EXECUTIVE SUMMARY

Treatment Technologies for Removal of Methyl Tertiary Butyl Ether (MTBE) from Drinking Water:

- Air Stripping
- Advanced Oxidation Processes
- Granular Activated Carbon
- Synthetic Resin Sorbents

SECOND EDITION

A Report Written for:
The California MTBE Research Partnership

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List of Acronyms

ACWA	Association of California Water Agencies
AOP	advanced oxidation process
AWR	air/water ratio
BTEX	benzene, toluene, ethylbenzene, xylene (*o*-, *m*-, *p*-xylene)
DHS	(California) Department of Health Services
E-beam	high energy electron beam
EBCT	empty bed contact time
EPA	United States Environmental Protection Agency
GAC	granular activated carbon
H	Henry's Constant
H_2O_2	hydrogen peroxide
LP-UV	continuous wave low-pressure mercury vapor lamps
MCL	maximum contaminant level
MP-UV	continuous wave medium-pressure mercury vapor lamps
MTBE	methyl tertiary butyl ether
NDMA	*N*-nitroso dimethyl amine
NOM	natural organic matter
•OH	hydroxyl radicals
O_3	ozone
O&M	operation and maintenance
OFA	Oxygenated Fuels Association
SOC	synthetic organic chemical
PCE	perchloroethylene (also known as tetrachloroethylene)
TBA	tertiary-butyl alcohol
TBF	tertiary-butyl formate
TCE	trichloroethylene
UST	underground storage tank
UV	ultraviolet
WSPA	Western States Petroleum Association

1.0 Introduction

This Executive Summary is being published as a stand alone summary of the key findings from the report, *Treatment Technologies for Removal of Methyl Tertiary Butyl Ether (MTBE) from Drinking Water: Air Stripping, Advanced Oxidation Processes, Granular Activated Carbon, and Synthetic Resin Sorbents, Second Edition* (MTBE Treatability, 2000). The complete report is available from the National Water Research Institute (NWRI) in hardcopy or as a CD-ROM. The report presents the results of an extensive feasibility study for methyl tertiary butyl ether (MTBE) removal from drinking water. The study was conducted to evaluate the most promising and/or widely accepted technologies used to remove volatile organic compounds from drinking water: namely, air stripping, advanced oxidation processes (AOPs), granular activated carbon (GAC), and synthetic resin sorbents. These technologies were evaluated as they apply specifically for removal of MTBE.

The first edition of this document was published in December 1998. The second edition (MTBE Treatability, 2000) is a significant improvement from the first edition. The most notable changes are the addition of a new chapter on synthetic resin sorbents, refinement and update of costs for all technologies, significant revisions to the AOP section, a new introductory chapter, and a new chapter with overall conclusions and recommendations

1.1 The California MTBE Research Partnership

In October 1997, the Western States Petroleum Association (WSPA), Oxygenated Fuels Association (OFA), and Association of California Water Agencies (ACWA) formed the California MTBE Research Partnership to develop a statewide research program concerned with MTBE treatment technology and source-protection issues. The mission of the Partnership is *to identify, prioritize, plan, and sponsor practical research projects to protect, treat, or remove MTBE contamination from drinking water supplies.* To fulfill this mission, the Partnership has created two focus-area subcommittees to investigate and develop Partnership projects: the Treatability Committee and Source Water Protection Committee. Each group is composed of engineers and scientists who represent water utilities, regulatory agencies, the petrochemical industry, academia, and the environmental consulting field.

2.0 MTBE in the Environment

MTBE is an oxygenate compound added to gasoline to enhance octane level and meet the oxygen requirements mandated in the Clean Air Acts Amendments. When gasoline is released into the environment, a variety of chemical compounds — including MTBE — can be transferred into the air or water. Although MTBE is credited with significantly reducing air emissions from gasoline-powered vehicles, it has also contaminated water supplies through accidental gasoline releases at dispensing sites, leaking product pipelines, and via leaks from underground storage tanks (USTs). Because of MTBE's particular physio-chemical properties (such as high solubility, low soil-to-water partition coefficient, and low Henry's constant), it is somewhat difficult to remove from water.

Treatment costs depend on existing system conditions, most specifically system flow rates, MTBE influent concentrations, and the level of treatment needed for MTBE to reach the desired effluent goal. The water-supply flow rates were considered at 6,000, 600, and 60-gallons per minute. At each of these flow rates, the technologies were analyzed for MTBE influent concentrations of 2,000, 200, and 20 micro-grams per liter (µg/L). The MTBE effluent levels were considered at 20 µg/L, 5 µg/L, and non-detect.

It has been suggested that the treatment of MTBE in drinking water using conventional treatment processes (i.e., air stripping and GAC) poses challenges relative to other organic contaminants — particularly benzene, toluene, ethylbenzene, and xylene (BTEX) compounds — because of MTBE's unique physical and chemical properties. MTBE's Henry's constant is approximately an order of magnitude lower than those of BTEX compounds. Since the air stripping potential of a compound is primarily determined by its Henry's constant, air stripping of MTBE will tend to be more difficult and more costly relative to BTEX compounds. Furthermore, the relatively low organic carbon partitioning coefficient and the high water solubility of MTBE make GAC adsorption less effective for MTBE relative to BTEX compounds.

3.0 MTBE Monitoring and Standards

In February 1997, the California Department of Health Services (DHS) added MTBE to the list of unregulated chemicals that require monitoring. According to California monitoring data (November 19, 1999), MTBE concentrations greater than the detection level have impacted 62 of the 6,409 drinking water sources sampled.

MTBE drinking water standards throughout the United States vary considerably. The concentrations range from 5 µg/L in California to over 240 µg/L in Michigan. In December 1997, the U.S. Environmental Protection Agency (EPA) Office of Water issued a Drinking Water Advisory on MTBE (Drinking Water Advisory Consumer Acceptability Advice and Heath Effects on Methyl Tertiary-Butyl Ether). The advisory was not a mandatory standard for action, but discussed the limitations of estimating a risk level for MTBE in drinking water and characterized the hazards associated with this route of exposure. The Drinking Water Advisory concluded that "keeping the concentrations in the range of 20 µg/L to 40 µg/L or below will likely avert unpleasant taste and odor effects." Approximately 17 states have not adopted state standards and are relying on the EPA Drinking Water Advisory or waiting for EPA to adopt a maximum contaminant level (MCL).

4.0 Drinking Water Treatment Conclusions

4.1 Air Stripping

The tendency for a compound to be removed from water by air stripping is characterized by its Henry's constant. MTBE's Henry's constant is several times lower than those of other organic compounds commonly treated through air stripping (e.g., trichloroethylene [TCE] and benzene) and, thus, air stripping of MTBE is more difficult and more costly than for these other compounds. However, air stripping is a proven technology that has been used successfully to remove MTBE from drinking water. Packed tower air strippers are being used successfully for drinking water treatment in La Crosse, Kansas and Rockaway Township, New Jersey.

Packed tower aeration was found to be superior to the other air stripping technologies from a cost perspective, regardless of hydraulic capacity, removal efficiency requirements, or initial MTBE concentrations. At higher flow rates (>600 gpm) and higher removal efficiencies (>95 percent), packed towers are not only less expensive but, often, the only technology capable of achieving the treatment goal. However, for lower flow rates (<100 gpm), low profile air strippers become cost competitive with packed towers ($1.80 to $1.86 vs. $1.75 per 1,000 gallons treated, respectively, for 97.5 percent MTBE removal). In addition, low profile air strippers are generally easier to install, maintain, and modify for changing flow and water quality conditions than packed towers. Thus, for hydraulic capacities less than 100 gpm, which may be a remediation or a small drinking water application, a low profile air stripper is generally recommended. For drinking water applications requiring hydraulic capacities greater than 100 gpm, the packed tower aeration technology is recommended. A summary of the total amortized costs ($/1,000 gallons; in 1999 $) associated with packed tower and low profile air strippers is presented in Table ES-1.

Table ES-1

Summary of Total Amortized Costs ($/1,000 Gallons) for Recommended Air Stripping Technologies

System Flow (gpm)	Packed Tower ($/1,000 gal)		Low Profile ($/1,000 gal)	
	90% removal[1]	**99% removal[2]**	**90% removal[1]**	**99% removal[1]**
60	$1.66	$1.79	$1.70	$1.90
600	$0.32	$0.36	$0.85	$0.96
6000	$0.15	$0.17	$0.41	NE

Costs are in 1999 dollars.

NE = not evaluated due to lack of data. System may require custom design.

[1] 90% removal is for 200 µg/L influent concentration.

[2] 99% removal assumes 2,000 µg/L influent concentration.

The evaluation of air stripping assumed that off-gas treatment is required when MTBE gas phase concentrations exceed 1 lb/day. If off-gas treatment is required and MTBE influent concentrations are low (<200 µg/L), vapor phase GAC is generally the most cost-effective off-gas technology because carbon usage rates are low (as a result of the very dilute MTBE stream) and, thus, O&M costs remain low. If MTBE influent concentrations are higher (e.g., the 2,000 µg/L scenario), oxidation is the recommended technology for an air stream from a packed tower system. The cost analysis indicates a small difference in costs between catalytic and thermal oxidation. Thermal oxidation is the recommended technology to evaluate in conjunction with the selected aeration technology because, like GAC, it is a commonly used and proven technology. Both GAC and thermal oxidation demonstrate equally high levels of reliability, flexibility, removal efficiencies, and cost-effectiveness. Table ES-2 lists the costs associated with the most cost-effective off-gas treatment technologies, vapor phase GAC, and thermal oxidation. For the assumptions used in the cost analysis of air stripping and off-gas treatment systems, as well as more detailed cost breakdowns, see Chapter 2 of the report (MTBE Treatability, 2000).

Table ES-2

Summary of Total Amortized Costs ($/1,000 Gallons) for Recommended Off-gas Treatment Technologies

System Flow		Vapor Phase GAC ($/1,000 gal)		Thermal Oxidation[2] ($/1,000 gal)	
Water (gpm)	**Air[1]** (cfm)	**0.5 ppmv Influent MTBE**	**5 ppmv Influent MTBE**	**0.5 ppmv Influent MTBE**	**5 ppmv Influent MTBE**
60	1,200	$0.54	$1.86	$1.18	$1.18
600	12,000	$0.24	$1.56	$0.54	$0.54
6000	120,000	$0.23	$1.55	$0.44	$0.44

Costs are in 1999 dollars.

[1] Based on an air/water ratio (AWR) of 150.

[2] Recuperative thermal oxidation at 60 and 600 gpm and recuperative flameless thermal oxidation at 6,000 gpm.

4.2 AOPs

AOPs destroy MTBE and other organic contaminants directly in the water through chemical oxidation, as opposed to simply transferring them from the liquid phase into a gas phase (in the case of air stripping) or into a solid phase (in the case of GAC and resins). Removal of organic compounds from water by AOPs is primarily accomplished through the reaction of organic contaminants with highly reactive hydroxyl radicals (•OH) that can be produced through a variety of mechanisms. Compared to more established drinking water treatment alternatives, such as air stripping and GAC, AOPs are generally considered an emerging technology. Currently, there are several full-scale applications where organic contaminants (e.g., perchloroethylene [also known as tetrachloroethylene, or PCE] and *N*-nitroso dimethyl amine [NDMA]) are being removed from drinking water using an AOP. There are, however, no full-scale installations of AOPs for removal of MTBE from drinking water. Thus, thorough pilot- and field-scale testing of an AOP system is required before it can be implemented for MTBE removal in drinking water applications.

Some of the challenges with respect to the implementation of AOPs in drinking water treatment are associated with the formation and fate of oxidation by-products (e.g., tertiary-butyl alcohol [TBA] and tertiary-butyl formate [TBF]), non-selective radical oxidation, radical scavenging, and bromate formation (for ozone-based AOPs). Although it is possible to overcome these challenges, costs will increase as a result of the required greater energy usage, greater chemical dosage, and/or secondary treatment polishing steps.

The report (MTBE Treatability, 2000) evaluated the following established and emerging AOPs potentially applicable for the removal of MTBE from drinking water:

Established Technologies

- Hydrogen Peroxide/Ozone (H_2O_2/O_3)
- Ozone/Ultraviolet Irradiation (O_3/UV)
- Hydrogen Peroxide/Continuous Wave Medium-Pressure Mercury Vapor Lamps (H_2O_2/MP-UV)

Emerging Technologies

- High Energy Electron Beam Irradiation (E-beam)
- TiO_2-catalyzed UV
- Sonication/Hydrodynamic Cavitation
- Fenton's Reaction

The two most promising AOP technologies appear to be H_2O_2/O_3 and H_2O_2/MP-UV. Both of these processes are well understood and have been demonstrated at several bench- and field-scale sites to successfully remove MTBE from water to meet drinking water standards. In addition to these two relatively well-established AOPs, E-beam and cavitation are two emerging AOPs that warrant further consideration due to their technical feasibility for removing MTBE from drinking water to meet standards. These technologies are still in their commercial developmental stages for removal of organic contaminants in drinking water applications; however, they have been widely demonstrated for disinfection and remediation applications.

Besides being the most technically feasible, these two technologies (in addition to cavitation) appear to be the most economically feasible. However, these costs are strongly dependent on source water quality and are difficult to verify due to the untested nature of these technologies in large-scale applications. Cavitation costs involve the most uncertainty because there are no pilot, field, or full-scale drinking water treatment applications for MTBE removal. Consequently, while there is significant uncertainty for all the cost estimates, H_2O_2/O_3 and H_2O_2/MP-UV technologies are essentially equivalent in cost and less expensive than the other AOPs evaluated. A summary of the total amortized costs ($/1,000 gallons; in 1999 $) for H_2O_2/O_3 and H_2O_2/MP-UV are summarized in Table ES-3.

Table ES-3

Summary of Total Amortized Costs ($/1,000 Gallons) for Recommended AOP Technologies

System Flow (gpm)	H_2O_2/O_3 ($/1,000 gal)		H_2O_2/MP-UV ($/1,000 gal)	
	90% removal[1]	99% removal[2]	90% removal[1]	99% removal[1]
60	$2.65	$3.29	$2.32	$3.07
600	$0.84	$1.07	$0.71	$1.52
6000	$0.37	$0.56	$0.42	$0.65

Costs are in 1999 dollars.

Note: Costs do not include polishing treatment for oxidation by-products.

[1] 90% removal assumes 200 µg/L influent concentration.

[2] 99% removal assumes 2,000 µg/L influent concentration.

4.3 GAC

Carbon adsorption technology has been widely used in the past for removal of organic contaminants from drinking water. Simplicity and stable operations are the primary advantages of GAC relative to other water treatment technologies. GAC systems are easy to implement due to wide commercial availability for other applications, and numerous vendors can supply GAC and the necessary equipment (e.g. vessels, piping, and pumps). Because of the simplicity of the equipment and materials, capital and installation costs are relatively low compared to more innovative technologies. Finally, there is no off-gas treatment required for GAC systems and the creation of by-products is limited to spent carbon that can either be thermally regenerated or discarded. However, in spite of these advantages, GAC field-application knowledge specifically for MTBE removal from large-scale drinking water systems is currently limited.

The effectiveness of GAC for the treatment of MTBE has been limited by its poor physical and chemical adsorption characteristics. In particular, MTBE's high solubility causes the compound to preferentially remain in solution rather than be adsorbed onto a solid surface. In addition, natural organic matter (NOM) and other synthetic organic chemicals (SOCs) compete with MTBE for the adsorption sites of GAC. Since MTBE is only weakly adsorbed by GAC, other more preferentially adsorbed SOCs in the contaminated water can result in the desorption or the displacement of previously sorbed MTBE from the GAC matrix. Based on the MTBE isotherms currently available, coconut shell GAC appears to have better MTBE adsorption characteristics than coal-based GAC.

As presented in the report (MTBE Treatabiltiy, 2000), carbon usage rates and unit treatment costs are highly dependent on influent MTBE concentrations, background water quality, and the concentration of other SOCs. The cost analysis suggests that GAC is most cost-effective for the removal of lower MTBE concentrations, which result in lower carbon usage rates and, consequently, lower operation and maintenance (O&M) costs. GAC is also more likely to be cost-effective for waters that are relatively clean with respect to NOM (e.g., some groundwaters). For example, computer modeling predicts that carbon fouling from NOM can cause approximately 50 percent increases in carbon usage rates for the removal of 20 µg/L MTBE. Finally, GAC is more cost-effective for waters contaminated solely with MTBE since other SOCs will preferentially occupy adsorption sites and thereby increase carbon usage rates. Adsorption modeling and cost estimates show that moderate loads of total BTEX (800 µg/L) can cause greater than 50 increases increases in carbon usage rates for MTBE removal for systems treating influent with 20 µg/L MTBE.

The total amortized costs ($/1,000 gallons; in 1999 $) associated with GAC systems are summarized in Table ES-4. The cost estimates developed for GAC systems are all based on non-detect (<0.5 µg/L) effluent concentrations, resulting in removal efficiencies ranging from 97.5 to >99 percent, depending on influent concentrations. These costs were developed assuming a 30-year design life. It is important to note that due to GAC's high O&M to capital ratio, this technology is more likely to be cost-effective for shorter duration projects.

Table ES-4

Summary of Total Amortized Costs ($/1,000 Gallons) for Recommended GAC Systems

GAC Systems ($/1,000 gal)*			
System Flow (gpm)	**Influent Concentrations and Removal Efficiencies**		
	20 µg/L (97.5%)	**200 µg/L (99.75%)**	**2,000 µg/L (99.975%)**
60	$2.30	$2.92	$4.43
600	$0.77	$1.15	$2.37
6000	$0.50	$0.97	$2.22

Costs are in 1999 dollars.

*Effluent concentrations assumed to be non-detect (<0.5 µg/L) for influent concentrations of 20, 200, and 2,000 µg/L.

4.4 Synthetic Resin Sorbents

Synthetic resin sorbents, like GAC, rely on the process of sorption to remove organic compounds from water. The primary advantages of resin sorbents over GAC is their on-site regenerability and their resistance to competitive NOM sorption. Resins used for drinking water applications could be regenerated on-site through steam stripping or microwave irradiation. Resin isotherm data for MTBE suggests that Ambersorb 563, a carbonaceous resin manufactured by Rohm and Haas (Philadelphia, PA), is currently the resin industry's most promising candidate for MTBE removal from water. Two independent studies found Ambersorb 563 to have superior sorption capacity for MTBE compared to Filtrasorb 400, a coal-based GAC widely used by the water industry.

Limited data are available on the effects of background water quality toward the MTBE removal efficiency of resins. Available data suggest that the performance of Ambersorb resins is unaffected by pH (6.5 to 8.5), temperature (10 vs. 25°C), oxidants (HOCl, H_2O_2, and O_3), and the presence of NOM and TBA. Ambersorb resins have also been found to be unsusceptible to biofouling. However, *m*-xylene, which can be considered representative of BTEX compounds, has been found to decrease resin MTBE sorption capacity when it is present at relatively high concentrations (43.2 mg/L).

For the 6,000 gpm flow scenario, parallel resin sorption followed by either low profile air stripping or GAC treatment of the regenerant was found to be the most cost effective treatment option, with costs ranging from (1999 $) $0.30/1,000 gallons (75 percent removal efficiency) to $0.58/1,000 gallons (99.98 percent removal efficiency). For all other flow rates, series operation followed by GAC treatment of the regenerant was found to be the least expensive option ranging from (1999 $) $1.02/1,000 gallons (600 gpm; 20 µg/L to 0.5 µg/L) to $24.86/1,000 gallons (6 gpm; 2,000 µg/L to 0.5 µg/L). A summary of the total amortized costs ($/1,000 gallons; in 1999 $) associated with resin systems is presented in Table ES-5. These costs are highly contingent on the breakthrough times predicted by the AdDesignS model, which should be verified in the field. In addition, the costs are dependent on limited field data regarding regeneration effectiveness and resin lifetime. Costs could vary depending on site-specific conditions, especially with respect to the presence of other SOCs. For information regarding the assumptions used in the cost analysis of resin sorbents, as well as more detailed cost breakdowns, refer to the report (MTBE Treatability, 2000).

Table ES-5

Summary of Total Amortized Costs ($/1,000 Gallons) for Recommended Synthetic Resin Systems

System Flow (gpm)	Synthetic Resin with Regeneration System ($/1,000 gal)	
	90% Removal[1]	99% Removal[2]
60	$4.16	$4.56
600	$1.16	$1.32
6000	$0.39	$0.53

Costs are in 1999 dollars.

[1] 90% removal assumes 200 µg/L influent concentration.

[2] 99% removal assumes 2,000 µg/L influent concentration.

4.5 Integration of Technologies

During the formation of the Treatability Subcommittee of the Research Partnership, it was recognized that other emerging technologies (e.g., membranes, biological processes) may also be applicable for MTBE drinking water treatment. The Partnership continues to recognize these and other alternative treatment processes as representing significant potential; however, they were not reviewed in this report due to their limited pilot- and field-testing and emerging nature for MTBE removal.

Despite the relatively proven nature of the treatment processes selected for review in this report, many treatment and remediation scenarios may require a combination of treatment processes to meet effluent criteria. For example, all drinking water treatment processes in California will require redundant treatment (i.e., a treatment process that serves as a barrier between the consumer and the contamination). In many cases, GAC will be used as the redundant process. Similarly, AOPs will often employ additional treatment processes to remove oxidation by-products or residual oxidants.

Alternatively, some singular treatment processes may not be able to reach drinking water effluent criteria, especially in cases where the influent concentrations are high (e.g., 2,000 µg/L) and the effluent criteria is non-detect. In these circumstances, two treatment processes may be required — the first process would be used to lower concentrations by 90 to 99 percent and the second process would be used as a polishing step to remove the remaining 1 to 10 percent. Throughout this report, the economic evaluations for each treatment process were completed such that this process integration analysis is possible. For example, it is possible to estimate air stripping or AOP costs for removal of MTBE from 2,000 µg/L to 200 or 20 µg/L and GAC costs for removal of MTBE from 200 or 20 µg/L to 0.5 µg/L. The costs presented in this report have relied on similar assumptions and, thus, the accuracy of the cost estimate for MTBE removal should not be affected by combining individual process costs.

4.6 Overall Cost Effectiveness

Detailed cost estimates have been completed for each of the four technologies evaluated in this report; however, these costs are intended for comparative purposes only and should not be used in place of a detailed site-specific engineering cost analysis. A summary of the total amortized costs ($/1,000 gallons; in 1999 $) for the various treatment technologies is presented in Table ES-6.

Table ES-6

Summary of Total Amortized Costs ($/1,000 Gallons) for Various Recommended Treatment Systems

Flow (gpm)	Influent (µg/L)	Effluent (µg/L)	Removal	AIR STRIPPING			AOPs		GAC	RESIN SORPTION	Lowest Unit Cost Amongst the Technologies Evaluated
				Packed Tower	Low Profile	Packed Tower w/ OGT	H_2O_2/MP-UV	O_3/H_2O_2			
60 gpm	20	5	75.00%	**$1.66**	NE	NR	$2.18	$2.63	NE	$2.50	Packed Tower
	20	0.5	97.50%	**$1.75**	$1.86	NR	$2.50	$2.68	$2.30	$2.81	Packed Tower
	200	20	90.00%	**$1.66**	$1.70	NR	$2.32	$2.65	NE	$4.16	Packed Tower
	200	5	97.50%	**$1.75**	$1.80	NR	$2.50	$2.68	NE	$4.16	Packed Tower
	200	0.5	99.75%	**$1.82**	$1.89	NR	$2.72	$2.98	$3.10	$4.16	Packed Tower
	2000	20	99.00%	*$1.79*	*$1.90*	**$3.08**	$3.07	$3.29	NE	$4.56	Packed Tower with OGT
	2000	5	99.75%	*$1.82*	*$2.02*	**$3.20**	$3.47	$3.31	NE	$4.57	Packed Tower with OGT
	2000	0.5	99.98%	NE	NE	NE	$4.11	**$3.62**	$4.61	$4.57	O_3/H_2O_2
600 gpm	20	5	75.00%	**$0.30**	$0.78	NR	$0.57	$0.82	NE	$1.01	Packed Tower
	20	0.5	97.50%	**$0.34**	$0.92	NR	$0.91	$0.90	$0.77	$1.01	Packed Tower
	200	20	90.00%	*$0.32*	*$0.85*	**$0.57**	$0.71	$0.84	NE	$1.16	Packed Tower with OGT
	200	5	97.50%	*$0.34*	*$0.96*	**$0.59**	$0.96	$0.90	NE	$1.17	Packed Tower with OGT
	200	0.5	99.75%	*$0.37*	*$1.09*	**$0.62**	$1.27	$0.95	$1.15	$1.17	Packed Tower with OGT
	2000	20	99.00%	*$0.36*	*$0.96*	**$0.90**	$1.52	$1.07	NE	$1.32	Packed Tower with OGT
	2000	5	99.75%	*$0.37*	*$1.09*	**$0.91**	$1.75	$1.13	NE	$1.36	Packed Tower with OGT
	2000	0.5	99.98%	NE	NE	NE	$2.08	**$1.19**	$2.37	$1.38	O_3/H_2O_2
6,000 gpm	20	5	75.00%	*$0.13*	*$0.34*	$0.36	$0.32	$0.35	NE	**$0.30**	Resin Sorption
	20	0.5	97.50%	*$0.16*	*$0.48*	$0.39	$0.52	$0.43	$0.50	**$0.36**	Resin Sorption
	200	20	90.00%	*$0.15*	*$0.41*	$0.38	$0.42	**$0.37**	NE	$0.39	O_3/H_2O_2
	200	5	97.50%	*$0.16*	*$0.48*	**$0.39**	$0.60	$0.43	NE	$0.41	Packed Tower with OGT
	200	0.5	99.75%	*$0.17*	*$0.64*	**$0.40**	$0.74	$0.48	$0.97	$0.41	Packed Tower with OGT
	2000	20	99.00%	*$0.17*	NE	NE	$0.65	$0.56	NE	**$0.53**	Resin Sorption
	2000	5	99.75%	*$0.18*	NE	NE	$1.24	$0.59	NE	**$0.54**	Resin Sorption
	2000	0.5	99.98%	NE	NE	NE	$1.59	$0.68	$2.22	**$0.58**	Resin Sorption

Costs are in 1999 dollars.

[1] NE = not evaluated due to lack of data.

[2] NR = off-gas treatment not required.

[3] Boxed numbers indicate the lowest unit cost amongst the technologies evaluated.

[4] Air stripping costs are italicized and underlined when off-gas treatment is expected to be required based on 1 lb/day emission standards.

[5] OGT = off-gas treatment.

[6] AOP Treatment Costs for by-product and residual oxidant removal not included.

5.0 Recommendations for Future Research

5.1 Air Stripping

Air stripping is a well-understood technology with many full-scale installations across the country. However, other than the packed tower air stripper at La Crosse, Kansas and Rockaway Township, New Jersey, there appears to be a lack of published data for air stripper applications for MTBE removal from drinking water. Consequently, there is a need to collect cost and other operational data from a variety of air stripping sites to better evaluate the applicability and cost effectiveness in MTBE treatment scenarios. Cost data should include both real capital and O&M costs. Operational data should include influent concentrations, removal efficiencies, air and water flow rates, off-gas concentrations, and costs.

5.2 AOPs

AOPs are not as well understood as air stripping and adsorptive processes due to the large number and variety of chemical and physical processes involved in advanced oxidation reactions. Thus, there remains a significant amount of uncertainty regarding the technical and economic effectiveness of AOPs for removing MTBE from drinking water under a variety of water quality scenarios. More pilot- and field-scale studies need to be conducted to determine the removal efficiencies that can be achieved under different water quality conditions and operational parameters. In addition, the following specific topics warrant further research:

1) *Water Quality Impacts on AOP Effectiveness.* The effectiveness of AOPs is directly related to water quality parameters such as pH, alkalinity, NOM, TOC, turbidity, and concentrations of other interfering compounds (e.g., nitrates and bromide). Future studies on AOP treatment of MTBE must independently evaluate the impact of each of the above-listed water quality parameters. The evaluation criteria must include MTBE removal efficiency, oxidation by-product formation, DBP formation potential, and costs. For ozone-based AOPs, the effect of influent bromide concentration on bromate formation must also be evaluated. Similarly, a detailed analysis of the effect of influent water turbidity and nitrate concentrations on the effectiveness of AOPs relying on UV-light (LP-UV, MP-UV, pulsed-UV) is warranted.

2) *By-product Formation and Control.* In addition to more testing and demonstration, one of the most significant areas of future research is the issue of by-product formation and control. The oxidation of MTBE to carbon dioxide and water involves many steps and the formation of many oxidation by-products (e.g., TBA, TBF, acetone). If these by-products are not completely mineralized, they will be present in treated water, resulting in elevated concentrations of potentially toxic by-products in the treated water. A better understanding of by-product formation mechanisms and subsequent mitigation strategies will be necessary prior to the acceptance of AOPs by the regulatory community for drinking

water applications. This includes research to determine the most cost-effective treatment option, such as biologically activated carbon, for by-product removal in drinking water applications.

3) *Cost Evaluation as a Function of Water Quality and Contamination Scenario.* Finally, future research should evaluate engineering costs for MTBE oxidation by AOPs. Capital and O&M costs for each AOP process should be developed as a function of water quality, flow rate, influent MTBE concentration, and required removal efficiency. These cost evaluations must be performed under uniform design criteria (e.g., required removal efficiency) and operational assumptions (e.g., power rate). A unified costing approach will enable a direct comparison of the various AOPs for specific water qualities.

5.3 GAC

Based on the literature review, the results of the computer modeling, and the cost analyses, there are several topics that require more research before GAC usage for MTBE removal from drinking water is fully understood. These topics are:

1) *Reproducible Isotherms.* Standardized testing should be performed to obtain comparable and reproducible isotherms for a range of GAC types, including high-grade coconut shell carbon and coal-based carbon.

2) *Dynamic GAC Adsorption Capacities.* Dynamic column tests should be performed to determine GAC usage rates, optimum empty bed contact times (EBCTs), and other operating parameters for a variety of MTBE influent concentrations, background water quality conditions, and GAC types. These tests will allow for better prediction of full-scale performance of GAC systems for MTBE removal. In addition, more information is needed on MTBE desorption from GAC and on the competitive effects of other SOCs (e.g., BTEX, TBA) in the source water.

3) *Full-scale Performance.* To date, there are limited data regarding the successful use of full-scale GAC systems for removing MTBE from drinking water. As such, it is recommended that GAC performance for MTBE removal be evaluated under full-scale field conditions. Collection of cost and operational data, including long-term NOM fouling effects and pretreatment requirements, will allow for meaningful comparison with results of dynamic column testing and cost estimates. Currently, a 400-gpm GAC system is planned for installation in Santa Monica, California. This system will provide financial and performance data during pilot-scale testing.

5.4 Synthetic Resin Sorbents

There are four primary areas where additional information is critical to design a cost-effective resin treatment system for MTBE removal from water:

1) *Dynamic Resin Adsorption Capacities.* Dynamic column tests should be performed in order to determine the optimum EBCT and other operating parameters for treating MTBE-impacted groundwater under varying background water quality conditions such as temperature, pH, and the presence of other SOCs and NOM. In addition, more information is needed on the adsorptive capacities of various resins for TBA, BTEX, and NOM and their interference with the adsorption of MTBE.

2) *Mechanisms of Regeneration and Optimization of Regenerative Processes.* To date, only a limited number of bench- and pilot-scale studies have been completed to investigate the effectiveness of steam and microwave regeneration for MTBE applications. Further information on the feasibility and economics of these regeneration processes is needed to allow for a detailed cost evaluation and comparison.

3) *Effectiveness of Biological Degradation as a Regenerant Treatment.* Further research is necessary to determine the most cost-effective treatment for the concentrated MTBE solution created by regeneration processes. In particular, biological degradation of concentrated regenerant solutions should be evaluated as a potentially cost-effective treatment option.

4) *Synergistic Advantage of Resins in Combination with Alternative Treatment Process.* The potential economic advantages of combining resin systems with the other technologies evaluated in the full report should be investigated.

6.0 References

The 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, 2nd ed.* Fountain Valley, CA: National Water Research Institute, 2000.