate of no less than 10% of those samples analyzed. Results and procedures used for these analyses are also included in Appendix E.

All site visits and sampling were completed within a 3-week period so that samples from this study could be analyzed at the laboratory at the same time. All laboratory analyses, along with QA/QC information, were mailed to the API Study Project Manager in a single package. Site visit data were also mailed from field engineers to the API Study Project Manager. All data were then tabulated for each site including file data, site visit data and laboratory analyses.

Appendices B and C contain the compiled data from each site with relevant information contained on two succeeding pages. The first page contains treatment system parameters, cost data and miscellaneous site-specific comments. The second page presents analytical data for the site. For each site, two sets of parametric and analytic information are presented, where available. The design data are comprised of values used in the design specifications for the individual systems. These data are important because capital costs and, to a lesser degree, operating costs are directly related to these values. The actual data include values measured onsite.

All cost data in Appendices B and C were compiled from project files. The costs listed and totaled as Total Initial Cost are considered capital costs. The Total Annual Cost represents annual operating and maintenance (O&M) costs, including monitoring. Cost calculation procedures are documented in Appendix A. Site-specific comments were collected from project files and site visit notes.

Appendix D contains the laboratory analytical data for influent and effluent water samples. These water quality data are also presented in tabular form in Appendices B and C with percent removal effectiveness calculations, number of transfer units (NTU) and height of transfer units (HTU). Transfer unit calculations were computed as follows:

1) Percent Removal

$$R = \frac{C - C_e}{C} \times 100$$

Where, R = Percent Removal
 C = Influent Concentration
 C_e = Effluent Concentration

2) Number of Transfer Units

$$NTU = \frac{R}{R-1} \ln \frac{(C_i/C_e) (R-1) + 1}{R}$$

Where, NTU = Number of Transfer Units

C_i = Influent Concentration

C_e = Effluent Concentration

$$R = \left(\frac{A}{W} \right) \left(\frac{\bar{d}A}{\bar{d}w} \right) \left(\frac{H}{P_T} \right)$$

Where: R = Stripping factor

A = air rate at average in-column conditions, m³/min

W = water rate at average in-column conditions, m³/min

$\bar{d}A$ = density of air at average in-column conditions,
mol/m³

$\bar{d}w$ = density of water at average in-column conditions,
mol/m³

H = Henry's Law Constant, atm/mol fraction

P_T = Total (ambient) pressure, atm

3) Height of Transfer for Unit

$$HTU = \frac{Z}{NTU}$$

Where, HTU = Height of Transfer Unit

Z = Packing Height

NTU = Number of Transfer Units

Percent removal, NTU and HTU are important performance and design parameters for air strippers. These parameters have specific mathematical relationships to many of the system parametric data collected in this study. A detailed explanation of the theory and mathematical development of these equations is beyond the scope of this study. Two excellent sources of this information are:

"Design of Aeration Towers to Strip Volatile Contaminants from Drinking Water," by Michael C. Kavanaugh and R. Rhodes Trussel, published in the Journal of the American Water Works Association, December, 1980.

Mass Transfer Operations, by R. E. Treybal, McGraw-Hill Book Company, of New York. 1968.

Appendix E contains quality control information relevant to this study. This information includes analytical results for duplicate samples, a table of detection limits relevant to this study and relevant excerpts from GTI's Standard Operating Procedures Manual and Laboratory QA/QC Program.

RESULTS AND DISCUSSION

Cost Information

Cost data developed during this study demonstrated substantial variability. Considering the diversity of treatment systems reviewed, such results were expected. Attempts to statistically correlate data in anything more than a general way did not prove to be useful. Indeed, even mathematical averages representing a variety of system parameters proved to be misleading. Median values proved to be more reliable predictors of system costs.

Tables I through IV provide summaries of the cost information for air stripping systems. Detailed cost data for individual systems are included in Appendices A through C. It is important to note that air stripping systems documented in this study did not include vapor phase treatment of hydrocarbons exhausted to the atmosphere.

Table II indicates that median operating and maintenance costs for air stripping were \$2.80 per thousand gallons for flow rates in the range of 10 to 50 gpm. Median installed costs (Table III) were \$1,627 per gpm for this 10 to 50 gpm flow range. Cost data for 11 sites are included.

For those 26 systems operating at less than 10 gpm, the costs per gallon treated were considerably higher. The median operating and maintenance cost was \$6.40 per thousand gallons and the investment cost was \$5,839 per gpm. At very low flow rates (1 gpm or less), the costs per gallon processed were considerably higher, as expected. For example, O&M costs at site W-39 at 0.8 gpm flow were \$50 per thousand gallons. Investment cost was \$29,125 per gpm.

At flow rates above 50 gpm, O&M costs were \$.40 to \$.60 per thousand gallons, with investment costs between \$511 and \$556 per gpm. Cost data for only two sites were available in this flow range.

Frequently there was a distinct difference between the costs per gallon estimated for the design of the systems and the costs actually experienced in the field. Table IV indicates that the median ratio of actual unit costs to those initially estimated for the design was approximately 1.4/1. The differences between design estimates and actual costs were partly due to operating at flow rates that were often considerably less than the rates for which the systems were designed.

Costs for carbon treatment are shown in Table V. There were only five sites where such cost data were available; therefore, no statistical analyses were attempted. Actual flow rates for these carbon adsorption systems were 2 gpm or less. At these low flow rates, the carbon treatment costs were comparable to air stripping costs at similar flow rates (Table I). Additional details are provided in Appendix C.

TABLE I. RAW COST DATA FOR AIR STRIPPING SYSTEMS

OBS SITE NO.	ACTUAL			DESIGN		
	FLOW RATE (GPM)	CAPITAL COST (\$/GPM)	O&M COST (\$/1000 GAL)	FLOW RATE (GPM)	CAPITAL COST (\$/GPM)	O&M COST (\$/1000 GAL)
1 MA-2	--	--	--	9.0	2000	1.1
2 MA-3	--	--	--	20.0	1018	0.8
3 MA-4	--	--	--	60.0	303	0.1
4 MA-5	--	--	--	11.0	1045	0.6
5 MA-8	--	--	--	5.0	2700	11.0
6 MA-9	--	--	--	50.0	640	1.8
7 MA-10(1)	15.00	1133	0.4	30.0	567	0.2
8 MA-10(2)	6.00	3083	0.9	30.0	617	0.2
9 MA-10(3)	8.00	2088	0.6	30.0	557	0.2
10 MA-10(4)	7.00	2386	0.7	30.0	557	0.2
11 MA-15	--	--	--	175.0	132	0.1
12 MA-16	--	--	--	175.0	149	0.1
13 MW-1	0.95	30705	127.0	--	--	--
14 MW-6	1.20	19443	130.0	0.5	46664	313.0
15 MW-7	0.50	55110	415.0	2.0	13778	104.0
16 MW-10	2.50	12724	87.0	2.0	15905	109.0
17 MW-13	15.00	2210	9.6	15.0	2210	9.6
18 MW-16	--	--	--	40.0	574	3.0
19 NE-4	2.00	30412	32.0	50.0	1216	1.3
20 NE-6	7.50	5427	6.4	10.0	4070	4.8
21 NE-9	5.20	4808	3.3	5.0	5000	3.4
22 NE-18	3.60	10556	32.0	5.0	7600	23.0
23 NE-19	11.50	2113	2.8	25.0	972	1.3
24 NE-21	42.00	1085	1.2	40.0	1139	1.3
25 NE-22	3.75	4720	0.2	10.0	1770	0.1
26 SC-1	5.00	2822	0.4	3.5	4032	0.6
27 SC-2	4.50	3031	0.5	3.0	4546	0.7
28 SC-3	4.00	3584	2.5	3.0	4779	3.3
29 SC-4	3.80	2812	1.7	4.0	2671	1.6
30 SC-5	8.00	1497	0.2	7.0	1710	0.2
31 SE-7	32.40	739	1.2	28.0	855	1.4
32 SE-18	22.20	1483	2.6	22.0	1496	2.6
33 SE-22	3.00	6913	18.0	4.0	5184	13.0
34 SE-23	14.50	2559	4.0	16.0	2319	3.7
35 SE-29	30.00	683	1.9	30.0	683	1.9
36 SE-31	1.40	6250	5.0	5.0	1750	1.4
37 SE-32	14.30	2091	5.4	30.0	997	2.6
38 SE-33(1,2)	16.00	2331	3.7	20.0	1865	2.9
39 SE-35	9.50	3474	6.7	17.0	1941	3.7
40 SE-36	15.00	1627	3.9	50.0	488	1.2
41 W-1	0.80	30865	135.0	10.0	2469	11.0
42 W-2	8.50	3835	4.2	60.0	543	0.6
43 W-4	8.50	6824	7.6	--	--	--
44 W-14	1.10	61364	55.0	10.0	6750	6.0
45 W-17	--	--	--	5.0	1430	0.3
46 W-18	3.50	14372	--	60.0	838	--
47 W-19	--	--	--	60.0	877	--
48 W-31(1,2)	270.00	511	0.4	--	--	--
49 W-38	52.20	556	0.6	30.0	967	1.0
50 W-39	0.80	29125	50.0	15.0	1553	2.7



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TABLE II. DOCUMENTED ANNUAL OPERATING AND MAINTENANCE COSTS
FOR AIR STRIPPING SYSTEMS (\$/1000 GALLONS)

FLOW RATE (GPM)	SAMPLE SIZE (N)	MEDIAN	AVERAGE	COST RANGE
<10	25	\$6.40	\$44.88	\$0.20-\$415.00
10-50	11	\$2.80	\$3.34	\$0.40-\$9.60
>50	2	\$0.50	\$0.50	\$0.40-\$0.60

TABLE III. DOCUMENTED CAPITAL COSTS FOR AIR STRIPPING SYSTEMS
(\$/GPM)

FLOW RATE (GPM)	SAMPLE SIZE (N)	MEDIAN	AVERAGE	COST RANGE
<10	26	\$5839	\$13778	\$1497-\$61364
10-50	11	\$1627	\$1641	\$683-\$2559
>50	2	\$534	\$534	\$511-\$556

TABLE IV. RATIOS OF ACTUAL VS. DESIGN PARAMETERS FOR
AIR STRIPPING SYSTEMS

	COUNT (N)	MEDIAN OF RATIOS	AVERAGE OF RATIOS	RANGE OF RATIOS
FLOW RATE	36	0.74	0.73	0.04 - 2.40
CAPITAL COST	36	1.36	3.95	0.42 - 25.0
O&M COST	35	1.38	3.48	0.42 - 24.6

NOTE: For the capital and O&M costs, the average ratio may be a misleading estimate of the typical ratio because of the skewed distributions. The median is the preferred and recommended estimate.

TABLE V. RAW COST DATA FOR LIQUID-PHASE
ACTIVATED CARBON ADSORPTION SYSTEM

Site	ACTUAL			DESIGN		
	Flowrate (GPM)	Capital Cost (\$/GPM)	O&M Cost (\$/1000 GAL)	Flowrate (GPM)	Capital Cost (\$/GPM)	O&M Cost (\$/1000 GAL)
MW-5	0.75	2,8141	170	0.5	4,2212	255
MW-14	2	26,866	144	2	16,866	144
NE-7	2	7,160	13	20	716	1.3
NE-20	0.5	1,200	46	0.5	1,200	46
NE-23	0.17	176,471	604	1	30,000	103

Removal Effectiveness

As indicated in Table VI, most air stripping systems achieved significant reductions of dissolved volatile organic concentrations. Benzene reductions were generally greater than 99%.

Fifteen air stripping systems also provided data on MTBE removal effectiveness (Table VI). Percent removal ranged from 55.6% to 99.9% with a median value of approximately 91%. Removal effectiveness for IPE was documented at three sites and ranged from 97.8% to 99.9%.

The air stripping systems generally met their design requirements of 99% removal of dissolved volatile hydrocarbon contaminants. However, as shown in Table VII, there were six exceptions noted. In five of the six cases shown, the problem was fouling of the packing with either biological growth or precipitated metal salts (probably iron hydroxide).

Fouling was found to be a common problem with the air stripping systems. Of the 55 air stripping systems listed in Appendix B, fouling was noted in 30 of these systems. For 21 of these 30 systems where fouling was noted, some type of fouling prevention or treatment was used (either antifouling pretreatment or periodic cleaning).

The information in Appendix B indicates that the treatment for fouling was effective in all cases, with one possible exception. The information given in Appendix B for site NE-6 does not show how well the treatment for fouling worked. The only data provided in the Appendix for that site show that performance was seriously affected by fouling and that treatment for fouling was

started. Of eight other systems where fouling occurred and where there was no specified treatment, four failed to meet design performance requirements.

It is clear that fouling often occurs in air stripping columns. However, with proper cleaning or pretreatment, air stripping systems can operate acceptably in services that would otherwise significantly degrade system performance.

All five carbon adsorption systems where cost and performance data were available were small units (Table VIII). Actual flows ranged from 0.5 to 2 gpm. Benzene reductions ranged from 85.1% to 99.9%. One datum is documented for MtBE at 87.2% removal. This same system removed 50% of the IPE in the feed.

It is intuitive that at any given site, treatment to effluent concentrations below 1 ppb will be more expensive than treatment to some higher concentration. However, statistical analysis of actual cost data (ANOVA linear regression) did not demonstrate a significant difference between treatment to concentrations above versus below 1 ppb benzene.

Both within and between treatment systems, sample variances were very high. The sources of variance among sites included multiple factors: varying influent and effluent concentrations, overdesign (flow rates less than design), analytical sources of error, a wide range of flow rates, and the use of benzene as the single indicator contaminant in evaluating treatment. For example, benzene concentrations in the influent varied from nondetectable to 29,000 ppb, and in the effluent ranged from nondetectable to 1,900 ppb.

TABLE VI. PERFORMANCE, PARAMETERS FOR AIR STRIPPING SYSTEMS

Site	Water Temperature Of	Air Temperature Of	Air-to-Water Ratio CFM/GPM	Benzene %Removal	Additives %Removal
MA-10(1)	55.4	84.2	37.3:1	99.5	--
MA-10(2)	59.9	82.4	100:1	--	--
MA-10(3)	57.2	82.4	75:1	--	--
MA-10(4)	57.2	87.8	85.7:1	99.2	--
MW-1	49.3	97.6	1,396:1	99.8	--
MW-6	53.3	95.0	233:1	>99.9	MtBE - 99.9
MW-7	49.0	91.7	2,478:1	99.9	--
MW-10	55.0	85.0	11.2:1	***	--
MW-13	55.0	69.0	115:1	99.6	--
NE-4	65.0	85.0	477:1	99.9	--
NE-6	59.0	74.5	20.4:1	26.9	--
NE-9	54.7	80.8	33:1	99.7	--
NE-18	62.3	77.2	29.4:1	>99.9	MtBE - >99.9, IPE - >99.9
NE-19	70.8	81.8	11:1	***	MtBE - 95.1
NE-21	57.5	87.0	5.5:1	96.1	MtBE - 62.0
NE-22	63.8	83.3	73.3:1	>99.9	MtBE - 76.0**
SC-1	81.1	78.0	40:1	>99.9	--
SC-2	73.0	89.0	43.5:1	>99.9	IPE - >99.9
SC-3	71.0	81.0	11:1	>99.9	IPE - 97.8
SC-4	70.0	87.0	52.6:1	***	MtBE - >99.9
SC-5	68.0	77.0	49.8:1	99.8	--

Note:

- * = No water quality data were available for MA-2, 3, 4, 5, 8, 9, 15, 16; MW-16
 ** = These values were calculated using one half of the appropriate detection limit
 *** = No calculations performed

TABLE VI. (CONCLUDED)

Site	Water Temperature Of	Air Temperature Of	Air-to-Water Ratio CFM/GPM	Benzene %Removal	Additives %Removal
SE-7	81.2	95.6	21.4:1	**	--
SE-18	82.7	97.0	10.4:1	98.6	MtBE 84.9
SE-22	82.4	90.2	352.1	99.7**	MtBE 90.9
SE-23	81.5	86.0	11.1:1	99.8**	--
SE-29	NA	NA	NA	**	--
SE-31	68.4	79.0	224:1	>99.9	MtBE >99.9
SE-32	81.5	93.8	60:1	99.6	MtBE 99.2**
SE-33(1)	78.8	79.1	35.4:1	>99.9	MTBE 99.8
SE-33(2)	78.8	97.1	37:1	**	MTBE 55.6
SE-35	82.4	86.0	47.8:1	>99.9	MTBE >99.9
SE-36	82.0	95.0	29.3:1	99.1	--
W-1	80.0	100.0	402.5:1	99.2	--
W-2	78.0	88.5	--	--	MtBE 78.6
W-4	76.5	93.8	18.9:1	--	--
W-14	68.0	84.2	111.8:1	--	--
W-18	68.0	75.0	100:1	**	--
W-31(1)	64.4	86.0	7.3:1	**	--
W-31(2)	64.4	95.0	0.4:1	**	--
W-38	67.6	84.7	8.05:1	98.9	MtBE 72.7
W-39	73.2	74.1	380:1	--	--

Note:

- * = No water quality data were available for W-11, 17, 19, 32, 35
 ** = These values were calculated using one half of the appropriate detection limit
 *** = No calculations performed
 NA = Not available

TABLE VII. SITES NOT ACHIEVING DESIGN EFFICIENCY

<u>SITE</u>	<u>DESIGN REMOVAL CRITERIA</u>	<u>ACTUAL REMOVAL ACHIEVED</u>	<u>COMMENTS</u>
MA-10(3)	99% for petroleum hydrocarbons	88.17% Average* for BTEX	iron and/or biological fouling of packing
MA-10(4)	99% for petroleum hydrocarbons	>98.9% Average for BTEX	iron and/or biological fouling of packing
MW-7	100% for petroleum hydrocarbons to nondetectable levels	96.9% Average or 2 ppb average BTEX concentration	high target removal
NE-6	99% for petroleum hydrocarbons	32.6% Average for BTEX	biological fouling of air stripper
NE-9	99% for petroleum hydrocarbons	92.1 Average for BTEX	iron and/or biological fouling of air stripper
NE-19	99% for petroleum hydrocarbons	92.09% Average for BTEX	iron bacteria fouling of treatment system

NOTE: *unable to find how calculation was accomplished

TABLE VIII. PERFORMANCE PARAMETERS FOR CARBON ADSORPTION SYSTEMS*

Site	Water Temperature Of	Air Temperature Of	Retention Time Min/Tank	Benzene %Removal	Additives %Removal
MW-5	55.0	85.0	73.3	>99.9 ¹	
MW-14	63.0	90.0	27.5	99.9 ¹	**
NE-7	82.0	96.0	27.5	99.9 ¹	
NE-20	58.0	80.0	80.0	85.1 ¹ 99.1 ²	MtBE - 87.2 ¹ , IPE - 50 ¹
NE-23	74.0	78.0	323.0	**	--

Notes:

- 1 = These removal values are based on the first of two carbon tanks in series
 2 = These removal values are based on the second of two carbon tanks in series
 * = No water quality data were available for MW-9, MW-12
 ** = Removal rate data not calculated

We discourage the use of data from individual sites for predicting treatment costs. However, the median values for actual costs derived from this database provide reasonable values for estimating treatment costs. The wide ranges associated with these data imply that any estimates based on this information can be viewed only as rough approximations.

CONCLUSIONS

1. Median operating and maintenance costs for air stripping systems in the range of 10 to 50 gpm were \$2.80 per thousand gallons. Median investment costs were \$1,627 per gpm.
2. For those air stripping systems operating below 1 gpm, the median operating and maintenance cost was \$6.40 per thousand gallons. The median investment cost was \$5,839. At flow rates below 1 gpm, costs per gallon were substantially greater, as would be expected.
3. For the two air stripping systems operating at rates higher than 50 gpm, the operating and maintenance costs were \$0.40 and \$0.60 per thousand gallons. Investment costs were \$511 and \$556 per gpm.
4. There was a considerable difference between the costs per gallon estimated for the design of the air stripping systems and the costs per gallon actually obtained in the field. The actual costs per gallon appear to be about a factor of 1.4 higher than those originally estimated. Part of the reason for this is that actual flow rates were often much less than the design flow rates.
5. There were only five carbon treatment systems in this survey where data on treatment effectiveness were available. Consequently, there was no attempt to statistically analyze the data. Actual flow rates for all five of these carbon adsorption systems were 2 gpm or less. At these low flow rates, the carbon treatment costs are comparable to air stripping costs at similar flow rates.

6. Benzene reductions ranged from 85.1% to 99.9% in the five carbon adsorption systems where cost and performance data were available. One datum is documented for MtBE at 87.2% removal. This same system removed 50% of the IPE in the feed.
7. Almost all air stripping systems achieved a high degree of removal of the dissolved volatile hydrocarbons in the water. Benzene removals were normally 99% or more.
8. In five of the six cases where air stripping design contaminant removal requirements were not met, fouling was responsible. Fouling was caused by biological growth or precipitated metal salts (probably iron hydroxide).
9. Fouling was found to be a common problem with the air stripping systems. Of the 55 air stripping system studied, fouling was noted in 30 of these systems. For 21 of these 30 systems where fouling was noted, some type of fouling prevention or treatment was used. Such treatment was generally successful.
10. Many of the air stripping systems were operated at considerably lower water flow rates than those for which they were designed. Consequently, in such cases the systems were usually able to exceed their design requirements for contaminant removal.
11. MTBE removal ranged from 55.6% to 99.9% with a median of 91% in the 15 systems where MTBE was treated by air stripping.
12. There were three sites listed in Table VI where IPE was shown to be removed with the air stripping systems. Removal rates for IPE ranged from 97.8% to 99.9%.

13. The major sources of variation in the data among sites include multiple factors: varying influent and effluent concentrations, overdesign (flow rates less than design), analytical sources of error, and a wide range of flow rates.
14. Because of the wide variability in the data, we discourage the use of data from individual sites for predicting treatment costs. However, the median values for actual costs derived from this data base provide reasonable values for estimating treatment costs.

APPENDIX A

UNIT COST CALCULATION PROCEDURES

AND

COST SUMMARY TABLES, AIR STRIPPING SYSTEMS

A-1



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Various design cost data presented throughout this report were calculated as follows:

$$\text{Unit Permitting Cost} \quad C_p = \frac{C_{tp}}{F_d}$$

where, C_p = Unit Permitting Cost
 F_d = Design Flow Rate
 C_{tp} = Total Permitting Cost from Appendices B or C

$$\text{Unit Annual Operating and Maintenance Costs} \quad C_o = \frac{C_{to}}{Q_d}$$

where, C_o = Unit Annual Operating Cost
 C_{to} = Total O&M cost from Appendices B or C
 Q_d = Total annual flow rate in 1,000's of gallons.

Actual cost data were calculated as follows:

Unit Permitting Cost

$$C_p = \frac{C_{tp}}{F_a}$$

and,

Unit Operating Costs

$$C_o = \frac{C_{to}}{Q_a}$$

where,

F_a = Actual Flow rate
 Q_a = 1,000's gallons treated per year

Site summary Tables I(a) and I(b) present cost data for air stripping systems designed to achieve two different levels of treatment effectiveness (<1 ppb and >1 ppb). Summary Tables II(a) and II(b) contain similar data for air stripping systems actually achieving the two different levels of treatment effectiveness.

TABLE I(A). COSTS FOR AIR STRIPPING SYSTEMS
(Based on Design Flowrate)

Costs for Systems Designed to Achieve Less than 1 ppb Benzene in Effluent

Site	Design Flowrate		Design		Permitting		Equipment and Construction		Total Initial Capital		Annual O&M*		Initial Date of Operation	
	GPM		\$/GPM		\$/GPM		\$/GPM		\$/GPM		\$/1000 GAL./Y.			
MA-2	9		--		--		2000		2000		1.1		11/84	
MA-9	50		40		120		480		640		1.8		10/86	
MA-10(1)	30		--		67		500		567		0.2		1984	
MA-10(2)	30		--		67		550		617		0.2		1984	
MA-10(3)	30		--		67		4990		557		0.2		1984	
MA-10(4)	30		--		67		490		557		0.2		1984	
MW-6	0.5		3,504		4,800		38,360		46,664		313		Summer 1986	
MW-7	2		876		1,200		11,702		13,778		104		2/87	
MW-10	2		876		1,200		13,829		15,905		109		8/17/84	
MW-13	15		117		224		1,870		2,210		9.6		8/86	
NE-4	50		41		40		1,136		1,216		1.3		9/9/86	
NE-18	5		100		300		7,200		7,600		23		6/30/86	
SC-2	3		833		600		3,113		4,546		0.7		4/30/85	
SC-3	3		667		600		3,512		4,779		3.3		7/24/85	
SE-7	28		--		3.6		851		855		1.4		--	
SE-18	22		--		--		1,496		1,496		2.6		8/86	
SE-23	16		62		6.2		2,250		2,319		3.7		11/5/86	
SE-29	30		30		7.0		646		683		1.9		--	
SE-32	30		--		--		997		997		2.6		12/84	
SE-35	17		118		--		1,824		1,941		3.7		9/6/85	
W-1	10		319		200		1,950		2,469		11		4/87	
W-2	60		--		--		543		543		0.6		9/86	
W-14	10		1,350		700		4,700		6,750		6.0		4/87	
W-38	30		--		67		900		967		1.0		2/87	
W-39	15		--		100		1,453		1,553		2.7		2/87	

TABLE I(B). COSTS FOR AIR STRIPPING SYSTEMS
(Based on Design Flowrate)

Costs for Systems Designed to Achieve Greater than 1 ppb Benzene in Effluent

Site	Design Flowrate	Design	\$/GPM	Permitting	\$/GPM	Equipment and Construction	\$/GPM	Total Initial Capital	Annual O&M*	Initial Date of Operation
	GPM								\$/1000 GAL	
MA-3	20	25		500		492		1,018	0.8	5/86
MA-4	60	8.3		100		195		303	0.1	3/87
MA-5	11	--		9		1,036		1,045	0.6	10/86
MA-8	5	--		400		2,300		2,700	11	10/86
MA-15	175	--		29		103		132	0.1	7/85
MA-16	175	--		34		115		149	0.1	6/84
MW-16	40	44		60		470		574	3.0	3/87
NE-6	10	200		300		3,570		4,070	4.8	4/85
NE-9	5	100		1,000		3,900		5,000	3.4	4/87
NE-19	25	32		100		840		972	1.3	4/86
NE-21	40	12		20		1,106		1,139	1.3	3/3/87
NE-22	10	75		150		1,545		1,770	0.1	1/87
SC-1	3.5	629		514		2,889		4,032	0.6	9/22/86
SC-4	4	550		450		1,671		2,671	1.6	1/85
SC-5	7	314		257		1,139		1,710	0.2	10/28/85
SE-22	4	--		--		5,184		5,184	13	9/86
SE-31	5	--		--		1,750		1,750	1.4	4/85
SE-33(1,2)	20	105		--		1,760		1,865	2.9	11/5/86
SE-36	50	36		--		452		488	1.2	4/15/87
W-17	5	--		--		1,430		1,430	0.3	5/19/86
W-18	60	54		101		683		838	--	3/86
W-19	60	--		--		877		877	--	1984

Notes: * = Operating and maintenance including monitoring
-- = Not available

TABLE II(A). COSTS FOR AIR STRIPPING SYSTEMS
(Based on Actual Flowrate)

Costs for Systems Actually Achieving Less than 1 ppb Benzene in Effluent

Site	Design Flowrate	Design	Permitting	Equipment and Construction	Total Initial Capital	Annual O&M*	Initial Date of Operation
	GPM	\$/GPM	\$/GPM	\$/GPM	\$/GPM	\$/1000 GAL.	
MA-10(1)	15	--	133	1,000	1,133	0.4	1984
MA-10(2)	6	--	333	2,750	3,083	0.9	1984
MA-10(3)	8	--	250	1,838	2,088	0.6	1984
MW-6	1.2	1,460	2,000	15,983	19,443	130	Summer 1986
MW-7	0.5	3,504	4,800	46,806	55,110	415	2/87
MW-10	2.5	701	960	11,063	12,724	87	8/17/84
NE-4	2	1,020	992	28,400	30,412	32	9/9/86
NE-19	11.5	70	217	1,826	2,113	2.8	4/86
NE-22	3.75	200	400	4,120	4,720	0.2	1/87
SC-2	4.5	556	400	2,075	3,031	0.5	4/30/85
SC-3	3	500	450	2,634	3,584	2.5	7/24/85
SC-4	3.8	579	474	1,759	2,812	1.7	1/85
SC-5	8	275	225	997	1,497	0.2	10/28/85
SE-7	32.4	--	3.1	735	739	1.2	--
SE-18	22.2	--	--	1,483	1,483	2.6	8/86
SE-22	3	--	--	6,913	6,913	18	9/86
SE-23	14.5	69	6.9	2,483	2,559	4.0	11/5/86
SE-29	30	30	7.0	646	683	1.9	--
SE-31	1.4	--	--	6,250	6,250	5.0	4/85
SE-32	14.3	--	--	2,091	2,091	5.4	12/84
SE-33(1,2)	16	131	--	2,200	2,331	3.7	11/5/86
SE-35	9.5	210	--	3,263	3,474	6.7	9/6/85
W-2	8.5	--	--	3,835	3,835	4.2	9/86
W-4	8.5	--	--	6,824	6,824	7.6	9/85
W-14	1.1	12,273	6,364	42,727	61,364	55	4/87
W-18	3.5	930	1,727	11,714	14,372	--	3/86
W-31(1,2)	270	--	--	511	511	0.4	5/84
W-39	0.8	--	1,875	27,250	29,125	50	2/87

TABLE II(B). COSTS FOR AIR STRIPPING SYSTEMS
(Based on Actual Flowrate)

Costs for Systems Achieving Greater than 1 ppb Benzene in Effluent

Site	Design Flowrate	Design	Permitting	Equipment and Construction	Total Initial Capital	Annual O&M*	Initial Date of Operation
	GPM	\$/GPM	\$/GPM	\$/GPM	\$/GPM	\$/1000 GAL	
MA-10(4)	7	--	286	2,100	2,386	0.7	1984
MW-1	0.95	1,844	3,537	25,324	30,705	127	4/23/87
MW-13	15	117	224	1,870	2,210	9.6	8/86
NE-6	7.5	267	400	4,760	5,427	6.4	4/85
NE-9	5.2	96	962	3,750	4,808	3.3	4/87
NE-18	3.6	139	417	10,000	10,556	32	6/30/86
NE-21	42	12	19	1,054	1,085	1.2	3/3/87
SC-1	5	440	360	2,022	2,822	0.4	9/22/86
SE-36	15	120	--	1,507	1,627	3.9	4/15/87
W-1	0.8	3,990	2,500	24,375	30,865	135	4/87
W-38	52.2	--	38	517	556	0.6	2/87

Notes: * = Operating and Maintenance, including monitoring

-- = Not available

APPENDIX B

SYSTEM DESCRIPTIONS, COSTS AND REMOVAL EFFECTIVENESS

FOR AIR STRIPPING SYSTEMS

B-1

SITE IDENTIFICATION -- MA-2

TECHNOLOGY -- AIR STRIPPING

<u>System Parameter</u>	<u>Design</u>	<u>Actual</u>
Tower Height	12.5'	
Packed Height	8.5'	
Tower Diameter	2.0'	
Packing Type	2" Tellerettes	
Water Temperature	55°F	
Air Temperature	Ambient	
Water Flow Rate	9 GPM	
Air Flow Rate	1000 CFM	
Air/Water Ratio	111:1 CFM/GPM	
Initial Date of Operation		11/84
Sampling Frequency		Monthly

Costs

Engineering Design	
Permitting	
Equipment	\$ 10,000
Piping	\$ 5,000
Site Preparation	\$ 2,000
Electrical	\$ 1,000
Pretreatment System	
Total Initial Costs	\$ 18,000
 Treatment System Operation	
Pretreatment System Operation	
Monitoring	\$ 3,600/year
Maintenance	\$ 2,400/year
Total Annual Costs	\$ 6,000/year

COMMENTS:

This site is an operating gasoline station in Pennsylvania.

MA -- 2

Water Quality

CONSTITUTENT	DESIGN			ACTUAL*				
	INF (ppb)	EFF (ppb)	Removal (%)	INF (ppb)	EFF (ppb)	Removal (%)	HTU (ft)	NTU
Benzene			<1.0					
Toluene								
Ethylbenzene								
Total Xylenes								
Petroleum Hydrocarbons			95					
EDB								
MTBE								
IPE								

Notes: * = No site visit was completed at this site

B-3

SITE IDENTIFICATION -- MA-3

TECHNOLOGY -- AIR STRIPPING

<u>System Parameter</u>	<u>Design</u>	<u>Actual</u>
Tower Height	17.0'	
Packed Height	14.0'	
Tower Diameter	1.0'	
Packing Type	#1/2 Tri-pack	
Water Temperature	55°F	
Air Temperature	Ambient	
Water Flow Rate	20 GPM	
Air Flow Rate	600 CFM	
Air/Water Ratio	30:1 CFM/GPM	
Initial Date of Operation		5/86
Sampling Frequency		Monthly

Costs

Engineering Design	\$ 500
Permitting	\$ 10,000
Equipment	\$ 5,750
Piping	
Site Preparation	\$ 600
Electrical	\$ 3,500
Pretreatment System	
Total Initial Costs	\$ 20,350
 Treatment System Operation	 \$ 700/year
Pretreatment System Operation	
Monitoring/Maintenance	\$ 7,200/year
Total Annual Costs	\$ 7,900/year

COMMENTS:

This site is an operating gasoline service station in New Jersey. GTI is testing for lead in the water discharge.

MA -- 3

Water Quality

CONSTITUTENT	DESIGN			ACTUAL*			HTU	NTU
	INF	EFF	Removal	INF	EFF	Removal		
	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	(ft)	

Benzene

Toluene

Ethylbenzene

Total Xylenes

Petroleum Hydrocarbons 99

EDB

MTBE

IPE

Notes: * = No site visit was completed at the site

B-5



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SITE IDENTIFICATION -- MA-4

TECHNOLOGY -- AIR STRIPPING

<u>System Parameter</u>	<u>Design</u>	<u>Actual</u>
Tower Height	12.5'	
Packed Height	8.5'	
Tower Diameter	2.0'	
Packing Type	#1 Jaeger Tri-pack	
Water Temperature	55°F	
Air Temperature	Ambient	
Water Flow Rate	60 GPM	
Air Flow Rate	600 CFM	
Air/Water Ratio	10:1 CFM/GPM	
Initial Date of Operation		3/87
Sampling Frequency		

Costs

Engineering Design	\$ 500
Permitting	\$ 6,000
Equipment	\$ 8,400
Piping	\$ 300
Site Preparation	\$ 3,000
Electrical	
Pretreatment System	
Total Initial Costs	\$ 18,200
 Treatment System Operation	 \$ 300/year
Pretreatment System Operation	
Monitoring/Maintenance	\$ 2,040/year
Total Annual Costs	\$ 2,340/year

COMMENTS:

This site is an operating gasoline station in Pennsylvania.

MA -- 4

Water Quality

CONSTITUTENT	DESIGN			ACTUAL*			HTU	NTU
	INF	EFF	Removal	INF	EFF	Removal		
	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	(ft)	

Benzene

Toluene

Ethylbenzene

Total Xylenes

Petroleum Hydrocarbons 99

EDB

MTBE

IPE

Notes: No site visit was completed at this site

B-7



Documents

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SITE IDENTIFICATION -- MA-5

TECHNOLOGY -- AIR STRIPPING

<u>System Parameter</u>	<u>Design</u>	<u>Actual</u>
Tower Height	17.0'	
Packed Height	14.0'	
Tower Diameter	1.0'	
Packing Type	#1 Tri-pack	
Water Temperature	55°F	
Air Temperature	Ambient	
Water Flow Rate	11 GPM	
Air Flow Rate	400 CFM	
Air/Water Ratio	36:1 CFM/GPM	
Initial Date of Operation		10/86
Sampling Frequency		Monthly

Costs

Engineering Design	
Permitting	\$ 100
Equipment	\$ 6,000
Piping	\$ 400
Site Preparation	\$ 3,000
Electrical	\$ 2,000
Pretreatment System	
Total Initial Costs	\$ 11,500
 Treatment System Operation	
Pretreatment System Operation	
Monitoring	\$ 2,400/year
Maintenance	\$ 1,200/year
Total Annual Costs	\$ 3,600/year

COMMENTS:

This site is an operating gasoline service station.

MA -- 5

Water Quality

CONSTITUTENT	DESIGN			ACTUAL*			HTU	NTU
	INF	EFF	Removal	INF	EFF	Removal		
	(ppb)	(ppb)	(%)	(ppb)	(ppb)	(%)	(ft)	
Benzene								
Toluene								
Ethylbenzene								
Total Xylenes								
Petroleum Hydrocarbons			>99%					
EDB								
MTBE								
IPE								

Notes: * = No site visit was completed at this site

SITE IDENTIFICATION -- MA-8

TECHNOLOGY -- AIR STRIPPING

<u>System Parameter</u>	<u>Design</u>	<u>Actual</u>
Tower Height	17.0'	
Packed Height	14.0'	
Tower Diameter	1.0'	
Packing Type	#1 Tri-pack	
Water Temperature	55°F	
Air Temperature	Ambient	
Water Flow Rate	5 GPM	
Air Flow Rate	600 CFM	
Air/Water Ratio	120:1 CFM/GPM	
Initial Date of Operation		10/86
Sampling Frequency		Monthly; Bi-monthly for December, January and February of 1986

Costs

Engineering Design	
Permitting	\$ 2,000
Equipment	\$ 6,000
Piping	\$ 500
Site Preparation	\$ 4,000
Electrical	\$ 1,000
Pretreatment System	
Total Initial Cost	\$ 13,500

Treatment System Operation	
Pretreatment System Operation	
Monitoring	
Maintenance	
Total Annual Cost	\$ 30,000/year

COMMENTS:

This site is an operating gasoline station in Maryland. This job was initiated as an emergency response.