

# Treating MTBE-Impacted Drinking Water Using Granular Activated Carbon

*Report Written for:*

The California MTBE Research Partnership

By:

Daniel N. Creek, P.E.

James M. Davidson, P.G.

Alpine Environmental, Inc.

December 2001

Published by the  
Center for Groundwater Restoration and Protection  
National Water Research Institute

NWRI-01-05

10500 Ellis Avenue ♦ P.O. Box 20865  
Fountain Valley, California 92728-0865  
(714) 378-3278 ♦ Fax: (714) 378-3375  
[www.NWRI-USA.org](http://www.NWRI-USA.org)

## **Limitations**

---

This document was prepared by Alpine Environmental, Inc (Alpine) and is intended for use by members of the California MTBE Research Partnership (Partnership) pursuant to the Partnership Agreement. Neither Alpine nor the Partnership warrants, guarantees, or attests to the accuracy or completeness of the data, interpretations, practices, conclusions, suggestions, or recommendations contained herein. Use of this document, or reliance on any information contained herein, by any party or entity other than members of the Partnership, is at the sole risk of such parties or entities.



## **Acknowledgements**

---

This report was prepared by Daniel N. Creek, P.E. and James M. Davidson, P.G. of Alpine Environmental, Inc. (Fort Collins, Colorado). The authors would like to thank the California MTBE Research Partnership and the National Water Research Institute for sponsoring this work. Many members of the Partnership's Research Advisory Committee provided valuable support and review of this work, for which the authors are grateful. Thanks also go to the many engineers, scientists, and manufacturer representatives who improved this report by sharing their documents, data, and time. In particular, the authors would like to thank Mel Suffet, Tom Shih, and Medhi Wangpaichitr of the University of California, Los Angeles; Neil Megonnell of Calgon Carbon Corporation; and Bill Reetz of the Kansas Department of Health and Environment. The authors also want to recognize the efforts of Gina Melin of the National Water Research Institute and Tim Hogan of Tim Hogan Design, who edited and designed this report.



## California MTBE Research Partnership

---

The California MTBE Research Partnership is comprised of the following individuals:

### Steering Committee

Mark Beuhler, Chair  
*Metropolitan Water District  
of Southern California*

Tracy Hemmeter,  
*Santa Clara Valley Water District*  
Dave Smith, *BP*  
Mike Wang,  
*Western States Petroleum Association*

### Research Advisory Committee

Walter Weber, Jr., Chair  
*University of Michigan at Ann Arbor*

Rey Rodriguez,  
Chair, Source Water Protection Subcommittee  
*H<sub>2</sub>O R<sup>2</sup> Consulting Engineers, Inc.*

Scott Tenney,  
Chair, Treatability Subcommittee  
*Exxon Mobil*

Rich Atwater, *Inland Empire Utilities Agency*  
Bruce Bauman, *American Petroleum Institute*  
Ivo Bergsohn, *South Tahoe Public Utilities District*  
Tim Buscheck, *Chevron Products Company*  
David Camille, *Tosco*  
Robert Cheng, *Long Beach Water Department*  
Chi-Su Chou, *Consultant*  
Krista Clark, *Association of California Water Agencies*  
Mike Cooper, *Placer Co.*  
Daniel Creek, *Alpine Environmental, Inc.*  
James Crowley, *Santa Clara Valley Water District*  
James Davidson, *Alpine Environmental, Inc.*  
Marshall Davis,  
*Metropolitan Water District of Southern California*  
Rula Deeb, *Malcolm Pirnie, Inc.*  
Shahla Farahnak,  
*State Water Resources Control Board*  
Jack Fraim, *Chevron*  
John Gaston, *CH2M Hill*  
Don Gilson, *Chevron Products Co.*  
John Gustafson, *Equilon, Inc.*  
Elliot Heide, *McClintock, Weston, Bens*  
Roy Hodgen, *Lyondell Chemical Company*

Rick Hydrick, *South Tahoe Public Utilities District*  
Steven Inn, *Alameda County Water District*  
Michael Kavanaugh, *Malcolm Pirnie, Inc.*  
Charles Kish, *Riverview Water District*  
John Kneiss, *Oxygenated Fuel Association*  
Sun Liang,  
*Metropolitan Water District of Southern California*  
Ronald Linsky, *National Water Research Institute*  
Ernie Lory, *U.S. Naval Facilities Engineering*  
Dave McKinney, *Shell*  
Ralph Moran, *BP*  
Stephen Morse,  
*Regional Water Quality Control Board,  
San Francisco Region*  
David Pierce,  
*Chevron Research and Technology Company*  
Roger Pierno, *Santa Clara Valley Water District*  
Dave Ramsden, *GZA, GeoEnvironmental, Inc.*  
Melinda Rho,  
*Los Angeles Department of Water and Power*  
Richard Sakaji,  
*California Department of Health Services*  
Dick Sloan, *Lyondell Chemical Company*  
Curt Stanley, *Equilon, Inc.*  
Paul Sun, *Equilon, Inc.*  
Martin Varga, *Kern County Water Agency*  
Christine White, *Equiva Services, LLC.*  
Ken Williams,  
*Regional Water Quality Control Board,  
Santa Ana Region*  
Jeff Wilson, *Western States Petroleum Association*  
Dick Woodward, *Sierra Environmental Services, Inc.*  
Nira Yamachika, *Orange County Water District*



<b>1.0 Introduction</b> .....	1
1.1 Objectives of this Report .....	2
1.2 Report Overview .....	2
<b>2.0 Column-testing Methods</b> .....	5
2.1 Overview of Column-testing Programs .....	5
2.2 Rapid Small-scale Column Tests .....	6
2.2.1 RSSCT Methodology and Scaling Relationships .....	6
2.2.2 Testing Materials .....	7
2.2.3 Experimental Testing Matrix .....	8
2.2.4 Analytical Methods .....	8
2.2.5 QA/QC Procedures .....	9
2.3 Accelerated Column Tests .....	9
2.3.1 ACT Methodology and Scaling Relationships .....	9
2.3.2 Testing Materials .....	10
2.3.3 Experimental Testing Matrix .....	11
2.3.4 Analytical Methods .....	11
2.3.5 QA/QC Procedures .....	11
<b>3.0 Results of Column Testing</b> .....	13
3.1 Impact of Background Water Quality .....	14
3.2 Effect of Influent MTBE Concentration on Breakthrough Curves .....	16
3.3 Impact of EBCT on MTBE Breakthrough .....	17
3.4 Impact of BTX Load on MTBE Breakthrough .....	20
3.5 Impact of TBA Load on MTBE Breakthrough .....	22
3.6 Comparison of Coconut Shell GAC versus Coal-based GAC .....	23
3.7 Comparison of RSSCT and ACT Methodology .....	24
3.8 Summary .....	27
<b>4.0 Cost Estimates for Full-scale Systems</b> .....	29
4.1 Cost-estimating Assumptions .....	29
4.2 Discussion of Cost Estimates .....	32
4.2.1 Impact of Influent MTBE Concentration .....	33
4.2.2 Impact of Background Water Quality .....	34
4.2.3 Impact of BTX .....	35
4.2.4 Impact of Flow Rate .....	35
4.2.5 Impact of System Design Life .....	36

<b>5.0 Case Studies of Full-scale GAC Systems</b> .....	37
5.1 Case Study A: Public-supply Wells, California .....	37
5.2 Case Study B: Public-supply Wells, Kansas .....	38
5.3 Summary .....	39
<b>6.0 Conclusions</b> .....	41
6.1 Comparison of Computer Modeling and Column Testing .....	41
6.2 Comparison of Column Testing and Full-scale Water Treatment .....	41
6.3 Impact of Treatment Conditions on GAC Performance and Cost .....	42
6.3.1 Background Water Quality .....	42
6.3.2 Influent MTBE Concentrations .....	43
6.3.3 EBCT .....	43
6.3.4 BTX Load .....	44
6.3.5 TBA Load .....	44
6.3.6 GAC Type .....	45
6.4 Cost Comparison to Other Technologies .....	45
6.5 Summary and Future Considerations .....	48
<b>7.0 References</b> .....	51
<b>Appendices</b>	
Appendix A: GAC System Cost Estimates .....	53
Appendix B: GAC System Case Studies .....	61

## Tables

---

Table 2.1	Analysis of Water-quality Parameters for RSSCTs . . . . .	8
Table 2.2	Experimental Testing Matrix for RSSCTs. . . . .	8
Table 2.3	Analysis of Water-quality Parameters for ACTs. . . . .	10
Table 2.4	Experimental Testing Matrix for ACTs . . . . .	11
Table 3.1	Breakthrough Usage Rates from Column Testing . . . . .	14
Table 3.2	Comparison of Breakthrough Usage Rates for Different Source Waters: PCB GAC, 10 minute EBCT, RSSCT Method. . . . .	15
Table 3.3	Comparison of Breakthrough Usage Rates for Different EBCTs: RSSCT Method. . . . .	20
Table 3.4	Comparison of Breakthrough Usage Rates with and without BTX: RSSCT Method . . . . .	21
Table 4.1	GAC Usage Rate Assumptions for Principal MTBE Treatment Scenarios . .	30
Table 4.2	GAC Usage Rate Assumptions for Sensitivity Analysis Scenarios . . . . .	30
Table 4.3	Cost Estimates for Principal MTBE Treatment Scenarios . . . . .	32
Table 4.4	Cost Estimates for Sensitivity Analysis . . . . .	33
Table 6.1	Comparison of Reference Cost Estimates for Different Technologies . . . .	46
Table A-1	Example Cost Spreadsheet: Estimated Costs for Carbon Adsorption . . . .	54
Table A-2	Predicted Carbon Usage Rates, Vessel Life, and Changeout Frequencies: Primary MTBE Treatment Scenarios . . . . .	55
Table A-3	Predicted Carbon Usage Rates, Vessel Life, and Changeout Frequencies: Sensitivity Analysis Scenarios . . . . .	56
Table A-4	Estimated Labor Costs for GAC Systems: Principal MTBE Treatment Scenarios . . . . .	57
Table A-5	Estimated Labor Costs for GAC Systems: Sensitivity Analysis Scenarios. . . . .	58



Figure 3.1	MTBE breakthrough for different water sources. Influent: MTBE at 20 to 50 ppb. ....	13
Figure 3.2	MTBE breakthrough for different influent concentrations. Influent: Tahoe groundwater with 20 or 1,950 ppb MTBE.....	16
Figure 3.3	MTBE breakthrough for different influent concentrations. Influent: Arcadia groundwater with 50 or 220 ppb MTBE.....	17
Figure 3.4	MTBE breakthrough for different EBCTs. Influent: Tahoe groundwater with ~2,000 ppb MTBE.....	18
Figure 3.5	MTBE breakthrough for different EBCTs. Influent: Arcadia groundwater with ~200 ppb MTBE.....	28
Figure 3.6	MTBE breakthrough for different EBCTs. Influent: Lake Perris surface water with 20 ppb MTBE. ....	19
Figure 3.7	MTBE breakthrough with and without BTX. Influent: Tahoe groundwater with ~2,000 ppb MTBE.....	21
Figure 3.8	MTBE breakthrough with and without BTX. Influent: Lake Perris surface water with 20 ppb MTBE. ....	22
Figure 3.9	MTBE breakthrough with and without 100 ppb TBA. Influent: Arcadia groundwater with 50 to 1,030 ppb MTBE. ....	23
Figure 3.10	MTBE breakthrough for different GAC types. Influent: Arcadia groundwater with 200 to 1,030 ppb MTBE, 100 ppb TBA.....	24
Figure 3.11	MTBE breakthrough for ACT and RSSCT. Influent: MTBE at 20 to 25 ppb in Lake Perris surface water. ....	25
Figure 3.12	MTBE breakthrough for ACT and RSSCT. Influent: MTBE at 20 to 22 ppb in Tahoe groundwater.....	26
Figure 4.1	Predicted carbon usage rate versus influent MTBE concentration (low to moderate NOM fouling, no other contaminants present).....	31
Figure 4.2	Estimated unit treatment cost versus influent MTBE concentration (low to moderate NOM fouling, no other contaminants present).....	34
Figure 4.3	Estimated unit treatment cost versus system flow capacity (low to moderate NOM fouling, no other contaminants present).....	35
Figure B-1	GAC system for public-supply wells, Kansas site. ....	64



## Acronyms

---

ACT	Accelerated column testing
AOP	Advanced oxidation process
ASTM	American Society for Testing and Materials
BTX	Benzene, toluene, and xylenes
EBCT	Empty bed contact time
EPA	Environmental Protection Agency
GAC	Granular activated carbon
GC	Gas chromatography
GC/MS	Gas chromatography/mass spectrometry
gpm	Gallons per minute
L	Liter
L/g	Liters per gram
mL	Milliliter
MTBE	Methyl tertiary butyl ether
NOM	Natural organic matter
O&M	Operation and maintenance
O&P	Overhead and profit
ppb	Parts per billion
ppm	Parts per million
QA/QC	Quality assurance/quality control
RSSCT	Rapid small-scale column testing
TBA	Tertiary butyl alcohol
TDS	Total dissolved solids
TOC	Total organic carbon
UCLA	University of California, Los Angeles
UST	Underground storage tank
UV	Ultraviolet
VOC	Volatile organic compounds



## 1.0 Introduction

---

Methyl tertiary butyl ether (MTBE) is an oxygenate compound added to gasoline to enhance octane levels and meet the oxygen requirements mandated in the Clean Air Act amendments. Because of MTBE's particular physio-chemical properties (such as high solubility and low soil-to-water partitioning coefficient), it is somewhat difficult to remove from water. With this in mind, the California MTBE Research Partnership (Partnership) was formed to evaluate the treatment of MTBE in drinking water. Previously, the Partnership (2000) completed a detailed evaluation and comparison of four water-treatment technologies considered promising for MTBE treatment; granular activated carbon (GAC) is one of those four technologies. This report summarizes the Partnership's research on the use of GAC for MTBE removal from drinking water.

Since 1998, the Partnership has sponsored a series of studies related to GAC performance for MTBE removal. These studies include:

- A preliminary Treatability report that compared GAC with three other water treatment technologies (Partnership, 2000).
- Rapid small-scale column testing (RSSCT) performed by the University of California, Los Angeles (UCLA).
- Accelerated column testing (ACT) performed by Calgon Carbon Corporation.

The Partnership's GAC research program was designed to allow for the comparison and correlation of the separate studies. The Treatability report prepared by the Partnership (2000) includes in-depth analyses of GAC, air stripping, advanced oxidation processes (AOP), and synthetic resin sorbents for MTBE removal or destruction. The GAC portion of that report presents the results of computer modeling and cost estimates for a range of MTBE-treatment scenarios. That Treatability report also includes recommendations for the further evaluation of GAC, including dynamic column studies for a detailed analysis of the numerous variables that impact GAC performance for MTBE removal.

Based on recommendations made in the Treatability report (Partnership, 2000), two separate column test studies were then sponsored by the Partnership and performed by UCLA and Calgon Carbon Corporation. These column studies used both the RSSCT and ACT methods for evaluating GAC performance. The variables that were evaluated via column testing include:

- Background water quality (natural organic matter [NOM]; benzene, toluene, and xylenes [BTX]; tertiary butyl alcohol [TBA]).
- GAC type (coconut shell, coal-based).
- Empty bed contact time (EBCT).
- Influent MTBE concentration.

The results of these new column tests represent a substantial quantity of new and important information regarding GAC performance for MTBE removal. As designed, these results are particularly useful because they can verify the computer modeling and cost estimates previously presented in the Treatability report (Partnership, 2000).

This report is the final step of the Partnership's GAC research program, and it presents a summary analysis of the three aforementioned GAC studies. While the primary focus is on new data from the column test studies, this report also presents and analyzes the results of full-scale GAC-system case studies. In addition to GAC performance results, detailed cost estimates are presented for a wide range of treatment scenarios, allowing the reader to better predict GAC performance and cost under site-specific conditions for treating MTBE-impacted drinking water.

## **1.1 Objectives of this Report**

The primary purpose of this report is to compile and analyze data from dynamic column testing and full-scale case studies to present a comprehensive and reliable evaluation of GAC performance for removing MTBE from public drinking-water supplies. The data presented herein can readily be used to predict GAC performance and cost under a wide variety of field conditions. Specific objectives of this report include:

- Present GAC performance data (GAC usage rates, MTBE breakthrough curves) for a range of influent MTBE conditions.
- Compare and contrast performance data for different GAC types (coconut shell, coal-based), background waters (NOM effects), and testing conditions (varying EBCTs, RSSCTs versus ACTs).
- Evaluate the impacts of BTX and TBA on GAC performance for MTBE removal.
- Modify cost estimates presented in the Partnership's Treatability report (2000), based on the results of dynamic column testing.
- Compile and analyze recently documented field case studies for MTBE treatment using GAC.

## **1.2 Report Overview**

This report is organized into the following primary sections:

- Section 2.* Column testing methods, including an overview of column test studies and specific methods used for column testing and chemical analysis.
- Section 3.* Results of column testing, including qualitative and quantitative evaluations of GAC performance as affected by background water quality, influent MTBE concentrations, EBCT, BTX and TBA, and GAC source materials.

*Section 4.* Cost estimates for full-scale systems, based on the results of dynamic column testing.

*Section 5.* Case studies of full-scale GAC systems.

*Section 6.* Conclusions.

Two appendices are also included with this report. Appendix A contains detailed backup information for the GAC system cost estimates presented in Section 4. Appendix B is a summary of two case studies in which GAC was used at full-scale for the treatment of MTBE-impacted drinking water.



## 2.0 Column-testing Methods

---

This section presents an overview of the column testing methodologies used for the Partnership's GAC research. Included are discussions of the column testing methods, the analytical procedures, and the quality assurance/quality control (QA/QC) measures used in the testing program. Matrices of testing parameters are also presented to clarify the scope of the column studies. Further details regarding methodologies used can be found in Partnership-sponsored research reports prepared by UCLA (2001) and Calgon Carbon Corporation (2000).

### 2.1 Overview of Column-testing Programs

To achieve the research objectives outlined in Section 1.1, dynamic column testing was performed using two different methods, RSSCT and ACT. The specific objectives for the column testing were to obtain reliable performance data that evaluates the:

- Effectiveness of GAC for the removal of varying MTBE-influent concentrations.
- Effects of NOM (different source waters).
- Different testing conditions (varying EBCTs, RSSCTs versus ACTs).
- Effectiveness of different GAC types (coconut shell GAC, coal-based GAC).
- Impacts of BTX and TBA on MBTE removal.

Previous computer modeling and cost estimates (Partnership, 2000) determined that, under most circumstances, MTBE removal using GAC is likely to be the most cost-competitive with other technologies (e.g., air stripping) at relatively low influent concentrations. As such, this research focused most of the testing on influent MTBE levels of approximately 20 parts per billion (ppb); however, several tests were also performed at 200 and 2,000 ppb to evaluate GAC effectiveness at these higher concentrations.

To evaluate the effectiveness of GAC for different background water-quality conditions, column testing was performed using waters from three municipal drinking-water supplies in California. These waters, which are described in greater detail later in this report, were selected to represent a range of background water-quality conditions; both groundwater and surface water sources were tested. Tests using similar influent MTBE concentrations were performed with each of the source waters to allow for a direct comparison of background NOM effects.

The column testing for this study also evaluated variations in testing procedures. EBCT is an important design parameter for full-scale systems, though it is not yet well understood for the design of MTBE removal systems. As such, column tests were performed with EBCTs of 10 and 20 minutes to span the likely range of effective and practical EBCTs. Tests using similar influent MTBE concentrations were performed to directly compare EBCT effects. In

addition, as mentioned previously, two different column-testing methods, the RSSCT and ACT, were used to evaluate GAC performance as predicted by different testing procedures.

The effectiveness of different types of GAC was evaluated by testing both coconut shell GAC and coal-based GAC. Based on established MTBE isotherms, coconut shell GAC is likely to be more cost-effective than coal-based GAC (Partnership, 2000). As such, this research focused primarily on evaluating coconut shell GAC. Carbon from two different commercial sources (i.e., Calgon Carbon Corporation and U.S. Filter/Westates) was tested to account for potential variations in coconut-shell source materials. In addition, two tests using coal-based GAC were performed to compare GAC-type effectiveness.

Because other synthetic organic compounds are often present in MTBE-impacted waters, influent waters for certain tests were spiked with several of the most prevalent compounds. Column tests were performed with BTX and TBA in the influent waters.

The data generated from this research allow for numerous quantitative and qualitative comparisons to be made. As described above, the data allow for evaluating background water quality, influent MTBE concentration, EBCT, column testing methods, and the impacts of BTX and TBA. Details regarding how the data were generated are presented in the following sections.

## **2.2 Rapid Small-scale Column Tests**

UCLA performed RSSCTs to model the dynamics of MTBE adsorption in GAC under field-scale conditions. This section briefly describes RSSCT methodology, in addition to the specific materials, analytical methods, and QA/QC procedures used in the study. At the end of this section, the matrix of experimental testing parameters evaluated by the RSSCT study is presented. The RSSCT method, which is currently under consideration as an American Society for Testing and Materials (ASTM) standard for GAC testing, is described in full detail by Crittenden et al. (1989).

### **2.2.1 RSSCT Methodology and Scaling Relationships**

The RSSCT method uses a scaled-down column of GAC to remove contaminants from a stream of water. A constant influent concentration is injected in the upstream end of the column at a defined and steady flow rate; on the effluent end, samples are collected for analytical testing. With the results of analytical testing of the column effluent, a contaminant breakthrough curve is established. The results of RSSCTs allow for the evaluation of full-scale design and operating parameters, such as EBCT, and the prediction of full-scale GAC usage rates.

To relate RSSCT results to full-scale field conditions, the column tests must be designed via scaling relationships. For this study, it was assumed that MTBE adsorption to GAC is a

diffusion-controlled process, which allows the constant diffusivity scaling relationship to be used:

$$\text{EBCT}(\text{ss}) / \text{EBCT}(\text{fs}) = [\text{d}(\text{ss}) / \text{d}(\text{fs})]^2 = \text{t}(\text{ss}) / \text{t}(\text{fs})$$

Where

- EBCT = empty bed contact time.
- d = mean diameter of GAC particles.
- t = time required for breakthrough.
- (ss) and (fs) refer to small-scale and full-scale columns, respectively.

All RSSCTs for this study were designed using this scaling relationship, which is discussed in detail by Crittenden et al. (1989). Simulated EBCTs of 10 and 20 minutes were modeled by the RSSCTs.

### **2.2.2 Testing Materials**

Three different carbon types were used for this testing program:

- Calgon PCB coconut shell carbon.
- Calgon F-600 coal-based carbon.
- US Filter/Westates CC-602 coconut shell carbon.

The GAC samples received from the vendors were crushed with a pestle and screened using the United States No. 60 x 80 mesh size sieve tray. UCLA followed GAC preparation procedures outlined by Crittenden et al. (1989).

Three different source waters were used for the RSSCT study. Groundwater from the Arcadia well field in Santa Monica, California (Arcadia groundwater), and South Tahoe Public Utility District (Tahoe groundwater) were tested in addition to surface water from Lake Perris in the Metropolitan Water District of Southern California (Lake Perris surface water). Results of background chemical testing on these waters are presented in Table 2.1. It is evident from these data that total organic carbon (TOC) and electrical conductivity vary substantially between the three waters. These differences are attributed to the variation in background NOM in the waters.

Details on laboratory-grade MTBE and other chemicals used for spiking influent water are described elsewhere (UCLA, 2001).

**Table 2.1**  
Analysis of Water-quality Parameters for RSSCTs

Water Source	pH	Conductivity (µmhos/cm)	TOC (ppm)	Background MTBE (ppb)	Background TBA (ppb)
Tahoe Groundwater	7.9	77	0.2	<1	<1
Arcadia Groundwater	7.8	1,130	1	<1	<1
Lake Perris Surface Water	8.5	640	3.2	Not Available	<1

### 2.2.3 Experimental Testing Matrix

UCLA completed a total of 16 RSSCTs for this project, closely following a testing matrix designed by the California MTBE Research Partnership to fulfill the research objectives set forth in Section 2.1. The final experimental testing matrix, which presents the primary testing conditions of each RSSCT, is presented in Table 2.2. As shown, the RSSCTs are designated with test numbers R1 through R16.

**Table 2.2**  
Experimental Testing Matrix for RSSCTs

Water Source	Test #	Influent MTBE (ppb)	GAC Vendor/Product	EBCT (min)	Other Testing Conditions
Tahoe Groundwater	R1	1,964	US Filter/CC-602	10	1,977 µg/L BTX*
	R2	1,950	US Filter/CC-602	10	
	R3	2,052	US Filter/CC-602	20	
	R4	1,958	US Filter/CC-602	10	
	R5	20	Calgon/PCB	10	
Arcadia Groundwater	R6	220	Calgon/PCB	10	100 µg/L TBA 300 µg/L BTX** 100 µg/L TBA
	R7	209	Calgon/PCB	20	
	R8	50	Calgon/PCB	10	
	R9	1,030	Calgon/PCB	10	
	R10	20	Calgon/F-600	10	
	R11	200	Calgon/F-600	20	
Lake Perris Surface Water	R12	20	US Filter/CC-602	10	300 µg/L BTX**
	R13	20	US Filter/CC-602	20	
	R14	20	Calgon/PCB	10	
	R15	20	Calgon/PCB	20	
	R16	20	Calgon/PCB	20	

\* 512 µg/L benzene, 540 µg/L toluene, and 925 µg/L p-xylene.  
\*\* Component breakdown unknown.

### 2.2.4 Analytical Methods

The RSSCT study used on-line monitoring equipment for analyzing volatile organic compounds (VOCs) in the effluent. Samples were analyzed every 30 to 60 minutes until 100-percent breakthrough was reached or exceeded.

During column testing, MTBE was analyzed according to modified United States Environmental Protection Agency (EPA) Method 524 using a purge-and-trap unit followed by gas chromatography (GC) with a flame ionization detector. The MTBE detection limit was 1 ppb

for a sample size of 5 milliliters (mL). Other VOCs were analyzed by EPA Method 524 using gas chromatography/mass spectrometry (GC/MS).

A fraction collector was used for the off-line monitoring of temperature, pH, ultraviolet (UV), and TOC. The analyzer had a detection limit of 0.04 parts per million (ppm) for a sample size of 1 mL. The pH was measured using an Orion pH meter (Model 925). UV-absorbance measurements were completed using EPA method 5910.B. TOC was analyzed by the Standard EPA Method 5310.C using UV-promoted persulfate oxidation and infrared spectrometry

Further details regarding analytical testing methods, including specific testing equipment, used are presented elsewhere (UCLA, 2001).

### **2.2.5 QA/QC Procedures**

All RSSCT analytical testing was performed under strict in-house QA/QC procedures. Prior to RSSCT testing, each of the source waters was analyzed in triplicate for MTBE and other VOCs. For these analyses, and those performed on effluent samples, equipment calibrations were performed depending on the range of the expected MTBE concentration. UCLA reports that the coefficient of linear correlation ( $r$ ) for all calibrations was greater than 0.998 (UCLA, 2001).

UCLA used a maximum holding time of 7 days for all VOCs, including MTBE. Prior to analysis, samples were kept headspace-free and refrigerated at 4°C. All samples were collected in glass vials with Teflon-coated septum and screw-top caps. Holding times and QA/QC procedures for other chemical parameters are presented elsewhere (UCLA, 2001).

## **2.3 Accelerated Column Tests**

### **2.3.1 ACT Methodology and Scaling Relationships**

Calgon's ACT procedure is similar in many ways to the RSSCT, with its primary purpose being to model large-scale adsorption processes using small-scale and rapid testing procedures. Compared to the RSSCT, the ACT uses a higher pressure gradient across the column, a smaller mesh-size carbon, and a smaller diameter column, all of which allow the ACT to be conducted in shorter times and with less water.

The exponent used in the ACT scaling equations is determined experimentally prior to testing, in contrast to the RSSCT, in which the exponent is pre-selected based on the assumption of constant diffusivity or proportional diffusivity at different particle sizes (Crittenden et al., 1991). For the ACT, several preliminary column tests must be performed for each GAC type to determine the scaling factor.

With the scaling factor known, the simulated full-scale time on-line — which allows for the calculation of GAC usage rate — can be determined using the following equation:

$$\text{Simulated days on line/ACT days on-line} = [d(\text{fs})/d(\text{ss})]^\alpha$$

Where

- $d(\text{fs})$  and  $d(\text{ss})$  represent the mean particle diameters for full-scale carbon particles and small-scale carbon particles, respectively.
- Alpha ( $\alpha$ ) is the experimentally determined scale factor that is the basis for the ACT scale-up.

As reported in greater detail by Calgon (2000), the scaling exponent, alpha, is determined by preliminary column testing of GAC at three mesh sizes, namely 60 x 100, 80 x 200, and 100 x 325. The alpha factor for this study was determined to be 1.1. The two ACTs performed for this research simulated a full-scale carbon vessel with a 7.72-foot bed depth and a 10-foot diameter operating at 227-gallons per minute (gpm). Both ACTs simulated a 20-minute EBCT.

### 2.3.2 Testing Materials

A single carbon type was used for the ACT study (i.e., Calgon PCB coconut shell carbon). The PCB GAC samples were crushed and screened using the United States No. 100 x 325 mesh-size sieve tray, simulating 12 x 30 mesh GAC at full-scale. Calgon (2000) presents detailed GAC data on apparent density, iodine number, and percent ash elsewhere.

Similar to the RSSCT study, the ACT study used Tahoe groundwater and Lake Perris surface water. The results of background chemical testing on these waters are presented in Table 2.3. Similar to water analyses performed for the RSSCTs, these data suggest that the variation of NOM results in substantial differences in measured TOC and conductivity.<sup>1</sup> The background MTBE levels measured by Calgon should not impact the results of the column testing because MTBE spiking of test water was performed prior to testing to reach the desired influent concentrations.

**Table 2.3**  
Analysis of Water-quality Parameters for ACTs

Water Source	pH	Conductivity (µmhos/cm)	TOC (ppm)	Background MTBE (ppb)	Background TBA (ppb)
Tahoe Groundwater	6.6	72.6	0.71	5.3	NM
Lake Perris Surface Water	8.1	495	3.61	7.3	NM

NM - not measured.

1. The reader should note that Calgon's measured pH value for Tahoe groundwater (6.6) is noticeably lower than that measured by UCLA (7.9). A discussion of differences between the waters used in the column studies is presented in Section 3.1.

### 2.3.3 Experimental Testing Matrix

Calgon completed two ACTs for this project, selecting experimental testing parameters requested by the California MTBE Research Partnership to help fulfill the research objectives set forth in Section 2.1. Calgon's experimental testing matrix, which presents the testing conditions of each ACT, is presented in Table 2.4. As shown, the two ACTs are designated by test numbers A1 and A2.

**Table 2.4**  
Experimental Testing Matrix for ACTs

Water Source	Test #	Influent MTBE (ppb)	GAC Vendor/Product	EBCT (min)	Other Testing Conditions
Tahoe Groundwater	A1	21.7	Calgon/PCB	20	–
Lake Perris Surface Water	A2	24.6	Calgon/PCB	20	–

### 2.3.4 Analytical Methods

For the ACT study, MTBE concentrations were determined using a Modified EPA 602 GC method with purge and trap. The MTBE was measured with a Flame Ionization Detector at a detection limit of 0.2 ppb. Details regarding sampling protocols are presented elsewhere (Calgon, 2000).

The pH of the waters was determined using a Fisher Scientific Accumet pH meter and the conductivity of the waters was determined using a HACH (Loveland, Colorado) Conductivity/Total Dissolved Solids (TDS) Meter. TOC was determined using a Shimadzu TOC-5000A equipped with a Shimadzu ASI-5000A Autosampler.

### 2.3.5 QA/QC Procedures

During the ACT study, water samples with known MTBE concentrations were injected daily into the GC to verify retention times and peak areas for MTBE (Calgon, 2000). No other data are presently available regarding other in-house QA/QC procedures performed by Calgon.



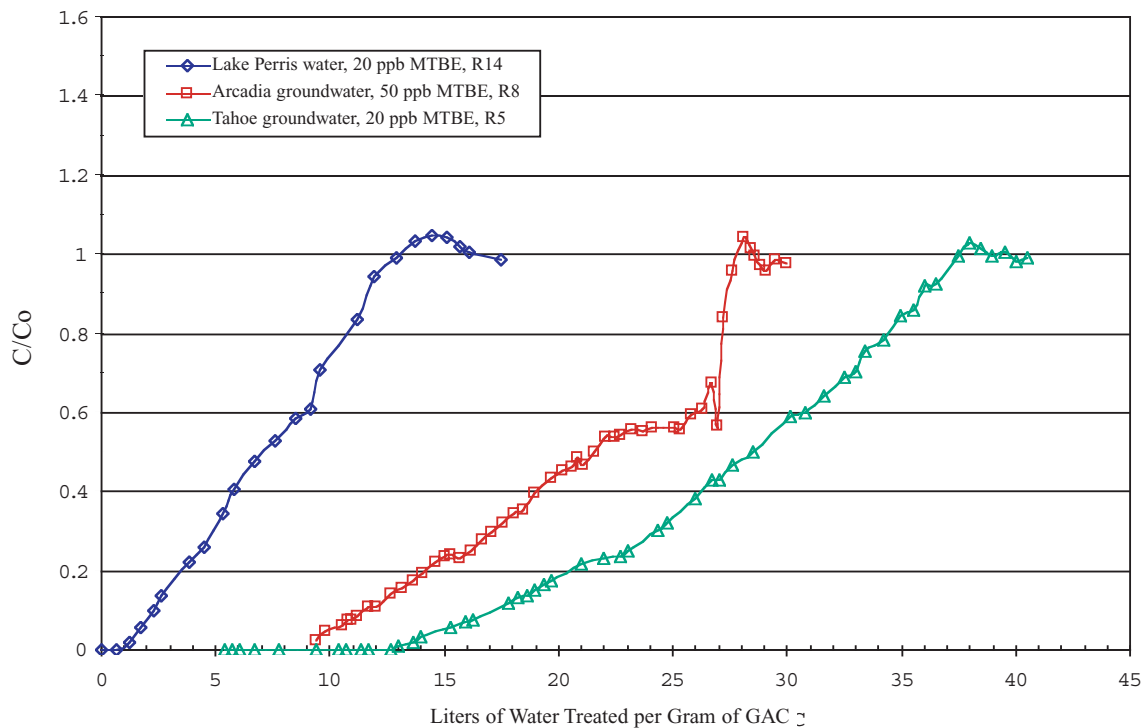
### 3.0 Results of Column Testing

This section presents and discusses data generated from the column studies, which were designed to allow for GAC performance comparisons to be made between different treatment scenarios. Experimental parameters that were varied in this bench-scale testing include:

- GAC type.
- Influent MTBE concentration.
- Background water quality.
- The presence or absence of BTX and TBA.
- EBCT.

The testing method was also varied by using both RSSCT and ACT methodologies. Because most of the data from the column studies were generated using the RSSCT methodology, the quantitative and qualitative analyses of this section are primarily based on the results of the RSSCTs.

The graphs generated by the column testing allow for the comparisons of MTBE breakthrough behavior for different testing scenarios; for each of the column tests, a breakthrough curve was plotted (e.g., Figure 3.1). Using these curves, GAC usage rates at key points along the breakthrough curve were measured. These data allow for the comparison of GAC usage rates from one test to another, giving a quantitative assessment of breakthrough characteristics as they relate to testing parameters (e.g., background water quality).



**Figure 3.1** MTBE breakthrough for different water sources. Influent: MTBE at 20 to 50 ppb (PCB GAC, 10 minute EBCT).

For this research, two breakthrough points were chosen for comparison: 50- and 100-percent breakthrough (or GAC saturation). These milestone usage rates are often used during system design as assumptions for predicting the changeout frequency of full-scale GAC systems. Table 3.1 presents a summary of testing conditions and measured usage rates for all of the column tests. As shown, this table presents raw data pulled from the breakthrough curves (treatment rate in liters per gram [L/g] of GAC) and usage rates (pounds of GAC per 1,000 gallons of treated water), as converted from the raw data.

**Table 3.1**  
Breakthrough Usage Rates from Column Testing

Water Source	Test #	Testing Method	GAC Product	Influent MTBE (ppb)	EBCT (min)	BTX/TBA (ppb)	Treatment Rate (L/g of GAC)*		Usage Rate (lb GAC/1,000 gal)	
							at 50% C/Co	at 100% C/Co	at 50% C/Co	at 100% C/Co
Tahoe Groundwater	R1	RSSCT	CC-602	1,964	10	0	7.0	12.0	1.19	0.70
	R2	RSSCT	CC-602	1,950	10	0	7.2	12.0	1.16	0.70
	R3	RSSCT	CC-602	2,052	20	0	6.8	12.1	1.23	0.69
	R4	RSSCT	CC-602	1,958	10	1,977 BTX	5.0	9.1	1.68	0.92
	R5	RSSCT	PCB	20	10	0	28.2	37.5	0.30	0.22
	A1	ACT	PCB	22	20	0	35.2	40.7	0.24	0.21
Arcadia Groundwater	R6	RSSCT	PCB	220	10	0	16.3	24.1	0.51	0.35
	R7	RSSCT	PCB	209	20	0	17.3	25.0	0.48	0.33
	R8	RSSCT	PCB	50	10	0	21.5	27.7	0.39	0.30
	R9	RSSCT	PCB	1,030	10	100 TBA	8.3	12.9	1.01	0.65
	R10	RSSCT	F600	20	10	300 BTX	7.7	13.6	1.08	0.61
	R11	RSSCT	F600	200	20	100 TBA	9.1	14.4	0.92	0.58
Lake Perris Surface Water	R12	RSSCT	CC-602	20	10	0	4.3	13.1	1.94	0.64
	R13	RSSCT	CC-602	20	20	0	8.1	20.2	1.03	0.41
	R14	RSSCT	PCB	20	10	0	7.0	13.1	1.19	0.64
	R15	RSSCT	PCB	20	20	0	11.1	20.5	0.75	0.41
	R16	RSSCT	PCB	20	20	300 BTX	7.8	15.4	1.07	0.54
	A2	ACT	PCB	25	20	0	15.1	25.0	0.55	0.33

\* Values taken from breakthrough curves (Figures 3.1 to 3.12).

To convert from L/g of GAC to pounds of GAC/1,000 gallons:  $8.344 / (\#L/g) = \# \text{ pounds}/1,000 \text{ gallons}$ .

The reader should note that GAC changeout criteria are site-specific and are likely to depend on multiple factors, such as system configuration and local effluent discharge regulations. Considering a typical GAC system design (i.e., in-series operation of two or more vessels), system operators typically changeout the lead GAC vessel when its effluent reaches a predetermined concentration. As such, the usage rate values presented in this report based on 50-percent breakthrough and saturation will not be appropriate for all sites.

The following subsections present the results and discussion of column testing for each of the experimental parameters.

### 3.1 Impact of Background Water Quality

A primary objective of the Partnership’s GAC research program was to evaluate GAC performance under a variety of background water-quality conditions. As discussed in Section 2, three different waters were used for the column test studies. These waters, which are all from California municipal drinking-water sources, vary markedly from each other.

The waters were chosen to span a range of background NOM conditions, as NOM is known to reduce GAC effectiveness due to competitive adsorption and the clogging of GAC pore space.

The results of analytical testing on the background waters, presented in Tables 2.1 and 2.3, show that TOC values vary from 0.2 ppm (Tahoe groundwater) to 3.6 ppm (Lake Perris surface water). While NOM is quantified by TOC, the reader should be aware that TOC is generally not considered to be an accurate predictor of NOM impacts on GAC adsorption effectiveness. Others (Zimmer et al., 1988; Summers et al., 1989) have shown that certain types of organic matter (e.g., fulvic acids, humic acids) have varying impacts on GAC adsorption effectiveness for synthetic organic compounds. At this time, there is no well-established analytical test that accurately predicts NOM impacts to GAC adsorption effectiveness (Hand, 1998).

The impact of background NOM on GAC effectiveness for MTBE removal is made evident by comparing usage rates and breakthrough curves from RSSCTs on the three water sources. Figure 3.1 shows breakthrough curves for RSSCTs performed with low influent MTBE concentrations (20 to 50 ppb) in each of the source waters, while other parameters were held equal (i.e., Calgon PCB GAC, 10-minute EBCT). Based on Figure 3.1, it appears that background water quality plays an important role in the effectiveness of MTBE adsorption by GAC. As expected, testing of the groundwaters, which are cleaner with respect to background NOM, resulted in delayed MTBE breakthrough in comparison to testing of the surface water. As presented in Table 3.2, the differences in breakthrough behavior correspond to almost a *four-fold* variance in GAC usage rates at 50-percent breakthrough (0.30 pounds/1,000 gallons for Tahoe groundwater versus 1.19 pounds/1,000 gallons for Lake Perris surface water), depending on background water conditions.

**Table 3.2**  
Comparison of Breakthrough Usage Rates for Different Source Waters:  
PCB GAC, 10 minute EBCT, RSSCT Method

Water Source	Background TOC (ppm)	Test #	Influent MTBE (ppb)	Usage Rate (lbs GAC/1,000 gallons)	
				at 50% C/Co	at 100% C/Co
Lake Perris Surface Water	3.2	R14	20	1.19	0.64
Arcadia Groundwater	1.0	R8	50	0.39	0.30
Tahoe Groundwater	0.2	R5	20	0.30	0.22

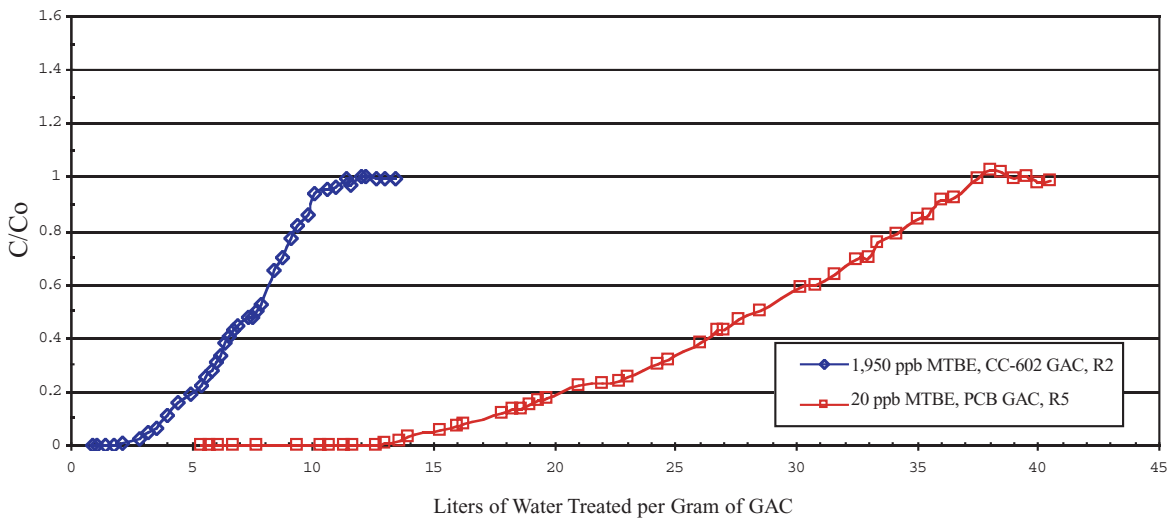
The results shown in Figure 3.1 and summarized in Table 3.2 suggest that TOC is inversely related to GAC effectiveness. For Lake Perris surface water, which has the highest TOC load (3.2 ppm), MTBE breakthrough occurs much more quickly than for the two groundwaters. In contrast, the Tahoe groundwater, which has the lowest TOC load (0.2 ppm), showed the slowest breakthrough. In spite of the uncertainty as to whether or not TOC is a good indicator

of GAC adsorption effectiveness for MTBE, the results of these RSSCTs show clearly that background water quality can have a dramatic impact (Figure 3.1).

Because of the impact of NOM on adsorption effectiveness, the reader is reminded that to accurately predict GAC performance for MTBE removal, site-specific testing is necessary; however, because the results presented in this report span a wide range of water-quality conditions, the RSSCT data should be useful for feasibility-level analyses of GAC at most MTBE-impacted sites.

### 3.2 Effect of Influent MTBE Concentration on Breakthrough Curves

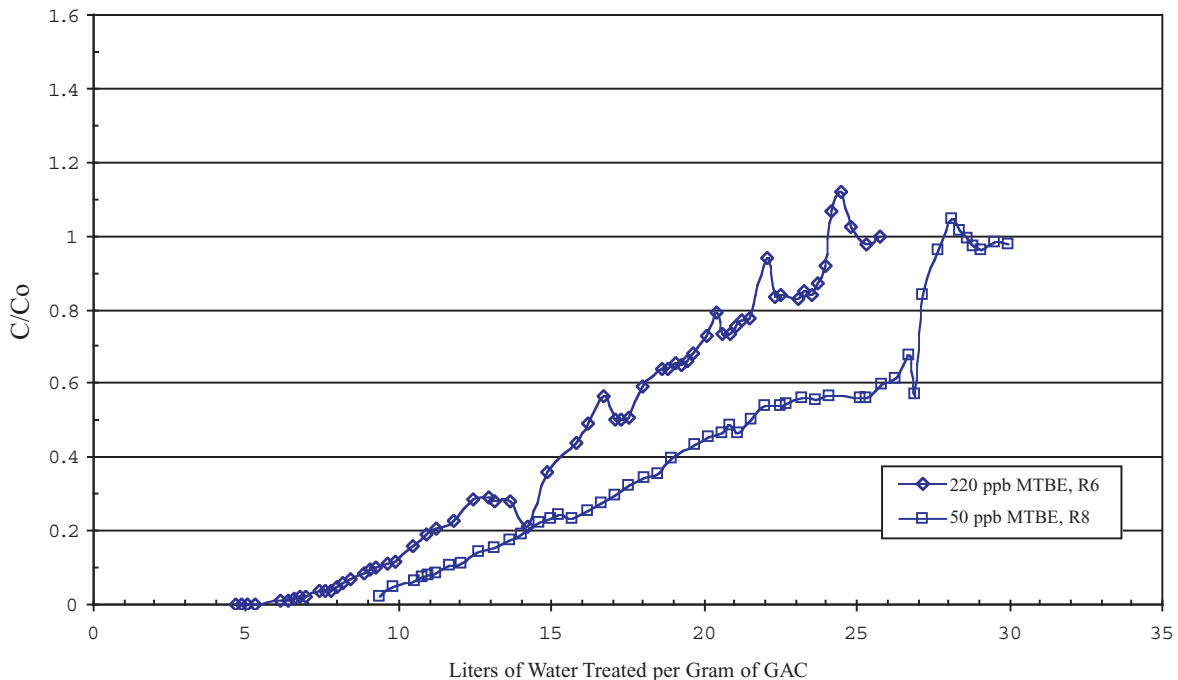
The impact of influent MTBE concentration on adsorption effectiveness is illustrated in Figure 3.2, which presents the results of RSSCTs on Tahoe groundwater spiked with relatively high (1,950 ppb) and low (20 ppb) concentrations of MTBE. As expected, breakthrough occurs earlier for the test with higher influent MTBE concentration. Comparing the breakthrough data for these two tests (see Table 3.1), the GAC usage rate at 50-percent breakthrough varies by almost 400 percent (1.16 pounds/1,000 gallons for 1,950 ppb MTBE versus 0.30 pounds/1,000 gallons for 20 ppb MTBE).<sup>2</sup>



**Figure 3.2** MTBE breakthrough for different influent concentrations. Influent: Tahoe groundwater with 20 or 1,950 ppb MTBE (Coconut Shell GACs, 10 minute EBCT).

A similar effect, though less exaggerated by a smaller influent concentration differential, is illustrated in Figure 3.3. This graph shows the results of RSSCTs on Arcadia groundwater spiked with either 50 or 220 ppb MTBE. GAC usage rate at 50-percent breakthrough occurs at approximately 0.51 pounds/1,000 gallons for influent MTBE of 220 ppb versus 0.39 pounds/1,000 gallons for influent MTBE of 50 ppb, representing a usage rate difference of approximately 31 percent.

2. The reader should note that the two RSSCTs depicted in Figure 3.2 were performed using different coconut-shell GAC products (U.S. Filter CC-602 and Calgon PCB).



**Figure 3.3** MTBE breakthrough for different influent concentrations. Influent: Arcadia groundwater with 50 or 220 ppb MTBE (PCB GAC, 10 minute EBCT).

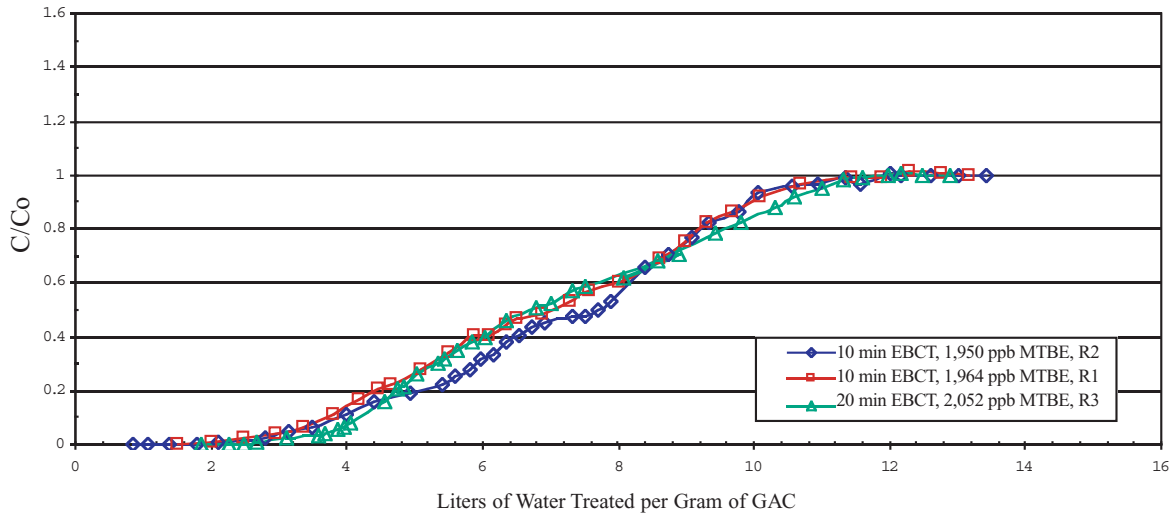
### 3.3 Impact of EBCT on MTBE Breakthrough

To fully evaluate GAC-adsorption effectiveness for MTBE, the testing of critical design parameters, such as EBCT, is necessary. As discussed elsewhere (Partnership, 2000), variations in EBCT can have a substantial effect on GAC adsorption of trace compounds. The optimum EBCT for a system depends on numerous factors, including carbon type, concentrations of organic compounds, and background water quality. The column testing performed by UCLA was designed to evaluate the impacts of EBCT on adsorption effectiveness.

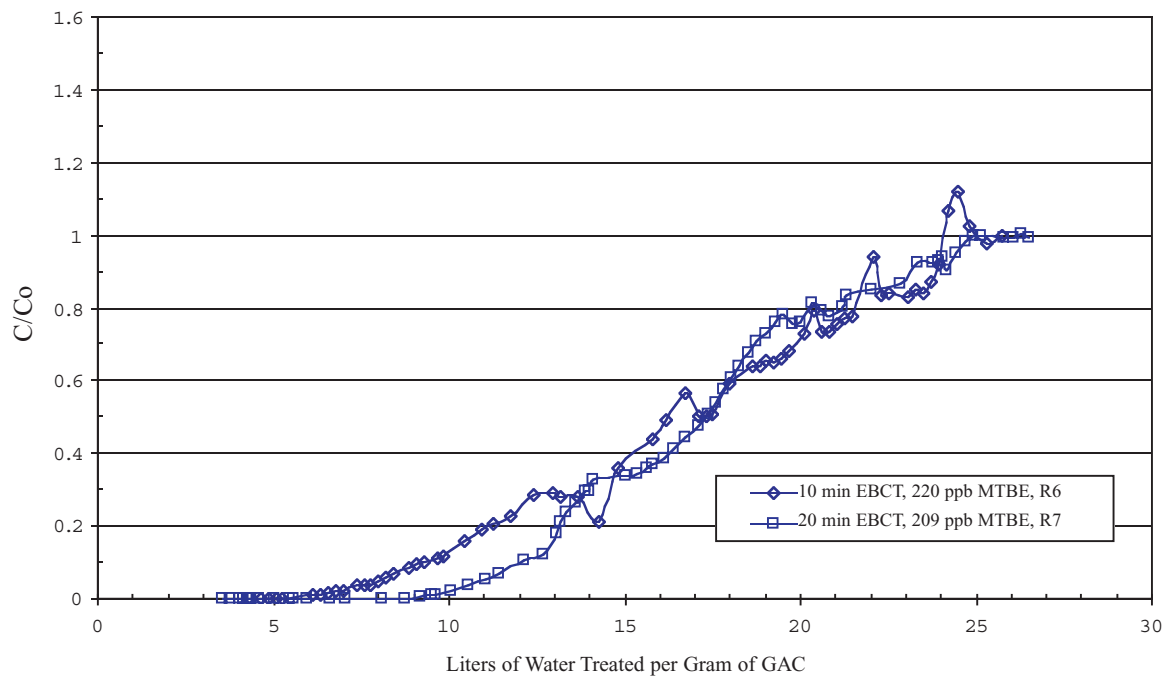
Using RSSCT methodology, each of the source waters were tested at two EBCTs (10 and 20 minutes) while holding GAC types and influent concentrations approximately constant.<sup>3</sup> Figures 3.4, 3.5, and 3.6 show the influence of EBCT on MTBE breakthrough for each of the source waters. Different results were observed for the different source waters, as discussed below.

Figure 3.4 shows MTBE breakthrough curves when Tahoe groundwater, spiked with MTBE at approximately 2,000 ppb, is passed through CC-602 GAC at EBCTs of 10 and 20 minutes. As Figure 3.4 shows, the breakthrough curves for these tests are very similar; no significant

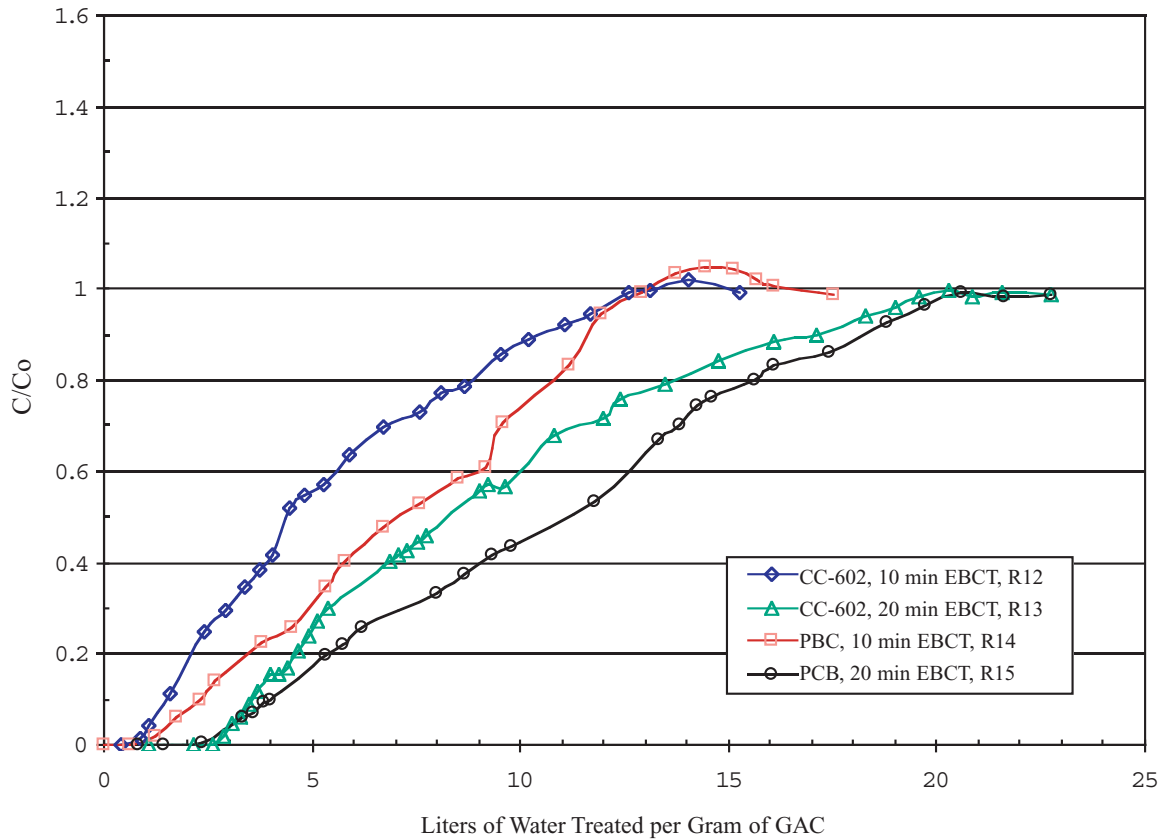
3. It should be noted that no attempt was made to optimize the EBCT for the given influent conditions. This level of evaluation would have required three or more different EBCTs to be tested; the resources available for this research were prohibitive for this level of evaluation.



**Figure 3.4** MTBE breakthrough for different EBCTs. Influent: Tahoe groundwater with ~2,000 ppb MTBE (CC-602 GAC, 10 to 20 minute EBCTs).



**Figure 3.5** MTBE breakthrough for different EBCTs. Influent: Arcadia groundwater with ~200 ppb MTBE (PCB GAC, 10 to 20 minute EBCTs).



**Figure 3.6** MTBE breakthrough for different EBCTs. Influent: Lake Perris surface water with 20 ppb MTBE (CC-602 and PCB GACs, 10 to 20 minute EBCTs).

variation in breakthrough usage rates is evident. Similar consistency can be seen in Figure 3.5, which shows breakthrough curves generated using Arcadia groundwater spiked with MTBE at approximately 200 ppb. Based on these test results, it appears that EBCT in the range of 10 to 20 minutes has no significant effect on MTBE breakthrough.

However, the conclusion offered above based on groundwater spiked with 200 to 2,000 ppb MTBE should not be over-generalized. For example, Figure 3.6 presents breakthrough curves for Lake Perris surface water spiked with 20 ppb MTBE. This figure shows that GAC performance appears to be somewhat dependent on EBCT. For both Calgon PCB and U.S. Filter CC-602, longer EBCTs result in substantially improved GAC performance (i.e., slower breakthrough, lower usage rates). Quantitative differences in usage rates are summarized in Table 3.3, indicating that different EBCTs caused a usage rate variance greater than 50-percent at both saturation and 50-percent breakthrough for both GACs. Figure 3.6 clearly shows that EBCTs greater than 10 minutes are required to optimize MTBE removal from Lake Perris surface water spiked with 20 ppb MTBE.

Based on the test comparisons presented in Table 3.3, it appears that the treatment of water with relatively high NOM (e.g., surface water) may require EBCTs greater than 10 minutes.

**Table 3.3**  
Comparison of Breakthrough Usage Rates for Different EBCTs: RSSCT Method

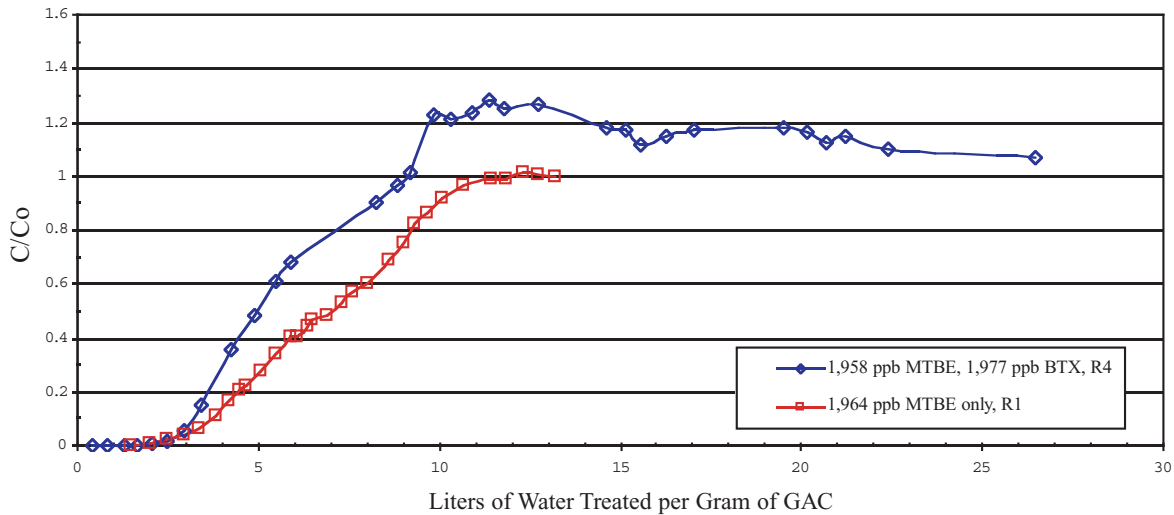
Source Water	Test #	EBCT (min)	GAC type	Influent MTBE (ppb)	Usage Rate (lbs GAC/1,000 gallons)	
					at 50% C/Co	at 100% C/Co
Lake Perris Surface Water	R14	10	Calgon PCB	20	1.19	0.64
	R15	20	Calgon PCB	20	0.75	0.41
	R12	10	U.S. Filter CC-602	20	1.94	0.64
	R13	20	U.S. Filter CC-602	20	1.03	0.41
Arcadia Groundwater	R6	10	Calgon PCB	220	0.51	0.35
	R7	20	Calgon PCB	209	0.48	0.33
Tahoe Groundwater	R1	10	U.S. Filter CC-602	1,964	1.19	0.70
	R2	10	U.S. Filter CC-602	1,950	1.16	0.70
	R3	20	U.S. Filter CC-602	2,052	1.23	0.69

In addition, it appears that MTBE-breakthrough behavior is not impacted by EBCTs between 10 and 20 minutes for waters with low to moderate NOM (e.g., groundwater); however, the reader should be aware that the EBCT effect noted here may also be attributed, in part, to MTBE concentrations. The RSSCTs that appear to be affected by EBCT (Figure 3.6) were performed on relatively low influent MTBE levels (i.e., 20 ppb) in comparison to the tests presented in Figures 3.4 and 3.5 (2,000 and 200 ppb, respectively). It is unknown whether the high NOM conditions or the low influent MTBE levels cause the EBCT dependence illustrated in Figure 3.6. Further research is required to more clearly identify water conditions under which EBCT impacts MTBE breakthrough.

### 3.4 Impact of BTX Load on MTBE Breakthrough

The impact of BTX compounds on GAC adsorption effectiveness was also investigated in this research. Figures 3.7 and 3.8 present data from two sets of RSSCTs, allowing for the comparison of MTBE breakthrough with and without BTX compounds present in the influent stream.

Figure 3.7 shows the breakthrough curve for Tahoe groundwater spiked with 1,958 ppb MTBE and 1,977 ppb Total BTX. The same figure also presents a breakthrough curve for similar test conditions (1,964 ppb MTBE), but without the BTX load. Comparing these two curves, it appears that MTBE breakthrough is accelerated in the presence of BTX. Data presented on Table 3.4 indicate that BTX caused usage rates to increase by 41 percent at the 50-percent breakthrough point (1.19 pounds/1,000 gallons to 1.68 pounds/1,000 gallons) and by 31 percent at saturation (0.70 pounds/1,000 gallons to 0.92 pounds/1,000 gallons).



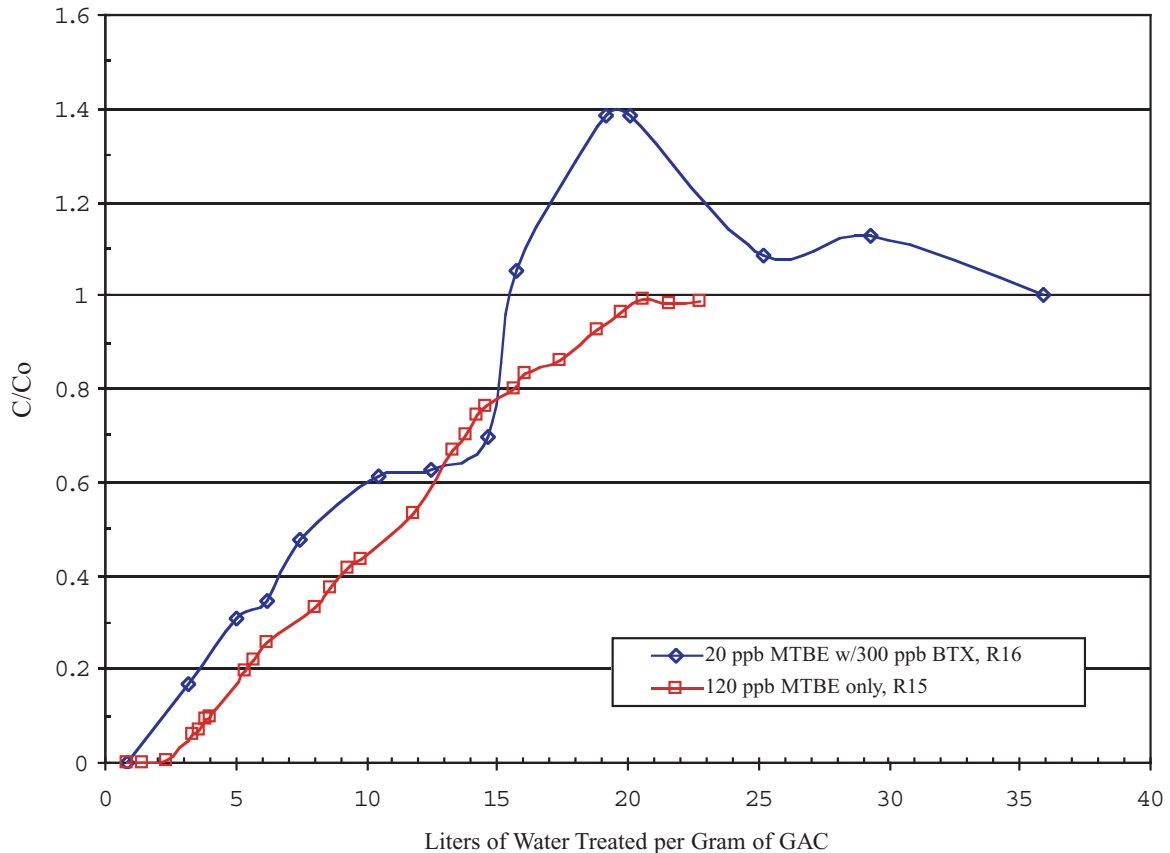
**Figure 3.7** MTBE breakthrough with and without BTX. Influent: Tahoe groundwater with ~2,000 ppb MTBE (CC-602 GAC, 10 minute EBCT).

Figure 3.7 also shows that, after saturation, effluent MTBE levels continue to rise higher than the influent level ( $C/C_o > 1$ ) for one of the RSSCTs (R4). This effect is attributed to MTBE desorption from the GAC matrix as the more strongly adsorbed BTX compounds move downgradient in the column and displace previously adsorbed MTBE molecules. Because of this effect, desorption is an important phenomenon to consider when designing GAC treatment systems and sampling protocol, particularly for weakly adsorbing compounds, such as MTBE.

Figure 3.8 illustrates similar results as those noted in Figure 3.7, though the data were generated by tests of Lake Perris surface water spiked with 20 ppb MTBE. The RSSCT results show that 50-percent MTBE breakthrough and saturation are both accelerated in the presence of BTX. The data presented in Table 3.4 indicate that GAC usage rates in the presence of 300 ppb Total BTX increased by 43 percent at the 50-percent breakthrough point (0.75 pounds/1,000 gallons to 1.07 pounds/1,000 gallons) and by 32 percent at saturation (0.41 pounds/1,000 gallons to 0.54 pounds/1,000 gallons). Figure 3.8 also illustrates that BTX-related desorption can cause effluent MTBE levels to rise above influent levels.

**Table 3.4**  
Comparison of Breakthrough Usage Rates with and without BTX: RSSCT Method

Source Water/ Testing Conditions	Test #	Influent MTBE (ppb)	Influent Total BTX (ppb)	Usage Rate (lbs GAC/1,000 gallons)	
				at 50% C/Co	at 100% C/Co
Lake Perris Surface Water, PCB GAC, 20 min EBCT	R16	20	300	1.07	0.54
	R15	20	0	0.75	0.41
Tahoe Groundwater, CC-602 GAC, 10 min EBCT	R4	1,958	1,977	1.68	0.92
	R1	1,964	0	1.19	0.70

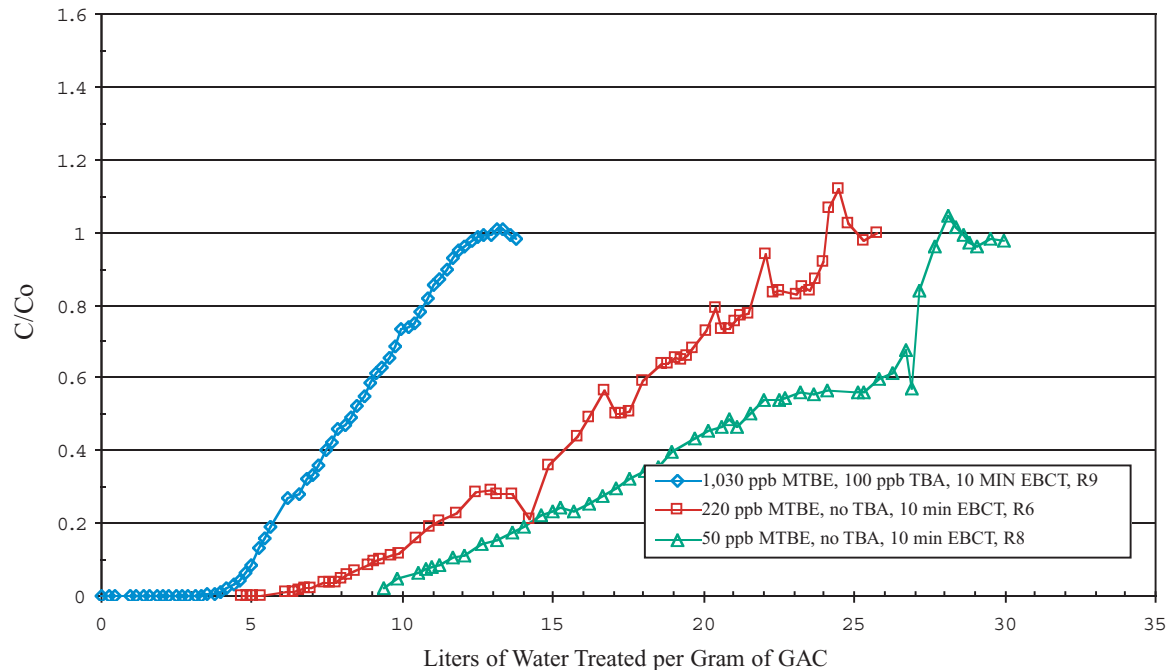


**Figure 3.8** MTBE breakthrough with and without BTX. Influent: Lake Perris surface water with 20 ppb MTBE (PCB GAC, 20 minute EBCT).

### 3.5 Impact of TBA Load on MTBE Breakthrough

Figure 3.9 presents results of three RSSCTs on Arcadia groundwater. One of these tests (R9) included TBA at 100 ppb and MTBE at 1,030 ppb, while the others had no TBA but MTBE at 50 ppb and 220 ppb (R8 and R6, respectively). Comparing the breakthrough curves and the usage rates measured for these tests, it is evident that the GAC usage rate increases substantially with the addition of TBA and higher MTBE concentrations. Considering 50-percent MTBE breakthrough, the GAC usage rate increased by over 150 percent (0.39 pounds/1,000 gallons to 1.01 pounds/1,000 gallons) with the addition of TBA and 1,030 ppb MTBE versus 50 ppb MTBE; the usage rate increased by almost 100 percent (0.51 pounds/1,000 gallons to 1.01 pounds/1,000 gallons) with the addition of TBA and 1,030 ppb MTBE versus 220 ppb MTBE.

Because two experimental parameters were varied (TBA and MTBE concentrations), it is unknown which of these parameters is responsible for the differences in the usage rates presented above; however, for comparison purposes, the usage rate at 50-percent breakthrough varied by almost 400 percent when MTBE concentration was increased from 20 to 1,950 ppb in Tahoe groundwater (see Section 3.2). While this is a larger MTBE concentration



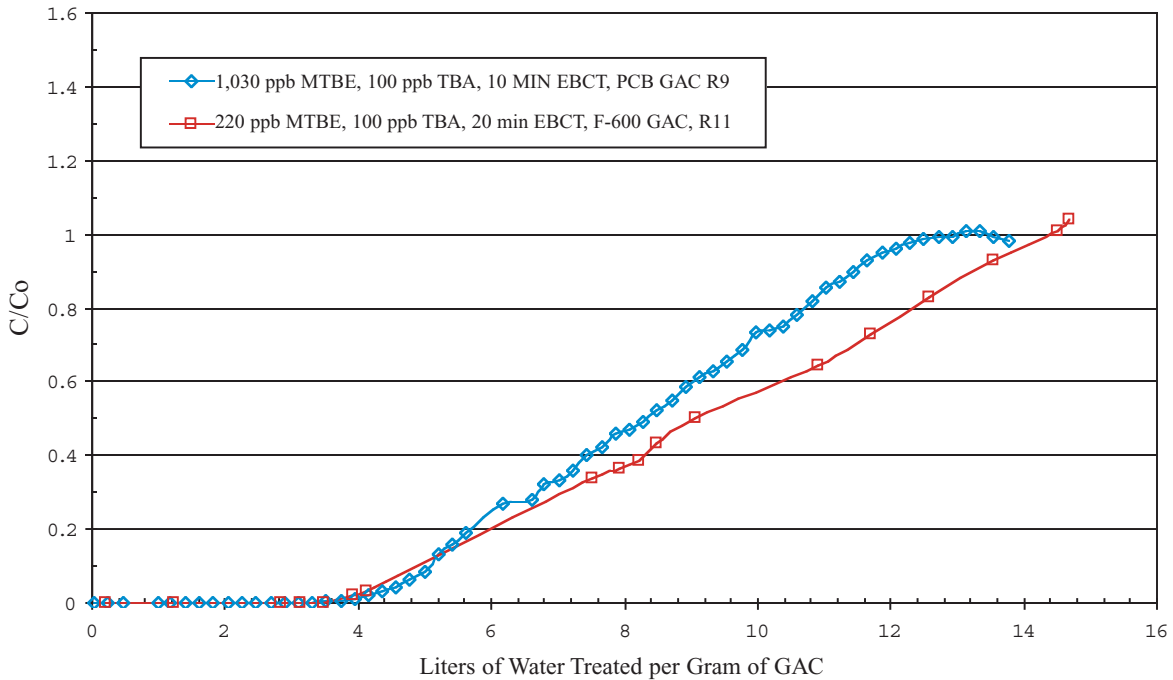
**Figure 3.9** MTBE breakthrough with and without 100 ppb TBA. Influent: Arcadia groundwater with 50 to 1,030 ppb MTBE (PCB GAC, 10 to 20 min EBCT).

differential than either of the two comparisons made above, it does indicate that influent MTBE concentration plays a large role in determining the GAC usage rate. Because the usage rates varied by only 100 and 150 percent (approximately) in the comparisons presented above (while the MTBE concentration differentials were substantial), it is suspected that the addition of 100 ppb TBA did not dramatically affect MTBE breakthrough behavior. It is important to note, however, that the effluent of the RSSCTs was not monitored for TBA; as such, it is unknown when, or if, TBA broke through the RSSCT column.

### 3.6 Comparison of Coconut Shell GAC versus Coal-based GAC

With the available RSSCT data, no direct quantitative comparisons can be made between coconut shell GAC and coal-based GAC; however, several tests with similar testing conditions were performed, allowing for qualitative comparisons to be made, as discussed below.

Figure 3.10 shows the results of two RSSCTs performed using different GAC types (i.e., coal-based F-600 and coconut shell PCB). The influent for the tests was Arcadia groundwater spiked with 100 ppb TBA. As shown on Figure 3.10, the breakthrough curves do not vary substantially for the two treatment scenarios, though influent MTBE concentrations were significantly different (200 and 1,030 ppb). Given the differential of influent MTBE concentrations, one might expect the breakthrough curves to be farther apart; however, for the two scenarios with TBA, GAC usage at 50-percent breakthrough varies by only 10 percent (1.01 pounds/1,000 gallons versus 0.92 pounds/1,000 gallons) in spite of the



**Figure 3.10** MTBE breakthrough for different GAC types. Influent: Arcadia groundwater with 200 to 1,030 ppb MTBE, 100 ppb TBA (PCB and F-600 GACs, 10 to 20 minute EBCTs).

varying influent MTBE concentrations (see Table 3.1). Similarly, the usage rate at saturation varies by only 12 percent (0.65 pounds/1,000 gallons versus 0.58 pounds/1,000 gallons). The similarity of these testing results suggests that coconut shell GAC can remove higher MTBE concentrations at approximately the same usage rate in comparison to coal-based GAC.

The reader should be aware that EBCTs varied for the tests presented in Figure 3.10; however, as discussed in Section 3.3, it is suspected that EBCTs between 10 and 20 minutes do not substantially impact MTBE removal from Arcadia groundwater with 200 to 2,000 ppb MTBE.

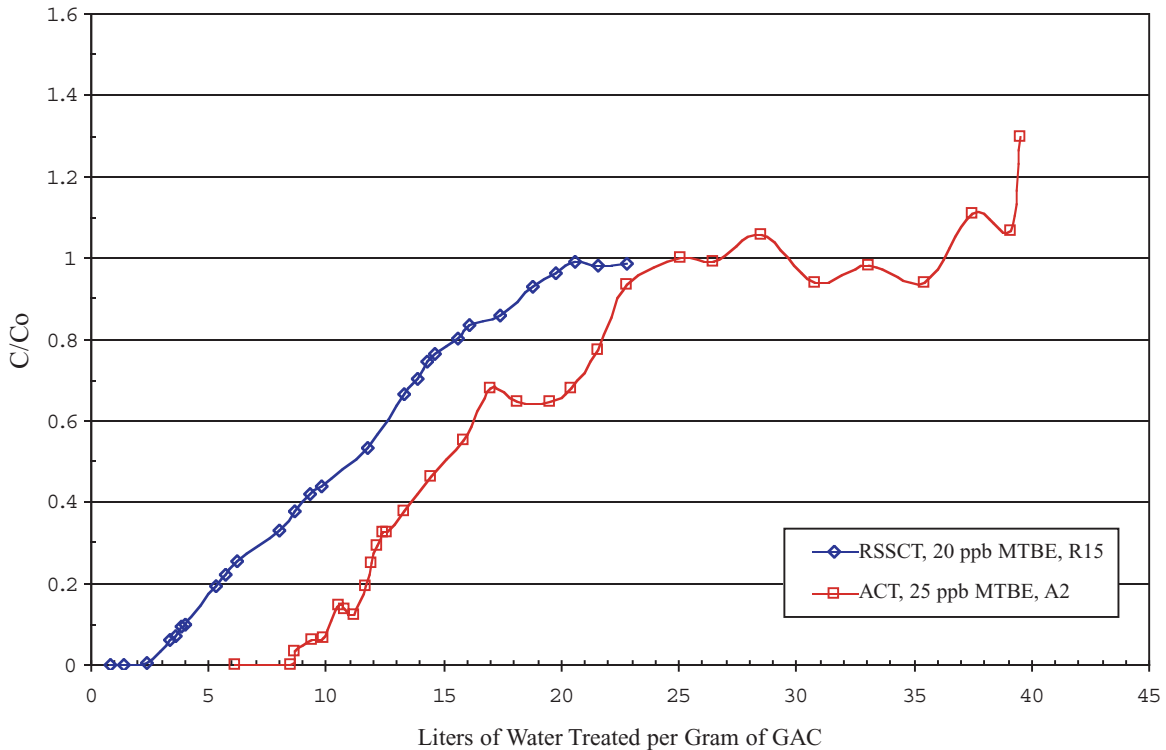
Based on the qualitative comparisons discussed above, it appears that coconut shell GAC is more effective for MTBE removal than coal-based GAC. This tentative conclusion is consistent with results of isotherm testing (Partnership, 2000) and with preliminary field study results; however, as discussed by Calgon (2000), it should be noted that the natural variability of coconut shell carbons is reportedly more difficult to control than that of coal-based carbons, which come from source materials that are more consistent. This variability of coconut shell carbons may cause the need for more comprehensive QA/QC efforts than are typically performed for coal-based GAC products.

### 3.7 Comparison of RSSCT and ACT Methodology

Data from duplicate RSSCTs and ACTs were generated to allow for the direct comparison of these two testing methodologies. Because 16 RSSCTs were performed versus only two ACTs, the results of the ACT tests were converted to units reported for the RSSCTs

(i.e., L/g of GAC). This conversion allowed for graphical comparison of breakthrough curves and quantitative analysis of performance results (i.e., GAC usage rates).

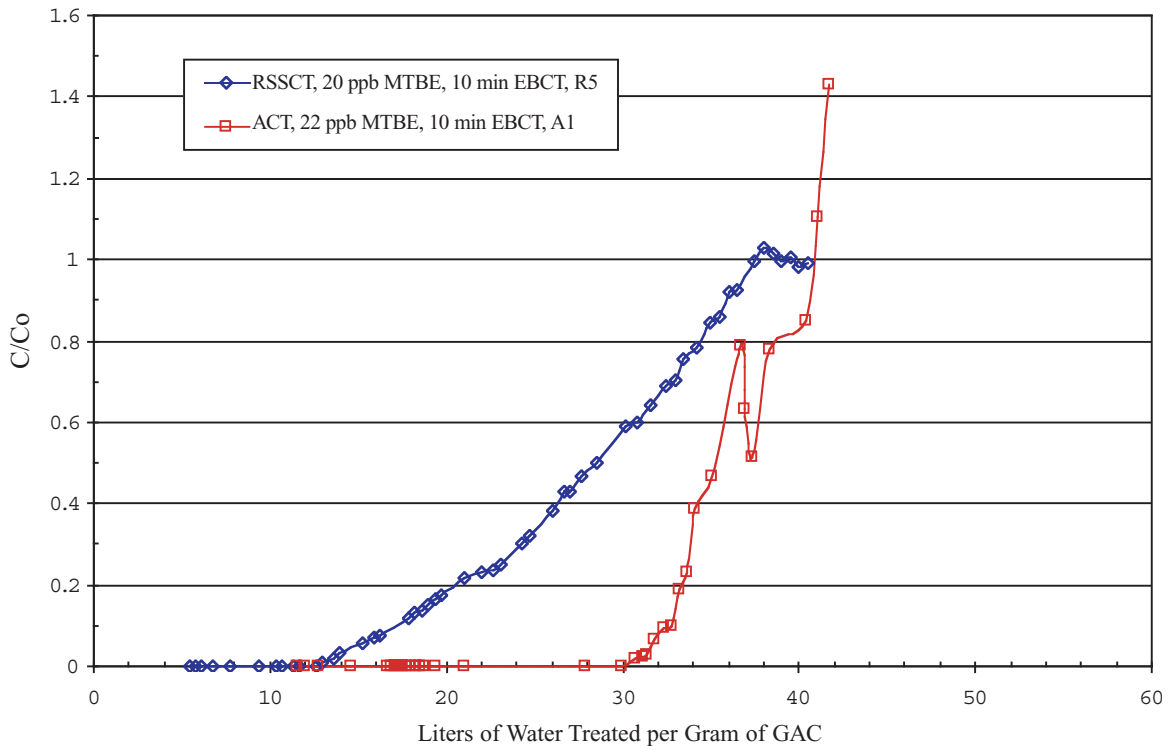
Two sets of column tests are available for comparing RSSCT and ACT methodologies. Figure 3.11 shows test results using Lake Perris surface water (MTBE concentrations at 20 to 25 ppb) and Figure 3.12 shows test results using Tahoe groundwater (MTBE concentrations at 20 to 22 ppb). Although slight variation is expected when performing duplicate bench-scale column tests, Figures 3.11 and 3.12 suggest that these two column-testing methods produce results with notable differences.



**Figure 3.11** MTBE breakthrough for ACT and RSSCT. Influent: MTBE at 20 to 25 ppb in Lake Perris surface water (PCB GAC, 20 minute EBCT).

In particular, the reader is directed to observe the difference in the initial breakthrough of the columns shown in Figure 3.11. For the RSSCT, the initial breakthrough occurred at approximately 3 L/g GAC while, for the ACT, the initial breakthrough did not occur until more than 8 L/g GAC. Usage rates at 50-percent breakthrough were 0.75 pounds/1,000 gallons for the RSSCT versus 0.55 pounds/1,000 gallons for the ACT, representing a usage rate difference of 36 percent. The usage rates at saturation differ by 24 percent (0.41 pounds/1,000 gallons GAC for the RSSCT versus 0.33 pounds/1,000 gallons for the ACT).

Figure 3.12 also illustrates the differences between breakthrough curves generated by RSSCTs and ACTs, though these tests were performed with Tahoe groundwater. In this



**Figure 3.12** MTBE breakthrough for ACT and RSSCT. Influent: MTBE at 20 to 22 ppb in Tahoe groundwater (PCB GAC, 10 to 20 minute EBCTs).

figure, similar to Figure 3.11, the initial breakthrough of the ACT occurs much later than for the RSSCT (approximately 30 L/g GAC versus 14 L/g GAC). The carbon usage rates at 50-percent breakthrough differ by 25 percent (0.30 pounds/1,000 gallons for the RSSCT versus 0.24 pounds/1,000 gallons for the ACT), while the usage rate differences at saturation are negligible (0.22 pounds/1,000 gallons for the RSSCT versus 0.21 pounds/1,000 gallons for the ACT).

Looking at the general shape of the breakthrough curves in Figure 3.12, it is evident that the RSSCT breakthrough is more gradual than that of the ACT, which shows a steep trend after a delayed initial breakthrough. In contrast, as shown on Figure 3.11, the breakthrough curves with Lake Perris surface water are similar in shape, though the ACT breakthrough is delayed in comparison to the RSSCT.

In conclusion, considering only Figures 3.11 and 3.12, it appears that the RSSCT generates more conservative results (i.e., higher expected usage rates) in comparison to the ACT<sup>4</sup>; however, the reader should be aware that slightly different testing conditions were used for the two-column test methods. In particular, minor variances were observed for the pH values of Tahoe groundwater and the conductivity of Lake Perris surface water. In addition, the tests

4. Calgon Carbon Corporation explains the difference in breakthrough characteristics as a function of the assumptions made regarding mean particle diameter (Megonnell, 2001).

using Tahoe groundwater at low influent MTBE levels (Figure 3.12) simulated different EBCTs. Since all of these variables (pH, conductivity, EBCT) can potentially impact GAC adsorption efficiency, a direct comparison of ACT and RSSCT results should only be made with an awareness of these potential limitations. The reader should also note that these comparisons and observations about breakthrough curve shapes and usage rates do not determine which test method is more accurate. To determine accuracy, a comparison with full-scale GAC performance is required.

### **3.8 Summary**

The column tests give valuable insight regarding the performance of GAC for removing MTBE from drinking water. The key findings of these column tests are summarized in the integrated conclusions (Section 6.3).



## 4.0 Cost Estimates for Full-scale Systems

---

This section presents cost estimates for the full-scale GAC treatment of MTBE. The results of the column testing (Section 3) provide for the GAC usage rates that were the basis for developing the cost estimates. Both principal MTBE treatment scenarios (as defined by the Partnership, 2000) and sensitivity analysis scenarios are addressed.

Based on the costing assumptions presented in Section 4.1, system capital, operation and maintenance (O&M), and unit treatment costs (\$/1,000 gallons) were estimated for a range of MTBE treatment conditions. The estimated costs were then used for discussions of cost sensitivity as it relates to treatment parameters, such as background water-quality conditions, influent MTBE concentration, and system flow rate (Section 4.2). The information presented here should allow the reader to estimate site-specific costs for GAC removal of MTBE under a wide variety of full-scale treatment scenarios.

It is important to note that all of the estimated costs presented here were developed using assumptions previously established by the Partnership (2000). These standardized assumptions, which are discussed in the following section, allow for a comparison of GAC costs with those previously estimated for other water-treatment technologies (e.g., air stripping) by the Partnership (2000).

### 4.1 Cost-estimating Assumptions

A matrix of principal MTBE treatment scenarios was developed by the Partnership to allow for a comparison of estimated costs for different treatment technologies (Partnership 2000). The treatment conditions specified in the Partnership matrix are:

- 20, 200, and 2,000 ppb MTBE in the treatment system influent.
- 60-, 600-, and 6,000-gpm treatment systems.

When considering these MTBE treatment scenarios, capital costs were developed using vendor estimates for preliminary system designs. For all of the treatment scenarios in this report, the GAC systems were assumed to have three (3) vessels in-series (two primary vessels and a backup). The number of parallel lines was varied depending on the flow rate requirements:

- The 60-gpm systems used one line.
- The 600-gpm systems used two parallel lines (300 gpm each).
- The 6,000-gpm system used 12 parallel lines (500 gpm each).

Details regarding specific GAC system designs assumed for these cost estimates are presented in Appendix A.

GAC usage rates and vessel breakthrough times were estimated based on results of the 18 dynamic column tests (Section 3.0). Tables 4.1 and 4.2 list the GAC usage rates estimated for the principal MTBE treatment scenarios and the sensitivity analysis scenarios, respectively. These assumed usage rates are based on results of one or more RSSCTs, as specified in the right-hand column of Tables 4.1 and 4.2. For the principal MTBE treatment scenarios (all low to moderate NOM fouling, no other contaminants present), the usage rate values presented in Table 4.1 were plotted, thereby illustrating the assumed relationship between the usage rate and influent MTBE concentration (see Figure 4.1).

**Table 4.1**  
GAC Usage Rate Assumptions for Principal MTBE Treatment Scenarios

Influent MTBE (ppb)	Usage rate* (lb/1,000 gal)	Reference RSSCT Conditions/Test #
20	0.35**	Arcadia groundwater, 50 ppb MTBE, PCB GAC, 10 min EBCT (R8) and Tahoe groundwater, 20 ppb MTBE, PCB GAC, 10 min EBCT (R5)
200	0.51	Arcadia groundwater, 220 ppb MTBE, PCB GAC, 20 min EBCT (R6)
2,000	1.19	Tahoe groundwater, 1,964 ppb MTBE, CC-602 GAC, 10 min EBCT (R1)

Conditions: Low to moderate NOM fouling, no other contaminants. Influent MTBE concentration varies.

\* Assumed GAC usage rates at 50-percent MTBE breakthrough measured during column testing.

\*\* GAC usage rate estimated based on results of column tests R5 and R8.

**Table 4.2**  
GAC Usage Rate Assumptions for Sensitivity Analysis Scenarios

NOM Conditions	Usage rate* (lb/1,000 gal)	Reference RSSCT Conditions
High Fouling	0.75	Lake Perris surface water, 20 ppb MTBE, PCB GAC, 20 min EBCT (R15)
Moderate Fouling	0.35**	Arcadia groundwater, 50 ppb MTBE, PCB GAC, 10 min EBCT (R8) and Tahoe groundwater, 20 ppb MTBE, PCB GAC, 10 min EBCT (R5)
Low Fouling	0.30	Tahoe groundwater, 20 ppb MTBE, PCB GAC, 10 min EBCT (R5)

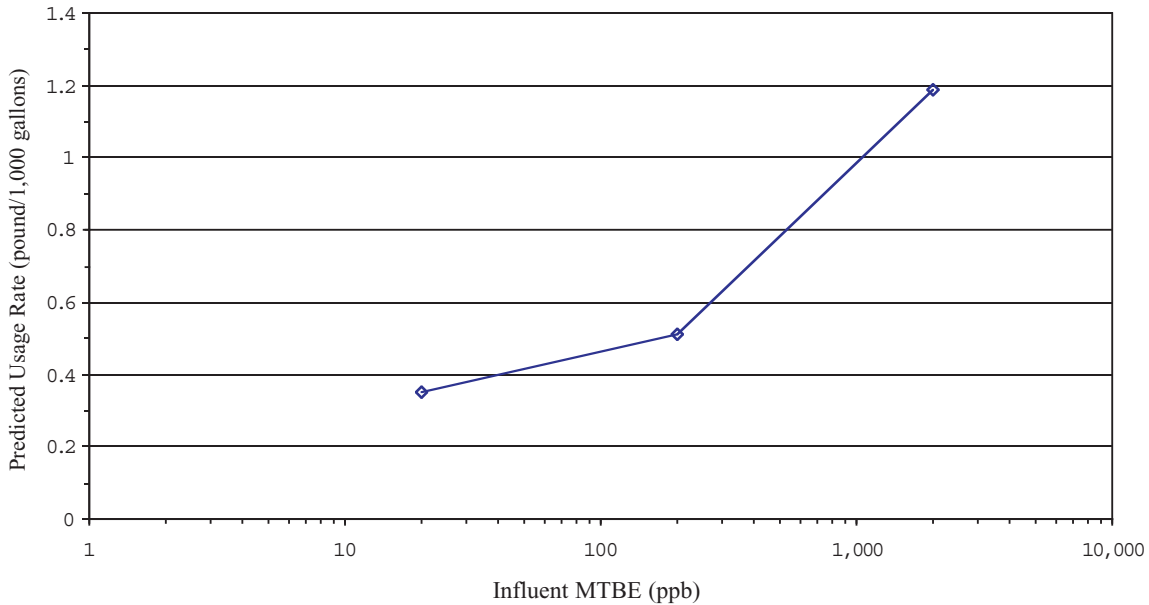
Conditions: 20 ppb MTBE influent, no other contaminants. NOM fouling varies.

Influent Conditions (ppb)	Usage rate* (lb/1,000 gal)	Reference RSSCT Conditions
20 MTBE 300 BTX High Fouling	1.07	Lake Perris surface water, PCB GAC, 20 min EBCT (R16)
1,958 MTBE 1,977 BTX Low Fouling	1.68	Tahoe groundwater, CC-602 GAC, 10 min EBCT (R4)
1,030 MTBE 100 TBA Moderate Fouling	1.01	Arcadia groundwater, PCB GAC, 10 min EBCT (R9)

Conditions: Influent MTBE, NOM conditions, and BTX/TBA load all vary.

\* Assumed GAC usage rates at 50-percent MTBE breakthrough measured during column testing.

\*\* GAC usage rate estimated based on results of column tests R5 and R8.



**Figure 4.1** Predicted carbon usage rate versus influent MTBE concentration (low to moderate NOM fouling, no other contaminants present). Usage rates determined by column testing. See Table 4.1 for details.

For each of the cost estimates, GAC changeout was assumed to be required when effluent from the lead vessel of the system reached 50 percent of influent concentration. This corresponds with usage rates at 50-percent breakthrough as determined by the column testing. No detectable MTBE (<0.5 ppb) is permitted in the system effluent (last vessel) for any of the scenarios. Other O&M costs, including labor costs, were summarized based on vendor quotes, engineering judgment, and predicted changeout frequencies (see Appendix A for further details).

General costing assumptions, which provide the standardized structure for the cost estimates presented in the Treatability report (Partnership, 2000), were incorporated into this report's cost estimates as shown on the example cost spreadsheet (Table A-1) in Appendix A. These general assumption include the following:

- Standard percentage rate assumptions based on capital<sup>5</sup> costs for design/engineering (15 percent), contractor overhead and profit (O&P) (15 percent), piping and electrical (30 percent), site work (10 percent), and contingency (20 percent).
- Standard system design life of 30 years with 7-percent interest rate for capital amortization.

5. System capital/installation costs and unit costs for GAC are based on 1998 vendor quotes from Calgon Carbon Corporation (Pittsburgh, Pennsylvania), U.S. Filter/Westates (Los Angeles, California), CARBTROL (Westport, Connecticut), and Carbonair (New Hope, Minnesota).

Appendix A includes backup cost tables that summarize predicted GAC-performance parameters for each of the scenarios. For the principal treatment scenarios (Table A-2) and for the sensitivity analyses (Table A-3), predicted vessel life and the number of changeouts per year are presented.<sup>6</sup> These values are based on the usage rates presented in Tables 4.1 and 4.2. Appendix A also includes details of the estimated labor costs for the principal treatment scenarios (Table A-4) and for the sensitivity analysis scenarios (Table A-5).

## 4.2 Discussion of Cost Estimates

This section compares the results of cost estimates impacted by treatment system variables, such as background water quality and influent MTBE concentrations. The cost for both principal MTBE treatment scenarios and sensitivity analysis scenarios defined by the Partnership (2000) for evaluation are considered. Table 4.3 presents a summary of estimated

**Table 4.3**  
Cost Estimates for Principal MTBE Treatment Scenarios

Treatment Scenario	Changeouts per Year <sup>A</sup>	Capital Cost (\$)	Annual O&M (\$)	Total Annual Cost (\$)	Unit Cost (\$/1,000 gal)
60-gpm treatment system, one line of three vessels-in-series. Low to moderate NOM fouling, no other contaminants.					
20 ppb MTBE	2.1	\$234,000	\$61,000	\$80,000	\$2.54
200 ppb MTBE	3.0	\$234,000	\$75,000	\$94,000	\$2.99
2,000 ppb MTBE	7.1	\$234,000	\$114,000	\$133,000	\$4.22
600-gpm treatment system, two lines of three vessels-in-series. Low to moderate NOM fouling, no other contaminants.					
20 ppb MTBE	2.8	\$1,019,000	\$248,000	\$331,000	\$1.05
200 ppb MTBE	4.0	\$1,019,000	\$314,000	\$396,000	\$1.26
2,000 ppb MTBE	9.4	\$1,019,000	\$626,000	\$708,000	\$2.24
6,000-gpm treatment system, twelve lines of three vessels-in-series. Low to moderate NOM fouling, no other contaminants.					
20 ppb MTBE	4.6	\$5,979,000	\$1,976,000	\$2,458,000	\$0.78
200 ppb MTBE	6.7	\$5,979,000	\$2,706,000	\$3,188,000	\$1.01
2,000 ppb MTBE	15.6	\$5,979,000	\$5,674,000	\$6,156,000	\$1.95

<sup>A</sup> Predicted based on RSSCT testing. (See Table 4.1 and Appendix A).

Primary assumptions for cost estimates given above; effluent from the system contains no detectable MTBE (<0.5 ppb).

6. As shown in the example cost-estimate spreadsheet included in Appendix A, the predicted number of changeouts per year is a critical parameter for the estimated costs.

**Table 4.4**  
Cost Estimates for Sensitivity Analysis

Treatment Scenario <sup>A</sup>	Changeouts per Year <sup>B</sup>	Capital Cost (\$)	Annual O&M (\$)	Total Annual Cost (\$)	Unit Cost (\$/1,000 gal)
<b>NOM Fouling</b>					
High Fouling	5.9	\$1,019,000	\$419,000	\$501,000	\$1.59
Moderate Fouling	2.8	\$1,019,000	\$248,000	\$331,000	\$1.05
Low Fouling	2.4	\$1,019,000	\$227,000	\$309,000	\$0.98
<b>BTX/TBA Load</b>					
High NOM Fouling, 20 ppb MTBE 300 ppb Total BTX	8.4	\$1,019,000	\$555,000	\$637,000	\$2.02
Low NOM Fouling, 1,958 ppb MTBE 2,000 ppb Total BTX	13.2	\$1,019,000	\$818,000	\$900,000	\$2.85
Moderate NOM Fouling, 1,030 ppb MTBE 100 ppb TBA	8.0	\$1,019,000	\$533,000	\$615,000	\$1.95
<b>Design Life</b>					
2 years	2.8	\$1,019,000	\$248,000	\$789,000	\$2.50
10 years	2.8	\$1,019,000	\$248,000	\$374,000	\$1.19
30 years	2.8	\$1,019,000	\$248,000	\$331,000	\$1.05

<sup>A</sup> Primary assumptions for cost estimates given above:  
600-gpm systems.  
Two parallel lines of three beds in-series.  
Moderate NOM fouling, unless otherwise noted.  
Influent MTBE = 20 ppb, unless otherwise noted.  
Effluent from system contains no detectable MTBE (<0.5 ppb).

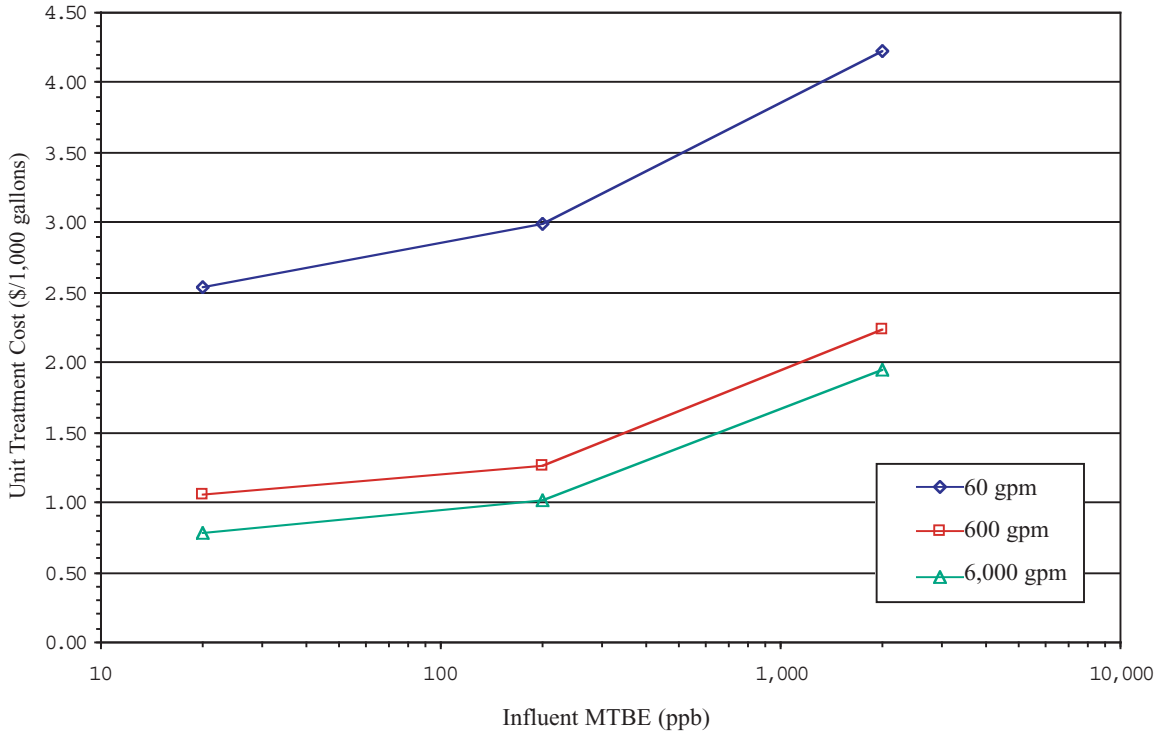
<sup>B</sup> Predicted based on RSSCT testing (see Table 4.1 and Appendix A).

costs for the principal MTBE treatment scenarios while Table 4.4 summarizes estimated costs for the sensitivity analysis scenarios.

All of the cost estimates in this report were developed for public drinking-water systems requiring a high level of treatment reliability. Cost accuracy is expected to be within  $\pm 50$  percent. Appendix A presents cost-estimating methods in enough detail such that the reader can estimate feasibility-level GAC costs for a wide range of treatment conditions by changing the appropriate variables for their own application.

#### 4.2.1 Impact of Influent MTBE Concentration

Figure 4.2 presents unit treatment cost versus influent MTBE concentration for the principal scenarios, illustrating that unit costs increase substantially with increasing influent concentrations. As presented in Table 4.3, for 20-ppb treatment systems, the estimated unit



**Figure 4.2** Estimated unit treatment cost versus influent MTBE concentration (low to moderate NOM fouling, no other contaminants present).

costs vary from \$0.78/1,000 gallons to \$2.54/1,000 gallons, depending on the system flow rate. For 200- and 2,000-ppb treatment systems, estimated unit costs vary from \$1.01 to \$2.99/1,000 gallons, and from \$1.95 to \$4.22/1,000 gallons, respectively.

Considering the 600-gpm systems, unit treatment costs vary by more than 100 percent depending on influent MTBE concentrations between 20 ppb (\$1.05/1,000 gallons) and 2,000 ppb (\$2.24/1,000 gallons).

#### 4.2.2 Impact of Background Water Quality

Sensitivity analyses based on RSSCT results show that optimal carbon usage rate<sup>7</sup> for MTBE removal varies by as much as 150 percent, depending on the degree of NOM fouling (Table 4.2). Table 4.4 shows that estimated unit treatment costs for a 600-gpm system treating 20 ppb MTBE vary from \$0.98/1,000 gallons to \$1.59/1,000 gallons for water with low and high NOM fouling, respectively. This variance in the carbon usage rate corresponds to unit treatment cost differences of over 60 percent.

7. The variance in the GAC usage rate for the range of water conditions is less than that reported in Section 3.1, in which EBCT was kept constant at 10 minutes for each of the water types. For the cost estimates, it was assumed that EBCT was optimized for each water type. High NOM fouling water requires longer EBCTs, as discussed in Section 3.3, which results in lower usage rates and, thus, less overall variation between water types.

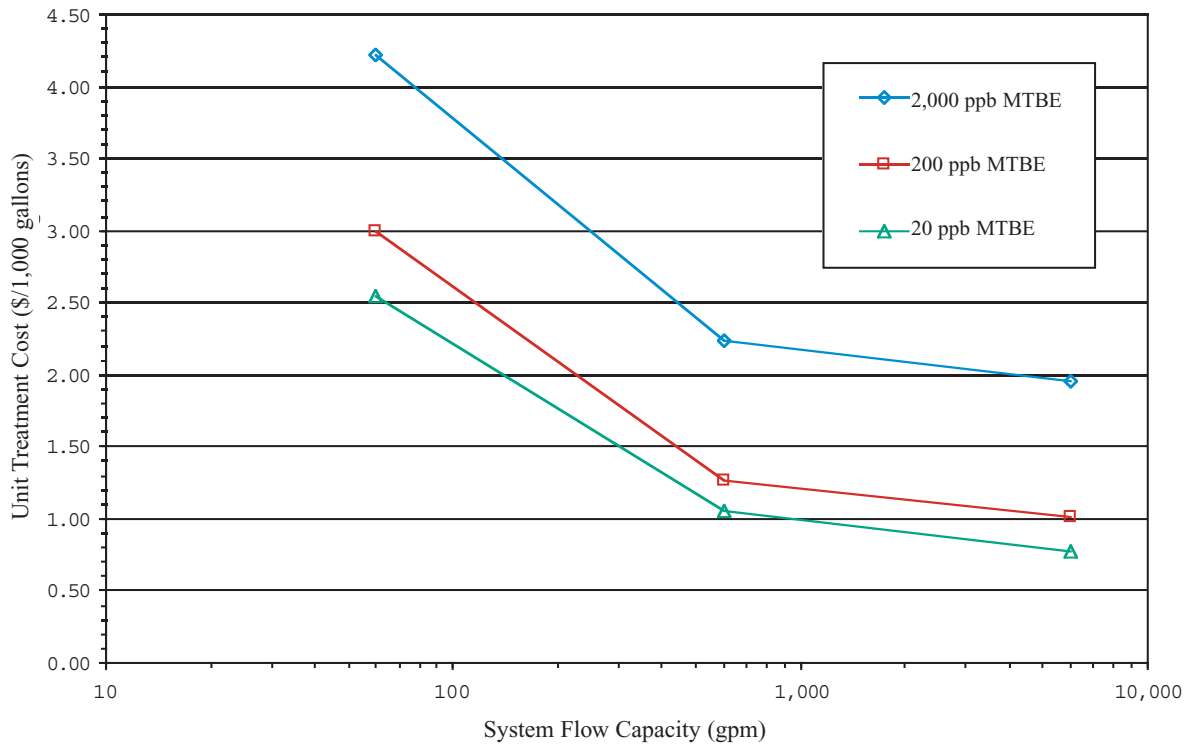
### 4.2.3 Impact of BTX

Two RSSCT comparisons are available for evaluating BTX impacts to GAC cost effectiveness for MTBE removal. The first pair of comparison tests (R1 and R4) are presented in Figure 3.7, which shows MTBE breakthrough curves for low NOM influent water (Tahoe groundwater) with approximately 2,000 ppb MTBE. For one of the tests, 1,977 ppb Total BTX was spiked into the influent water, causing unit treatment costs to increase by 27 percent (\$2.24/1,000 gallons versus \$2.85/1,000 gallons), as presented in Table 4.3 (600 gpm, 2,000 ppb MTBE) and Table 4.4.

The second pair of the comparison tests (R15 and R16) is presented in Figure 3.8, which shows MTBE breakthrough curves for high NOM influent water (Lake Perris surface water) with 20 ppb MTBE. For one of the tests, 300 ppb Total BTX was spiked into the influent water, causing unit treatment costs to increase by 27 percent (\$1.59/1,000 gallons versus \$2.02/1,000 gallons, see Table 4.4).

### 4.2.4 Impact of Flow Rate

Figure 4.3 shows the relationship of unit treatment cost versus system flow capacity for different influent MTBE concentrations. Based on the cost estimates, which are presented in Table 4.3, there is a distinct economy of scale at flow rates up to about 600 gpm. Up to this



**Figure 4.3** Estimated unit treatment cost versus system flow capacity (low to moderate NOM fouling, no other contaminants present).

capacity, unit costs decrease substantially as system flow capacity increases. With assumed conditions of 20 ppb MTBE influent, unit treatment costs decrease by over 140 percent as flow rate is increased from 60 to 600 gpm (\$2.54/1,000 gallons versus \$1.05/1,000 gallons). The economy of scale is less pronounced above 600 gpm, as unit treatment costs drop by 35 percent between 600 and 6,000 gpm (\$1.05/1,000 gallons versus \$0.78/1,000 gallons).<sup>8</sup>

#### **4.2.5 Impact of System Design Life**

To investigate how unit treatment costs are affected by system design life, this parameter was varied between 2 and 30 years. With assumed treatment conditions of 600 gpm and 20 ppb MTBE influent, unit costs were estimated for 2- and 10-year design periods, in addition to the 30-year period used for the principal scenario estimates. The results of these project duration sensitivity analyses, which are presented in Table 4.4 and Appendix A, indicate that the unit treatment cost increases by over 150 percent when the design period is changed from 30 to 2 years. As shown on Table 4.4, predicted unit costs increase from \$1.05/1,000 gallons for a 30-year design life to \$2.50/1,000 gallons for a 2-year design life. Although this may seem to be a dramatic change, it is less than the unit cost increases expected for more capital-intensive treatment technologies (Partnership, 2000). Because the total annual costs for GAC systems are highly dependent on O&M costs, the assumed system design life does not impact the unit treatment cost as much as for higher capital technologies. As such, the expected project duration is an important variable to consider when comparing the costs of treatment technologies.

---

8. This lack of economy of scale for flowrates higher than 600 gpm is primarily because the largest standard carbon vessels are designed for maximum flow rates of approximately 500 to 600 gpm. Flow rates above this level are handled by operating multiple vessels in parallel; hence, there are no significant capital savings for higher flow rates.

## 5.0 Case Studies of Full-scale GAC Systems

---

This section discusses the performance results of recent full-scale GAC systems as compared to the results of the column testing completed for this research. Two sites at which full-scale GAC systems have been used for MTBE removal from water were identified for this report; both of these sites are municipal drinking-water systems that have been impacted by MTBE. This section briefly summarizes the critical data for each of the case study sites, and then considers data from comparable column tests (Section 3) and comparable cost estimates (Section 4.0). For this report, the names and precise locations of both sites will be kept confidential. For further details regarding the case study sites, refer to Appendix B.

### 5.1 Case Study A: Public-supply Wells, California

At this site, public water-supply wells were impacted by MTBE and TBA from an extensive release of MTBE-enhanced gasoline. Column testing and full-scale GAC testing were completed at the case study site; the column tests modeled the performance of both coal-based GAC and coconut shell GAC, while the full-scale test was performed using coal-based GAC. The influence of TBA was also evaluated at the site.

Based on the results of column testing performed for this site, it appears that coconut shell GAC is substantially more effective for MTBE removal than coal-based GAC. For one column test scenario (200 ppb MTBE, no TBA), coal-based GAC usage rates at initial breakthrough, 50-percent breakthrough, and saturation were more than three times higher than those measured for coconut shell GAC.<sup>9</sup> The prediction that coconut shell GAC performs better for MTBE than coal-based GAC is consistent with isotherm tests presented by the Partnership (2000).

For the full-scale test, the site operators selected a coal-based GAC for evaluation (note: the rationale for this selection is unclear). With an average influent MTBE concentration of 175 ppb, MTBE first broke through the system 3.5 weeks after startup.<sup>10</sup> Assuming a constant flow rate of 300 gpm, the first breakthrough corresponds to a usage rate of approximately 1.9 pounds/1,000 gallons. This is consistent with the coal-based GAC usage rate (2.3 pounds/1,000 gallons) for initial breakthrough, as determined by column testing at the site. In comparison, an RSSCT with coconut shell GAC (test R7, 209 ppb MTBE, moderate NOM fouling) predicts an initial breakthrough usage rate of 0.8 pounds/1,000 gallons. Again,

---

9. The usage rate values presented for coconut shell GAC (0.55 pounds/1,000 gallons at 50-percent breakthrough; 0.4 pounds/1,000 gallons for saturation) are similar to those resulting from comparable RSSCT performed for this research (test R7, 209 ppb MTBE, PCB GAC: 0.48 pounds/1,000 gallons at 50-percent breakthrough; 0.33 pounds/1,000 gallons at saturation).

10. System operators suspect iron fouling caused early MTBE breakthrough of the lead vessel. This vessel, which required periodic backflushing during the test, was kept on-line as an iron pretreatment for the lag vessel. The usage rate calculations presented here ignore the contribution of the lead vessel.

based on GAC performance data from this site, it appears that coconut shell GAC will outperform coal-based GAC for MTBE removal.

In both laboratory and full-scale testing, TBA broke through the GAC system rapidly, suggesting that TBA, if regulated, may drive GAC changeout criteria at sites impacted with both MTBE and TBA. Not enough data are available to determine TBA impacts to GAC usage rates for the full-scale test.

## **5.2 Case Study B: Public-supply Wells, Kansas**

At this site, public water-supply wells were impacted by MTBE-enhanced gasoline that leaked from an underground storage tank (UST). A full-scale GAC system was installed to treat a combined, multi-well flow rate up to 450 gpm of groundwater with an expected MTBE concentration of less than 20 ppb. The system design includes two 20,000 pounds vessels in-series with a single vessel EBCT of 15 minutes. Bituminous coal-based GAC was selected for use.

The system was put on-line in May 2000 and has been operating successfully ever since; no GAC changeouts have been required thus far. Since startup, influent MTBE concentrations have averaged approximately 20 ppb, with a flowrate of about 300 gpm. A single high hit (184 ppb MTBE) was measured 2.5 weeks after startup, which likely accelerated the breakthrough of the lead vessel 30 days after system startup.<sup>11</sup> Other than this single high detection, all other influent measurements have shown MTBE at below 20 ppb. No other gasoline contaminants have been detected in the supply wells other than a single measurement of TBA at 21 ppb.

Appendix B presents a graph (Figure B-1) of influent and midfluent (between lead and lag GAC vessels) MTBE concentrations. It is suspected that the lead vessel has just about reached saturation, considering an average influent of approximately 20 ppb. At 50-percent breakthrough (about 10 ppb MTBE midfluent), the GAC usage rate is estimated to be 0.22 pounds/1,000 gallons. This coal-based GAC performed better than high-grade coconut shell GAC is expected to perform, based on results of RSSCTs performed using similar water conditions. In the two most comparable RSSCTs, the usage rates at 50-percent breakthrough varied from 0.30 pounds/1,000 gallons (Tahoe groundwater, PCB GAC, R5) to 0.39 pounds/1,000 gallons (Arcadia groundwater, PCB GAC, R8).

The results at this site show that bituminous coal-based GAC can sometimes perform as well as needed for MTBE removal. With this in mind, system designers should consider evaluating coal-based GAC during feasibility analysis and treatment system design, though coconut shell GAC is expected to perform better than coal-based GAC under most

---

11. At most sites, MTBE concentrations in extracted groundwater can be expected to vary like they have at this case study site.

conditions. The surprising performance results of this case study indicate that bench-scale testing with site-specific water and candidate GACs is a critical step for accurately predicting performance and determining optimum system design.

It is important to remember that the lag vessel (after it becomes the lead vessel) will not last as long as the initial lead vessel before saturation is reached, as it has already adsorbed some MTBE. At this site, the influent to the lag vessel (midfluent) contained MTBE since 30 days after startup (after the first breakthrough of the lead vessel). As such, the 50-percent GAC usage rate estimated for the initial lead vessel (i.e., 0.22 pounds/1,000 gallons) is considered a good, conservative assumption for estimating the *average* changeout frequency of all vessels that are used after the initial lead vessel is changed out, assuming that influent MTBE levels stay consistent.

Based on the costs reported for the GAC system at this case study site, installing and operating full-scale GAC systems can, in some cases, be significantly less costly than the estimates presented in Section 4 of this report. The discrepancy between these costs is attributed in part to the conservative assumptions made for the Section 4 cost estimate (e.g., fixed-percent costs for plumbing and electrical, contractor O&P, engineering, site work, and contingency). In addition, the costs at this site are particularly low because of oversight by cooperating local/state government agencies and because of competitive bidding between local GAC contractors and generally lower costs in Kansas.

### **5.3 Summary**

GAC usage rates estimated from these two full-scale systems are generally consistent with those predicted by the column tests presented in Section 3, though differing treatment conditions do not allow direct quantitative comparisons to be made. At the California case study site, coal-based GAC used at full-scale (300 gpm) performed poorly in comparison to coconut shell GAC at bench-scale, as predicted by column testing at the site; however, at the Kansas case study site, the performance of coal-based GAC was better than that expected from a high-quality coconut shell GAC based on RSSCTs performed for this research. The primary conclusion that can be drawn from this contradictory evidence is that site-specific testing of candidate GACs with site water is recommended for predicting full-scale GAC performance.

There are undoubtedly more full-scale GAC systems being used to remove MTBE from drinking-water supplies, though such field data were not available at the time of this report. As those additional sites produce more field data in the coming years, the scientific understanding of full-scale GAC systems is expected to improve.



## 6.0 Conclusions

---

This section summarizes the findings of the Partnership's GAC research program for MTBE. Section 6.1 compares the results of computer modeling presented elsewhere (Partnership, 2000) and the dynamic column testing discussed in Section 3 of this report. Section 6.2 discusses the relative accuracy of column testing by comparing results with data from full-scale GAC case studies, as presented in Section 5 and Appendix B. Section 6.3 blends together the results of column testing, cost estimates, and full-scale case studies to give the reader a sense of how different site conditions (e.g., background water quality, MTBE concentrations) impact the implementation of GAC. Section 6.4 gives a brief comparison of costs estimated in this report with those presented elsewhere for other water-treatment technologies (Partnership, 2000). Finally, Section 6.5 summarizes the major findings of this report and discusses some future considerations and research needs for MTBE removal using GAC.

### 6.1 Comparison of Computer Modeling and Column Testing

As part of the Partnership's overall research plan for GAC, the results of computer adsorption modeling<sup>12</sup> presented previously by the Partnership (2000) were compared with bench-scale GAC performance determined by dynamic column testing (Section 3). In general, the computer modeling did quite well predicting MTBE breakthrough behavior for the higher influent concentrations (200 and 2,000 ppb MTBE). Although different assumptions were used to determine changeout frequencies for this report and the Treatability report (Partnership, 2000), the predicted changeouts per year for all of the higher concentration scenarios were within 20 percent. In each case, the values predicted using the computer modeling results were less conservative (i.e., lower changeout frequencies) than those predicted using the column test data.

When influent MTBE concentrations were set at 20 ppb, the computer model underestimated the GAC usage rates such that changeout frequencies were significantly less (<50 percent) than those predicted using column test data. It should be noted that different assumptions were used for estimating changeout frequencies from GAC usage rates determined by computer modeling and dynamic column testing. These different assumptions may have contributed to the discrepancy between estimated changeout frequencies. Regardless, it is recommended that the reader consider the usage rate values and the cost estimates presented in this report to be more accurate than those presented previously (Partnership, 2000).

### 6.2 Comparison of Column Testing and Full-scale Water Treatment

Another aspect of the Partnership's GAC research program was to compare full-scale GAC performance with the results of dynamic column testing. Unfortunately, this "ground-

---

12. Modeling was performed using the AdDesignS computer model created by Michigan Technological University (Mertz et al., 1994). This model consists of equilibrium and mass transfer models that can be used to simulate multi-component adsorption in fixed-bed absorbers.

truthing” of the column tests was limited because the only two full-scale case studies identified for this research used coal-based GACs for MTBE removal. As the majority of the column testing focused on coconut shell GAC, no direct comparisons can be made between the results of the dynamic column testing presented in Section 3 and the full-scale GAC performance at the case study sites.

However, even with this constraint, the results of the case study sites remain interesting and educational. At first glance, it seems that the performance results of the case studies are contradictory. At the Kansas site, the coal-based GAC has performed quite well (no changeouts after 1 year of operation); at the California site, the coal-based GAC did not perform as well as hoped (MTBE breakthrough of lag vessel after 3.5 weeks). Results from the California case study, which included column testing with the site water, indicate that coconut shell GAC is likely to be a more cost-effective choice than coal-based GAC. In contrast, at the Kansas site, the coal-based GAC appears to be a cost-effective selection. Why are the results of these two case study sites so different? This question cannot be answered with certainty, though it is suspected that the coal-based GAC at the Kansas site is performing well because the influent MTBE concentrations are quite low (i.e., <20 ppb). In addition, it is likely that the groundwater at this Kansas site is quite clean with respect to NOM. In contrast, at the California site, the influent MTBE concentrations are higher (100 to 280 ppb) and the background NOM is suspected to be moderate. These two differences in treatment conditions (i.e., influent MTBE concentration and background NOM) can clearly have strong impacts on GAC usage rates, as shown by the column testing presented in this report (Sections 3.1 and 3.2). More extensive background water-quality analyses would be needed to verify these preliminary interpretations.

Again, the reader is reminded that background water quality and other site conditions, such as influent MTBE concentrations, can dramatically impact GAC performance for MTBE removal; as such, it is highly recommended that site-specific testing (either isotherm testing and/or column testing with site water) be performed prior to GAC system design.

### **6.3 Impact of Treatment Conditions on GAC Performance and Cost**

#### **6.3.1 Background Water Quality**

The impact of background NOM on GAC effectiveness for MTBE removal was evaluated in this report by comparing usage rates and breakthrough curves from RSSCTs using three separate water sources (two groundwaters and one surface water). The differences in breakthrough behavior illustrated in Figure 3.1 indicate that NOM conditions can cause up to a four-fold variance in GAC usage rates (at 50-percent breakthrough, equivalent EBCTs). Because of the dramatic impact that NOM can have on GAC adsorption effectiveness, site-specific testing is highly recommended to accurately predict full-scale GAC performance for MTBE removal.

The results of RSSCTs show that the carbon usage rate for MTBE removal, assuming best-case EBCT for each of the waters, varies by as much as 150 percent, depending on the degree of NOM fouling (Table 4.2). For a 600-gpm system treating 20 ppb MTBE, this variance in the carbon usage rate results in estimated unit cost differences of over 60 percent. Table 4.4 shows that estimated unit treatment costs for these assumed conditions vary from \$0.98/1,000 gallons to \$1.59/1,000 gallons for water with low and high NOM fouling, respectively.

With regards to predicting NOM impacts to GAC effectiveness, the water-quality analyses and results of RSSCTs presented in this report show that TOC is inversely related to GAC performance (Table 3.2). These results suggest that TOC can be used as an indicator of NOM fouling potential; however, other studies contradict this finding, indicating that TOC is not always a good indicator of GAC adsorption effectiveness for MTBE (Zimmer et al., 1988; Summers et al., 1989). Due to these contradictory findings, it is recommended that testing be performed using the site water and candidate GACs (column testing or, at the least, isotherm testing). Of course, if the water source is known to have high NOM levels (e.g., typical surface waters), it should be expected that GAC performance for MTBE removal will be relatively poor.

### **6.3.2 Influent MTBE Concentrations**

As expected, comparisons of RSSCT results show that the GAC usage rate is highly dependent on the influent MTBE concentration. The impact of the influent MTBE concentration on adsorption effectiveness is illustrated in Figure 3.2, which presents the results of RSSCTs on Tahoe groundwater spiked with relatively high (1,950 ppb) and low (20 ppb) concentrations of MTBE. Comparing the breakthrough data for the two tests (R2, R5), the GAC usage rate at 50-percent breakthrough varies by almost 400 percent. The same effect, though less exaggerated, is illustrated in Figure 3.3, which shows the results of column testing of Arcadia groundwater spiked with 50 and 220 ppb MTBE.

Figure 4.2 presents the relationship of unit treatment cost versus influent MTBE concentration for the principal scenarios, illustrating that unit costs increase substantially with increasing influent concentrations. For these scenarios, unit costs vary by more than 100 percent, depending on influent MTBE concentrations between 20 ppb (\$1.05/1,000 gallons) and 2,000 ppb (\$2.24/1,000 gallons).

### **6.3.3 EBCT**

Under certain conditions, EBCT can substantially impact the breakthrough of MTBE. For example, it appears that breakthrough behavior is dependent on EBCT for low influent MTBE concentrations in relatively high NOM water. Under these conditions, as illustrated in Figure 3.6, EBCTs longer than 10 minutes are required to optimize MTBE removal.

Although RSSCTs presented in this report suggest that EBCTs between 10 and 20 minutes do not measurably impact MTBE breakthrough behavior for low to moderate NOM waters (see Figures 3.4 and 3.5), it is uncertain whether influent MTBE concentration is also a factor. It is possible that breakthrough behavior is dependent on EBCT for relatively low influent MTBE (e.g., 20 ppb), regardless of the background water-quality conditions. Further research is required to more clearly identify water conditions under which EBCT impacts MTBE breakthrough. No analyses were performed to evaluate EBCT impacts to the cost of MTBE removal using GAC.

#### **6.3.4 BTX Load**

Results of RSSCTs confirm that the presence of BTX accelerates the breakthrough of MTBE. For Tahoe groundwater spiked with approximately 2,000 ppb MTBE, the addition of approximately 2,000 ppb Total BTX increased the GAC usage rate by over 40 percent at the 50-percent breakthrough point. Similar increases were observed for Lake Perris surface water spiked with 20 ppb MTBE, when Total BTX at 300 ppb was added to the influent. These increases in GAC usage caused by the presence of BTX resulted in estimated unit treatment cost increases of over 25 percent for both water types.

An important finding of the RSSCT study was observed during the testing that included Total BTX. As shown on Figures 3.7 and 3.8, effluent MTBE levels continue to rise higher than the influent level ( $C/C_0 > 1$ ) after reaching saturation. This effect is attributed to MTBE desorption from the GAC matrix as the more strongly adsorbed BTX compounds move downgradient in the column and displace previously adsorbed MTBE molecules. Because of this effect, desorption is an important phenomenon to consider when designing GAC treatment systems and sampling protocol, particularly for weakly adsorbing compounds, such as MTBE.

#### **6.3.5 TBA Load**

No direct comparison of RSSCT results can be made that clarify the impact of TBA on GAC effectiveness for MTBE removal; however, based on several RSSCTs with similar treatment conditions (Arcadia groundwater, PCB GAC; see Figure 3.9), it appears that the addition of 100 ppb TBA did not dramatically affect MTBE breakthrough behavior.

It is important to note that the effluent of the RSSCTs was not monitored for TBA; as such, it is unknown when, or if, TBA broke through the RSSCT column. This is important to note because at the California case study site, in both laboratory and full-scale testing, TBA broke through the GAC system rapidly, prior to MTBE breakthrough. These results suggest that TBA, if regulated, may drive GAC-changeout criteria at sites impacted with both MTBE and TBA.

### 6.3.6 GAC Type

No RSSCTs were performed that allow for direct quantitative comparisons between coconut shell GAC and coal-based GAC; however, indirect conclusions can be drawn from some of the tests. Figure 3.10 shows that under similar test conditions (Arcadia groundwater, 100 ppb TBA), coconut shell performed better than coal-based GAC, removing higher MTBE concentrations (1,000 ppb versus 200 ppb) at approximately the same usage rate. The similarity of the test results suggests that, in comparison to coal-based GAC, coconut shell GAC is more effective for MTBE removal from Arcadia groundwater.

This tentative conclusion is consistent with the results of isotherm testing (Partnership, 2000) and with the California case study where coconut shell GAC outperformed coal-based GAC; however, as discussed by Calgon (2000), it should be noted that the natural variability of coconut shell carbons is reportedly more difficult to control than that of coal-based carbons, which come from source materials that are generally homogeneous. This variability of coconut shell carbons may cause the need for increased QA/QC efforts during the approval of GAC products for changeout events.

In spite of the conclusion about GAC type effectiveness given above, the Kansas case study suggests that coal can sometimes work as well as needed. In addition, coal-based GAC is expected to be cheaper per pound though, at most sites, it is expected that, overall, coconut shell will be more cost-effective. Of course, site-specific testing is necessary for the selection of optimum GAC and other design parameters.

## 6.4 Cost Comparison to Other Technologies

This section discusses the estimated unit treatment costs for GAC in comparison with those of other technologies. The cost estimates presented here and those costs previously reported in the Treatability report (Partnership, 2000) were developed using a number of important costing assumptions. These assumptions are not meant to be representative of all sites and, therefore, those cost estimates should be viewed primarily for comparative purposes. The cost presented here are expected with be accurate within  $\pm 50$  percent.

Table 6.1 presents estimated costs for several technologies, including air stripping, AOPs, adsorptive resins, and GAC. These costs, which were developed for both the Treatability report and this report, were estimated for a 600-gpm flow rate system treating MTBE in water with moderate NOM fouling conditions.<sup>13</sup> As shown, there are three separate entries for air stripping (packed tower, low profile, packed tower with off-gas treatment), along with estimates previously developed for GAC, AOP, and resins. The new costs developed for GAC in this report, which used the results of column testing, are presented at the bottom of Table 6.1.

---

13. A number of standardized costing assumptions were used to develop these estimates. Details are presented in Appendix A.

**Table 6.1**  
Comparison of Reference Cost Estimates for Different Technologies

Treatment Technology	Unit Treatment Cost (\$/1,000 gals)		
	20 ppb <sup>A</sup>	200 ppb <sup>B</sup>	2,000 ppb <sup>B</sup>
Air Stripping, Packed Tower (Partnership, 2000)	0.34	0.37*	0.91*
Air Stripping, Low Profile (Partnership, 2000)	0.92	1.09	1.09
Air Stripping, Off-gas Treatment (Partnership, 2000)	Not Reported	1.09	1.09
Advanced Oxidation Processes (Partnership, 2000)	0.90	0.95	1.19
Adsorptive Resins (Partnership, 2000)	1.01	1.17	1.38
GAC (Partnership 2,000)	0.77	1.15	2.37
GAC per column testing of this report <sup>C</sup>	1.05	1.26	2.24

<sup>A</sup> Removal rates >97.5 percent.

<sup>B</sup> Removal rates >99.5 percent.

<sup>C</sup> Predicted based on RSSCT testing (see Table 4.1 and Appendix A).

\* May require off-gas treatment.

Primary assumptions for cost estimates given above; 600-gpm systems; moderate NOM fouling; system design life 30 years.

Consider first the GAC cost estimates generated previously (Partnership, 2000) in comparison with those developed for this report. At the two higher influent MTBE scenarios (200 and 2,000 ppb), estimated unit treatment costs were within 15 percent. Unit costs for the 20-ppb scenario, however, varied by 36 percent (\$1.05 versus \$0.77 per 1,000 gallons), as the computer model predicted better full-scale GAC performance than the column testing. As discussed in Section 6.1, column testing indicated that the model underestimated changeouts per year by 50 percent for the 20 ppb scenario, causing unit treatment costs for GAC to rise by 36 percent from those estimated using the modeling results.

Table 6.1 can also be used to see which technologies are cost-competitive for varying influent MTBE concentrations. From a comparative view, GAC appears to be the least cost-effective technology of the four treatment technologies evaluated in the Treatability report (Partnership, 2000), especially at higher MTBE concentrations. At 2,000 ppb, the unit treatment costs of the

technologies range from \$0.91 to \$2.24 per 1,000 gallons. GAC has the highest estimated costs for this treatment scenario, and it appears that air stripping, either with or without off-gas treatment, is the most cost-effective selection. Resins and AOP are competitive with stripping cost-wise, though neither of these emerging technologies has well documented treatment reliability (Partnership, 2000).

For 200 ppb MTBE, the estimated unit costs for a packed tower air stripper with no off-gas treatment are once again the least expensive (\$0.37/1,000 gallons). If off-gas treatment is required, the remaining technologies all become cost-competitive. Unit costs for the other technologies, including GAC (\$1.26/1,000 gallons), varied by no more than 33 percent, which is well within the expected accuracy of the estimates.

The results at 20 ppb influent MTBE were similar to those for 200 ppb. The unit treatment cost estimated for air stripping without off-gas treatment was \$0.34/1,000 gallons, which was more than 2.5 times cheaper than AOP, the closest cost competitor (\$0.90/1,000 gallons). GAC unit costs were estimated to be \$1.05/1,000 gallons, which is within 20 percent of the estimated cost for AOP. Excluding air stripping with packed towers, GAC is cost-competitive with all of the other technologies at 20 ppb.<sup>14</sup>

The reader should note that the estimated costs were developed using specific assumptions that allowed for a direct comparison between technology costs. As such, the cost magnitudes presented here are only relevant considering the specific costing assumptions used for the estimates (e.g., 30-year design life, percent markups for design, contingency, etc.). The Kansas case study site shows that actual project costs can be lower than those generically estimated using the costing assumptions of this report. As such, the cost estimates presented here should be used primarily for comparative purposes.

Given the effective performance of GAC and the low project costs at the Kansas case study site, it may be that GAC is more likely to be selected as a technology of choice than the cost comparisons on Table 6.1 suggest. In spite of its apparently higher costs versus other technologies, it is important to remember that GAC is a simple technology to implement. Design and capital costs are usually significantly less than more innovative technologies (AOPS, adsorptive resins), and achieving effluent with non-detectable contaminant levels is the expected performance for GAC. Also, no off-gas treatment or air discharge permits are required, and regulatory agencies generally view GAC as reliable. Considering these advantages, GAC is an important technology to consider when evaluating treatment options for removing MTBE, particularly for low influent MTBE levels.

---

14. If the estimated usage rate for the Kansas case study site is used in the Partnership's cost estimating structure, the calculated unit treatment cost is \$0.86/1,000 gallons.

## 6.5 Summary and Future Considerations

The major findings of this report include the following:

- Through modeling, column testing, and case studies, it has been shown that various types of GAC can successfully remove MTBE from groundwater, surface-water, and drinking-water sources.
- Computer modeling presented in the Partnership's Treatability report (2000) generally underestimates GAC usage; the results of column testing are more conservative and more reliable.
- Background water quality plays a large role in GAC effectiveness. The GAC usage rate is substantially higher when background NOM levels are high.
- GAC is more likely to be cost-effective for relatively low concentrations of MTBE. Based on cost estimates prepared for this research and the Treatability report, GAC is cost-competitive with most other technologies when MTBE is at or below 200 ppb. The exception is air stripping without off-gas treatment, which is consistently the least expensive treatment method where allowed.
- EBCT is an important variable to consider when designing GAC systems for MTBE removal. Column testing suggests that longer EBCTs (e.g., 20 minutes) are required when background NOM is high. Uncertainty remains as to whether low influent MTBE concentrations also require longer EBCTs for optimal MTBE removal.
- Column testing shows that the presence of BTX can increase the GAC usage rate for MTBE removal substantially. MTBE desorption from the GAC matrix, which results in effluent MTBE levels exceeding influent levels, should be expected when BTX is present.
- Column tests show that TBA breaks through GAC systems rapidly. Not enough data are available to determine the impact of TBA on GAC effectiveness for MTBE.
- It appears that coconut shell GAC will be more cost-effective for MTBE removal under most situations; however, as shown by one of the full-scale case studies, coal-based GAC can sometimes be cost-effective for low concentrations of MTBE.

The American Water Works Association is currently sponsoring research on the effects of GAC surface chemistry and pore structure on the adsorption of MTBE and atrazine from natural waters. This study, which is being performed by North Carolina State University, is expected to be completed in 2001. Other topics for future GAC research might include:

- Incorporation of dynamic column testing results as calibration data for computer modeling (which would allow for additional scenarios to be analyzed and, eventually, may allow computer models to be used with greater confidence for predicting GAC performance for MTBE removal).

- Correlation of column testing with full-scale coconut shell GAC performance.
- Clear quantitative performance comparison of coconut shell GAC with high-grade coal-based GAC under dynamic testing conditions.
- Research on coconut shell GAC variability.
- Development of an analytical test that reliably quantifies the expected NOM fouling potential of different waters.



## 7.0 References

---

Calgon Carbon Corporation. Unpublished research data prepared for the California MTBE Research Partnership, July 2000.

California MTBE Research Partnership. *Treatment Technologies for Removal of Methyl Tertiary Butyl Ether (MTBE) from Drinking Water: Air Stripping, Advanced Oxidation Processes, Granular Activated Carbon, Synthetic Resin Sorbents*. 2d ed. Fountain Valley, CA: National Water Research Institute, 2000.

Crittenden, J.C., P.S. Reddy, H. Arora, J. Trynoski, D.W. Hand, D.L. Perram, and R.S. Summers. "Predicting GAC Performance with Rapid Small-scale Column Tests," *Journal American Water Works Association* (January, 1991): 77-87.

Crittenden, J.C., P.S. Reddy, D.W. Hand, and H. Arora. "Prediction of GAC Performance Using Rapid Small-scale Column Tests," *American Water Works Association Research Foundation* (September 1989)

Hand, David. Senior Research Engineer, Environmental Engineering Center for Water and Waste Management, Michigan Technological University, Houghton, MI. Personal communication with author. May 1998.

Mertz, K.A., F. Gobin, D.W. Hand, D.R. Hokanson, and J.C. Crittenden. 1994. "Adsorption Design Software for Windows (AdDesignS)," Michigan Technical University.

Megonnell, Neal. Research and Development, Calgon Carbon Corporation, Pittsburgh, PA. Personal communication with author. April 2001.

Summers, R.S., B. Haist, J. Koehler, J. Ritz, G. Zimmer, and H. Sontheimer. "The Influence of Background Organic Matter on GAC Adsorption," *Journal American Water Works Association* (May 1989): 66-74.

University of California, Los Angeles. Unpublished research data prepared for the California MTBE Research Partnership, 2001.

Zimmer, G., J.C. Crittenden, H. Sontheimer, and D. Hand. "Design Considerations For Fixed-bed Adsorbers that Remove Synthetic Organic Chemicals in the Presence of Natural Organic Matter." Paper presented at The American Water Works Association Conference, Orlando, Florida, June 1988, 210-219.



## Appendix A: GAC System Cost Estimates

---

This appendix presents cost estimates for a range of MTBE-treatment scenarios using GAC technology. The cost estimates were developed based on the results of dynamic column testing (see Section 3 of this report), 1998 price quotes from carbon vendors, and standard cost estimating assumptions for feasibility-level evaluations (Partnership, 2000). The cost estimates presented here are considered to be accurate within  $\pm 50$  percent. For field applications, the actual carbon usage rates for site-specific conditions should be obtained via testing with site water, if higher accuracy cost estimates are required.

Table A-1 presents an example cost spreadsheet to illustrate the methods used for estimating costs. Details regarding the assumptions used in developing the predicted carbon usage rates, which impact the estimated O&M costs, are presented in Section 4; summaries of the changeout frequencies for the principal treatment scenarios and the sensitivity analyses are presented in Tables A-2 and A-3, respectively. Assumptions used for developing O&M labor costs for the principal treatment scenarios and the sensitivity analyses are presented in Tables A-4 and A-5, respectively. The assumptions used for developing the cost estimates are listed below.

### General Assumptions

Influent MTBE concentrations: 20 ppb, 200 ppb, 2,000 ppb.

Effluent water contains no detectable MTBE ( $<0.5$  ppb).

System flow rates: 60 gpm, 600 gpm, 6,000 gpm.

No pretreatment of influent water is required.

### Assumptions for Capital Costs

*Carbon adsorption unit:* Standard Carbonair vessels rated for the appropriate range of flow rates; costs for adsorber systems based on 1998 price quotes from Carbonair for purchasing and installing specific models. Capital cost includes initial fill with virgin, coconut shell GAC at \$1.25/pound (unit cost based on 1998 vendor price quote). All systems designed as a single line or parallel lines of three GAC vessels in-series.

*Piping, Valves, and Electrical:* 30 percent of capital cost for carbon adsorption unit.

*Site Work (e.g., clearing, grubbing, foundation placement):* 10 percent of capital cost for carbon adsorption unit.

*Contractor O&P:* 15 percent of capital cost for carbon adsorption unit, site work, and piping, valves, and electrical.

**Table A-1**  
**Example Cost Spreadsheet: Estimated Costs for Carbon Adsorption**

System Parameters: 60 gpm 20 ppb influent MTBE concentration Effluent contains no detectable MTBE (0.5 ppb)				
Item	Cost			
Carbon Adsorption Unit <sup>1</sup>	\$105,110			
SUBTOTAL+A40	\$105,110			
Piping, Valves, Electrical (30%)	\$31,533			
Site Work (10%)	\$10,511			
SUBTOTAL	\$147,154			
Contractor O&P (15%)	\$22,073			
SUBTOTAL	\$169,227			
Engineering (15%)	\$25,384			
SUBTOTAL	\$194,611			
Contingency (20%)	\$38,922			
TOTAL CAPITAL	\$233,533			
AMORTIZED CAPITAL <sup>2</sup>	\$18,820			
ANNUAL O&M	\$61,407			
TOTAL ANNUAL COST	\$80,226			
TOTAL COST PER 1,000 GALLONS TREATED	\$2.54			
Summary of Annual O&M Costs				
Item	Unit	Quantity	Unit Cost	Cost
Replacement Carbon <sup>3</sup>	event	2.1	\$3,125	\$6,563
Changeout Labor/Transport	event	2.1	\$1,000	\$2,100
O&M Labor <sup>4</sup>	year	1	\$21,000	\$21,000
Analytical Testing <sup>5</sup>	samples	156	\$200	\$31,200
Power (\$0.08/kWh)	kWhr	6,800	\$0.08	\$544
ANNUAL O&M				\$61,407

<sup>1</sup> Carbon system size: three 5,000-pound vessels in series.

<sup>2</sup> Amortization based on 30-year period at 7-percent discount rate.

<sup>3</sup> Based on \$1.25 per pound and 5,000 pound/event; changeout frequency per Table A-2.

<sup>4</sup> Includes analytical sampling, oversight during changeouts, and general system O&M.

<sup>5</sup> Based on three samples per weekly event, 52 weeks per year.

**Table A-2**  
**Predicted Carbon Usage Rates, Vessel Life, and Changeout Frequencies:**  
**Primary MTBE Treatment Scenarios**

Influent MTBE (ppb)	Measured Usage Rate <sup>A</sup> (lb/1000gal)	Predicted <sup>B</sup> Vessel Life (days)	Predicted <sup>B</sup> Changeouts per Year
20	0.35	175	2.1
200	0.51	120	3.0
2,000	1.19	52	7.1

Conditions: 60-gpm systems (moderate NOM fouling, no other contaminants).

Influent MTBE (ppb)	Measured Usage Rate <sup>A</sup> (lb/1000gal)	Predicted <sup>B</sup> Vessel Life (days)	Predicted <sup>B</sup> Changeouts per Year
20	0.35	132	2.8
200	0.51	91	4.0
2,000	1.19	39	9.4

Conditions: 600-gpm systems; two lines of 300 gpm (moderate NOM fouling, no other contaminants).

Influent MTBE (ppb)	Measured Usage Rate <sup>A</sup> (lb/1000gal)	Predicted <sup>B</sup> Vessel Life (days)	Predicted <sup>B</sup> Changeouts per Year
20	0.35	79	4.6
200	0.51	54	6.7
2,000	1.19	23	15.6

Conditions: 6,000-gpm systems; 12 lines of 500 gpm (moderate NOM fouling, no other contaminants).

<sup>A</sup> Fifty-percent breakthrough of MTBE per RSSCT results (see Tables 3.1 and 4.1).

<sup>B</sup> Calculated based on measured usage rate and system design (flow rate per line).

**Table A-3**  
 Predicted Carbon Usage Rates, Vessel Life, and Changeout Frequencies:  
 Sensitivity Analysis Scenarios

Influent Water Conditions	Measured Usage Rate <sup>A</sup> (lb/1000gal)	Predicted <sup>B</sup> Vessel Life (days)	Predicted <sup>B</sup> Changeouts per Year
High Fouling	0.75	62	5.9
Moderate Fouling	0.35	132	2.8
Low Fouling	0.30	154	2.4

Conditions: 600-gpm system, 20 ppb MTBE, no other contaminants (NOM fouling varies).

Influent Water Conditions	BTX/TBA Load	Measured Usage Rate <sup>A</sup> (lb/1,000gal)	Predicted <sup>B</sup> Vessel Life (days)	Predicted <sup>B</sup> Changeouts per Year
High NOM Fouling 20 ppb MTBE	300 ppb Total BTX	1.07	43	8.4
Low NOM Fouling 1,958 ppb MTBE	1,977 ppb Total BTX	1.68	28	13.2
Moderate NOM Fouling 1,030 ppb MTBE	100 ppb TBA	1.01	46	8.0

Conditions: 600-gpm system (MTBE varies, NOM fouling varies, BTX/TBA varies).

<sup>A</sup> Fifty-percent breakthrough of MTBE per RSSCT results (see Tables 3.1 and 4.2).

<sup>B</sup> Calculated based on measured usage rate and system design (flow rate per line).

Detailed configurations for each system are included in Appendix A.

**Table A-4**  
**Estimated Labor Costs for GAC Systems: Principal MTBE Treatment Scenarios**

Influent Concentration (ppb)	Sampling Frequency (samples/wk)	Analytical Sampling Annual Labor <sup>A</sup> (hours)	Predicted Changeouts per Year <sup>B</sup>	GAC Changeout Annual Oversight <sup>C</sup> (hours)	General O&M Annual Labor <sup>D</sup> (hours/wk)	Total Annual Labor (hours)	Total Annual Labor Cost <sup>E</sup> (\$)
2,000	3	156	7.1	28	208	392.4	\$31,000
200	3	156	3.0	12	104	272	\$22,000
20	3	156	2.1	8	104	268.4	\$21,000

Conditions: 60-gpm systems – One line of three vessels in-series.

Influent Concentration (ppb)	Sampling Frequency (samples/wk)	Analytical Sampling Annual Labor <sup>A</sup> (hours)	Predicted Changeouts per Year <sup>B</sup>	GAC Changeout Annual Oversight <sup>C</sup> (hours)	General O&M Annual Labor <sup>D</sup> (hours/wk)	Total Annual Labor (hours)	Total Annual Labor Cost <sup>E</sup> (\$)
2,000	5	260	9.4	75	416	751.2	\$60,000
200	5	260	4.0	32	208	500	\$40,000
20	5	260	2.8	22	208	490.4	\$39,000

Conditions: 600-gpm systems – Two lines of three vessels in-series.

Influent Concentration (ppb)	Sampling Frequency (samples/wk)	Analytical Sampling Annual Labor <sup>A</sup> (hours)	Predicted Changeouts per Year <sup>B</sup>	GAC Changeout Annual Oversight <sup>C</sup> (hours)	General O&M Annual Labor <sup>D</sup> (hours/wk)	Total Annual Labor (hours)	Total Annual Labor Cost <sup>E</sup> (\$)
2,000	25	1,300	15.6	749	1,664	3712.8	\$297,000
200	25	1,300	6.7	322	1,040	2661.6	\$213,000
20	25	1,300	4.6	221	520	2040.8	\$163,000

Conditions: 6,000-gpm systems – Twelve lines of three vessels in-series.

- <sup>A</sup> One hour/sample.      <sup>B</sup> See Table A-2.      <sup>C</sup> Four hours/changeout for each line of GAC vessels.  
<sup>D</sup> General system oversight and maintenance (e.g., pressure checks, backflushing):  
for 60-gpm system: 4 hours/week at 2,000 ppb; 2 hours/week at 200 ppb and 20 ppb.  
for 600-gpm system: 8 hours/week at 2,000 ppb; 4 hours/week at 200 ppb and 20 ppb.  
for 6,000-gpm system: 32 hours/week at 2,000 ppb; 20 hours/week at 200 ppb, and 10 hours/week at 20 ppb.  
<sup>E</sup> Labor rate at \$80 hour.

**Table A-5**  
**Estimated Labor Costs for GAC Systems: Sensitivity Analysis Scenarios**

NOM Fouling

Water Type	Sampling Frequency (samples/wk)	Analytical Sampling Annual Labor <sup>A</sup> (hours)	Predicted Changeouts per Year <sup>B</sup>	GAC Changeout Annual Oversight <sup>C</sup> (hours)	General O&M Annual Labor <sup>D</sup> (hours/wk)	Total Annual Labor (hours)	Total Annual Labor Cost <sup>E</sup> (\$)
Lake Perris (High Fouling)	5	260	5.9	47	208	521	\$42,000
Arcadia GW (Moderate Fouling)	5	260	2.8	22	208	493	\$39,000
Tahoe GW (Low Fouling)	5	260	2.4	19	208	490	\$39,000

Conditions:

600-gpm systems – Two lines of three vessels in-series.

Influent MTBE = 20 ppb (unless otherwise noted); effluent contains no detectable MTBE (<0.5 ppb).

BTX/TBA Load – Varies as noted.

Water Type	Sampling Frequency (samples/wk)	Analytical Sampling Annual Labor <sup>A</sup> (hours)	Predicted Changeouts per Year <sup>B</sup>	GAC Changeout Annual Oversight <sup>C</sup> (hours)	General O&M Annual Labor <sup>D</sup> (hours/wk)	Total Annual Labor (hours)	Total Annual Labor Cost <sup>E</sup> (\$)
20 ppb MTBE 300 ppb Total BTX	5	260	8.4	67	208	544	\$43,000
1,958 ppb MTBE 2,000 ppb Total BTX	5	260	13.2	106	208	587	\$47,000
1,030 ppb MTBE 100 ppb TBA	5	260	8	64	208	540	\$43,000

Conditions:

600-gpm systems – Two lines of three vessels in-series.

Influent MTBE = 20 ppb (unless otherwise noted); effluent contains no detectable MTBE (<0.5 ppb).

<sup>A</sup> One hour/sample.    <sup>B</sup> See Table A-3.    <sup>C</sup> Four hours/changeout for each line of GAC vessels.

<sup>D</sup> Four hours/week; includes general system oversight and maintenance (e.g., pressure checks, backflushing).

<sup>E</sup> Labor rate at \$80/hour.

*Engineering:* 15 percent of capital cost for carbon adsorption unit, site work, piping, valves, electrical, and contractor O&P.

*Contingency:* 20 percent of all other capital costs.

Total capital amortized over 30-year system design life using a 7-percent discount rate.

### **Assumptions for O&M Costs**

*Replacement GAC:* Carbon changeouts using virgin, coconut shell GAC at \$1.25/pound (unit cost based on 1998 vendor price quotes). Estimated changeout frequency based on results of column testing (see Tables 4.1, 4.2, A-2, and A-3).

*Changeout Labor/Transport:* Estimated costs based on 1998 vendor price quotes (\$0.10/pound for transport to off-site regeneration facility); assumed \$1,000 minimum cost per changeout event.

*O&M Labor:* Estimated costs for analytical sampling, GAC changeout oversight, and general system O&M (e.g., pressure checks, backflushing). Detailed assumptions presented in Tables A-4 and A-5.

#### *Analytical Testing:*

60-gpm systems - three samples per week per line (1 influent, 1 midfluent, 1 effluent).

600-gpm systems - five samples per week per line (1 influent, 2 midfluent, 2 effluent).

6,000-gpm systems - twenty-five samples per week per line (1 influent, 12 midfluent, 12 effluent).

Assumed testing cost - \$200 per sample, Method 524.2.

*Power:* Assumed unit cost at \$0.08 per kilowatt-hour; kilowatt-hours estimated based on flow rate and bed depth.

Note: These assumptions were discussed in greater details in the Partnership's Treatability report (2000).



## Appendix B: GAC System Case Studies

---

### Case Study: Public-supply Wells, California Site

#### Site Background

Public water-supply wells impacted by MTBE from an extensive release of MTBE-enhanced gasoline.

#### MTBE Concentrations in Groundwater

MTBE levels of 100 to 300 ppb expected in water-supply wells during full-scale testing. TBA detected in site groundwater up to approximately 50 ppb. No background water-quality data available; low to moderate NOM fouling expected.

#### Results of Column Testing

Dynamic column testing was performed using site water. Two different treatment scenarios were modeled, using both coal-based GAC and coconut shell GAC. Summary results are as follows:

##### Scenario 1: 200 ppb MTBE, no TBA

Coal-based carbon:

Usage rate at 100-percent MTBE breakthrough	=	1.2 pounds/1,000 gallons
Usage rate at 50-percent MTBE breakthrough	=	1.75 pounds/1,000 gallons
Usage rate at initial MTBE breakthrough	=	2.3 pounds/ 1,000 gallons

Coconut shell carbon:

Usage rate at 100-percent MTBE breakthrough	=	0.4 pounds/1,000 gallons
Usage rate at 50-percent MTBE breakthrough	=	0.55 pounds/1,000 gallons
Usage rate at initial MTBE breakthrough	=	0.7 pounds/ 1,000 gallons

##### Scenario 2: Approximately 1,000 ppb MTBE and 50 ppb TBA

Coal-based carbon:

Usage rate at 100-percent MTBE breakthrough	=	1.9 pounds/1,000 gallons
Usage rate at 50-percent MTBE breakthrough	=	13.3 pounds/1,000 gallons
Usage rate at 50-percent TBA breakthrough	=	19.0 pounds/1,000 gallons

Coconut shell carbon:

Usage rate at 100-percent MTBE breakthrough	=	0.5 pounds/1,000 gallons
Usage rate at 50-percent MTBE breakthrough	=	3.5 pounds/1,000 gallons
Usage rate at 50-percent TBA breakthrough	=	4.7 pounds/1,000 gallons

## **Full-scale System Design**

Flow rate: 300 gpm.

Vessel configuration: Two 20,000-pound vessels in-series.

EBCT = unknown.

GAC type: Bituminous coal, mesh size unknown.

Expected influent concentration levels: 100 to 300 ppb MTBE, 50 ppb TBA.

Design treatment standards to be established by full-scale testing.

## **Results of Full-scale Testing**

The full-scale test was performed for approximately 6 weeks; the system operated at approximately 300 gpm. During the testing period, MTBE influent levels ranged from 100 to 280 ppb (average 175 ppb).

MTBE breakthrough of the lead GAC vessel occurred after 1 to 2 days. System operators have speculated that this rapid breakthrough was attributable to iron fouling of the GAC matrix. The GAC vessel remained on-line in the lead position for the remainder of the testing, though it required periodic backflushing to maintain proper flow dynamics.

After 3.5 weeks, MTBE breakthrough of the lag vessel occurred. Ignoring the contribution of the lead vessel, the GAC usage rate based on the first MTBE detection from the lag vessel was estimated to be 1.9 pounds/1,000 gallons. The results of a comparable RSSCT from this report (test R7, coconut shell GAC) show 0.8 pounds/1,000 gallons at first breakthrough. These data suggest that coconut shell GAC may perform better than coal-based GAC at this site.

Following MTBE breakthrough, the influent water was spiked with TBA, which broke through the GAC system within several days.

## **Cost**

No cost data are available.

## **Key Findings**

In both laboratory and full-scale testing, TBA broke through the GAC system rapidly. In laboratory column tests with approximately 1,000 ppb MTBE and 50 ppb TBA, TBA broke through the coal-based and coconut shell GACs sooner than MTBE. In the full-scale test, TBA broke through the GAC system within several days of being spiked into the influent water. These findings suggest that TBA, if regulated, may drive GAC changeout criteria at sites impacted with both MTBE and TBA.

Based on results of column testing performed for this site, it appears that coconut shell GAC is substantially more effective for MTBE removal than coal-based GAC. For one scenario

(200 ppb MTBE, no TBA), coal-based GAC usage rates at 50- and 100-percent breakthrough were more than three times higher than those measured for coconut shell GAC.

Also, results of the full-scale test indicate that GAC fouling from iron or biogrowth can dramatically impact system performance.

## **Case Study: Public-supply Wells, Kansas Site**

### **Site Background**

Public water-supply wells impacted by MTBE-enhanced gasoline that leaked from a UST system. The well field is approximately 1,700 feet downgradient of the UST site. The source area has undergone active remediation using soil vapor extraction and air sparging for approximately 1 year.

### **MTBE Concentrations in Groundwater**

MTBE levels up to 285,000 ppb measured near the source-area free product.

MTBE levels up to 184 ppb (single hit) in supply wells. Typical MTBE concentrations are below 20 ppb in supply wells.

With the exception of a single hit of TBA (21 ppb), no other contaminants were detected in supply wells.

No background water quality data is available.

### **Full-scale System Design**

Flowrate: 450 gpm maximum.

Vessel configuration: Two 20,000-pound vessels in-series.

EBCT = 15 minutes.

GAC type: Bituminous coal, 8 x 30 mesh.

Expected influent concentration levels: <20 ppb.

GAC vessel design lifetime: 1.2 years for 20 ppb MTBE at 200 gpm.

Design treatment standards: Remove MTBE to non-detectable concentrations.

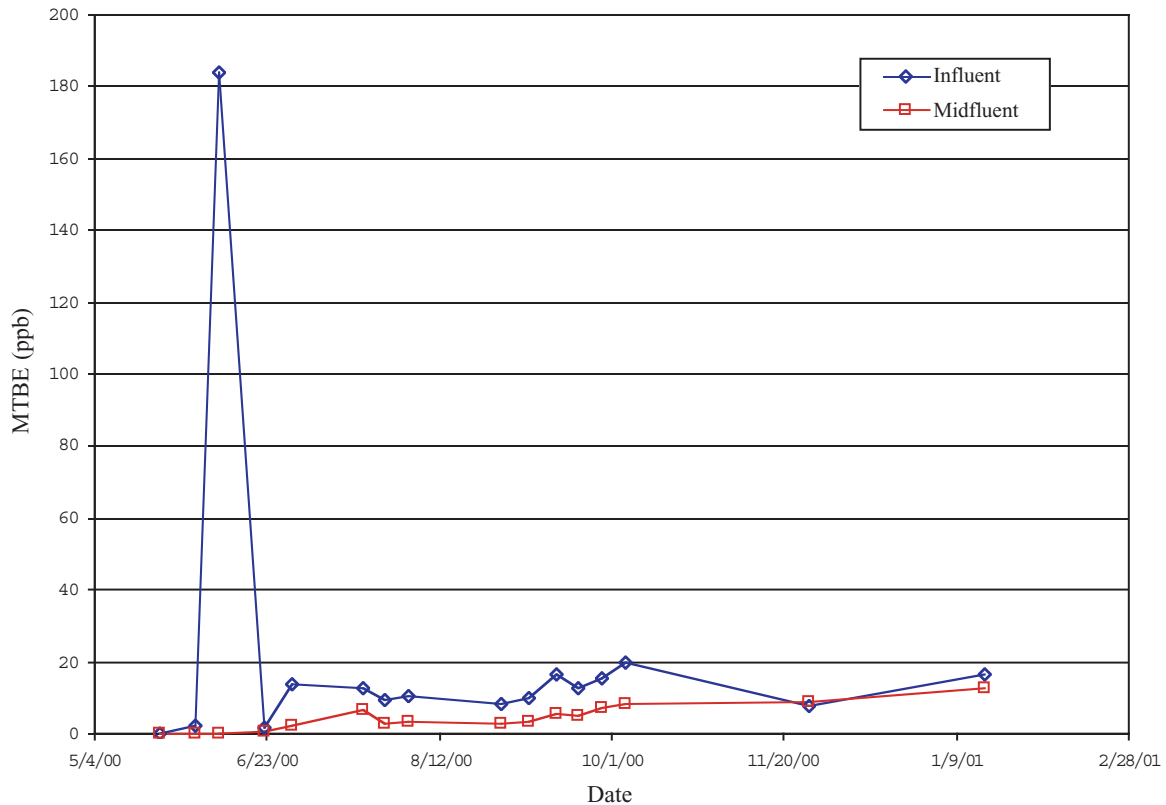
Treatment system is designed to be operated by city employees.

### **Treatment System Performance**

GAC system put on-line in May 2000.

System flowrate since startup = approximately 300-gpm average.

Since system startup, influent MTBE levels have stayed below 20 ppb, except for a single detection of 184 ppb (2.5 weeks after system startup). Figure B-1 shows the trends of influent MTBE concentrations through January 2001. As of January 17, 2001, the average influent concentration to system has been approximately 21.2 ppb.



**Figure B-1** GAC system for public-supply wells, Kansas site.

As shown on Figure B-1, the first MTBE detection in system’s mid-fluent (between lead and lag vessels) occurred after 30 days of operation, soon after the brief period of high influent concentrations. This corresponds to an approximate GAC usage rate at first breakthrough of 1.5 pounds/1,000 gallons.

For an average influent of 21 ppb MTBE, 50-percent breakthrough of the lead vessel occurred after approximately 209 days, which corresponds to an approximate GAC usage rate of 0.22 pounds/1,000 gallons. Assuming influent concentrations stay similar, this 50-percent usage rate can be used to predict the lifetime of the lag vessel (and subsequent vessels) after it replaces the current lead vessel.

As of January 17, 2001, midfluent concentrations (from the lead vessel) appear to be increasing steadily, with the latest measured concentration at 12.7 ppb. The lead vessel is still on-line as of May 9, 2001, indicating a current usage rate of 0.13 pounds/1,000 gallons. No recent effluent data are available.

Since system startup, the operators have backflushed the GAC vessels approximately once per month. During the first backflushing event, MTBE concentrations in the backflush water were measured to be 9.6 ppb. On another event, backflush water at the end of the procedure (after approximately 13,000 gallons had been backflushed) was measured to have 22.9 ppb MTBE.

The GAC changeout criteria for this system are flexible. While the treatment goal is no detectable MTBE in system effluent, the site operators have the flexibility to use other water sources if effluent from the system temporarily contains detectable MTBE. As such, the system can be used more aggressively (maximizing GAC saturation).

### **Cost**

Total project cost = \$233,000.

Cost includes the installation of the GAC system, including concrete slab, plumbing and piping, GAC vessels, initial GAC fill and one refill, control building, 2 years of O&M, and 2 years of sampling.

Cost does not include system design and local government supplied labor.

Note: The cost for this system is particularly low because of oversight by cooperating local/state government agencies, competitive bidding between local GAC contractors, and generally lower costs in Kansas.

### **Key Findings**

Bituminous coal-based GAC can perform well for MTBE removal at certain sites. As such, system designers should consider evaluating coal-based GAC during feasibility analysis and treatment system design, though coconut shell GAC is expected to perform better than coal-based GAC under most conditions. At this site, the coal-based GAC usage rate was approximately 0.22 pounds/1,000 gallons at 50-percent MTBE breakthrough, well below what would be expected based on the column test results presented in this report for coconut shell GAC (e.g., 0.30 pounds/1,000 gallons). The surprising performance results of this case study indicate that bench-scale testing with site-specific water and candidate GACs is a critical step for accurately predicting performance and determining optimum system design.

Based on the costs presented for this case study, the costs for installing and operating full-scale GAC systems can be significantly less under some circumstances than those presented in Section 4 of this report. The discrepancy between these costs is attributed in part to the conservative assumptions made for the Section 4 cost estimate (e.g., fixed-percent costs for plumbing and electrical, contractor O&P, engineering, site work, and contingency). Also, as stated above, the system costs at this site are particularly low because of oversight by cooperating local/state government agencies and competitive bidding between local GAC contractors.

