6.0 Conclusions and Recommendations

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6.1 Summary of Key Findings and Conclusions

This chapter summarizes the key findings and conclusions of the technology evaluations discussed in the previous chapters. Air stripping, AOP, GAC, and synthetic resin sorbents are compared on the bases of permitting, cost effectiveness, reliability, flexibility, adaptability, and potential for modifications. This chapter concludes with recommendations for future research.

6.1.1 Air Stripping

The tendency for a compound to be removed from water by air stripping is characterized by its Henry's constant. Because MTBE's Henry's constant is several times lower than those of other organic compounds commonly treated through air stripping (e.g., TCE and benzene), 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. To optimize the performance of air strippers, the contact between air and water is maximized while energy costs associated with the equipment design are minimized. This optimization provides the highest rate of mass transfer between the water and air at the lowest operating cost. The most common mass transfer design for air stripping systems is randomly packed towers. Packed tower air strippers are being used successfully for drinking water treatment in La Crosse, Kansas and Rockaway Township, New Jersey. In addition to packed towers, established and emerging air-stripping technologies potentially applicable for MTBE treatment in drinking water include low profile air strippers, bubble diffusion strippers, spray towers, and aspiration air strippers.

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. $1.75 per 1,000 gallons treated, respectively, for 97.5-percent MTBE removal). In addition, low profile air strippers are generally easier to install, maintain, and modify for changing flow and water quality conditions than packed towers. Thus, for hydraulic capacities less than 100 gpm, which may be a remediation or a small drinking water application, a low profile air stripper is recommended. For drinking water applications requiring hydraulic capacities greater than 100 gpm, the packed tower aeration technology is recommended. A summary of the total amortized costs ($/1,000 gallons; in 1999 $) associated with packed tower and low profile air strippers is presented in Table 6-1.

Table 6-1
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

NE = not evaluated due to lack of data. System may require custom design. Costs are in 1999 dollars.
[1] 90% removal is for 200 µg/L influent concentration.
[2] 99% removal assumes 2,000 µg/L influent concentration.

The evaluation in Chapter 2 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 6-2 lists the costs associated with the most cost-effective off-gas treatment technologies, vapor phase GAC, and thermal oxidation. See Chapter 2 for the assumptions used in the cost analysis of air stripping and off-gas treatment systems as well as more detailed cost breakdowns.

Table 6-2
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 AWR of 150.
[2] Recuperative thermal oxidation at 60 and 600 gpm and recuperative flameless thermal oxidation at 6,000 gpm.

6.1.2 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 (as in the case of air stripping) or solid phase (as 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., PCE and 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 byproducts (e.g., TBA and 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.

Chapter 3 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, H_2O_2/O_3 and H_2O_2/MP-UV — 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. While there is significant uncertainty for all the cost estimates, H_2O_2/O_3 and H_2O_2/MP-UV technologies appear to be 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 6-3.

Table 6-3
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.

6.1.3 GAC

Carbon adsorption technology is implemented by passing contaminated water through a vessel containing GAC. Intermolecular attraction between the dissolved organic contaminant (adsorbate) and the GAC surface (adsorbent) results in adsorptive forces that physically attract the adsorbate to the GAC as the water passes through the vessel. As such, the adsorbate remains attached to the GAC matrix while the water leaves the system with a decreased concentration. The adsorption potential of a type of GAC for a given contaminant depends on numerous factors, including the GAC structure (i.e., pore size distribution) and the physical and chemical characteristics of the adsorbate. Based on the MTBE isotherms currently available, coconut shell GAC appears to have better adsorption characteristics than coal-based GAC.

Simplicity and stable operations are the primary advantages of GAC relative to other water treatment technologies. In addition, GAC is well established for removing organic compounds from water. However, field application specifically for MTBE removal in large-scale drinking water systems is currently limited. GAC systems are easy to implement due to wide commercial availability for other applications. 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.

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, NOM and other 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.

As presented in Chapter 4, 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 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, thereby increasing carbon usage rates. Adsorption modeling and cost estimates show that moderate loads of total BTEX (800 μg/L) can cause greater than 50 percent 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 6-4. 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. Due to GAC's high O&M to capital ratio, this technology is more likely to be cost-effective for shorter duration projects.

Table 6-4

Summary of Total Amortized Costs ($/1,000 Gallons; in 1999 $) 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.

6.1.4 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°C vs. 25°C), oxidants (HOCl, H_2O_2, and O_3), the presence of NOM, and the presence of 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) (Davis and Powers, 1999).

An economic evaluation of resin systems was performed for various combinations of flow rates (6, 60, 600, and 6,000 gpm), influent concentrations (20, 200, and 2,000 µg/L MTBE), and effluent goals (0.5, 5 µg/L, and 20 µg/L). In addition, a comparison between the use of two resin vessels operated in series vs. two resin vessels operated in parallel was performed. The use of steam regeneration, currently the more established regeneration method for resin systems, was also evaluated in a variety of process configurations.

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 6-5.

As this range indicates, for low flow rates, resin systems are impractical due to their excessive unit costs. For all cases evaluated, the cost differential between series and parallel operation was small (<16 percent) suggesting that both configurations should be carefully considered depending on site-specific conditions. 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, see Chapter 5.

Table 6-5

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.

6.2 Comparative Discussion of the Different Technologies

Within each technology class, specific technology(ies) have been selected from each chapter as the preferred choice.

Air Stripping
- Packed towers (high flow rates)
- Low profile (low flow rates)

GAC
- Coconut shell-based GAC

Resins
- Carbonaceous resin sorption, steam regeneration, GAC regenerant treatment

AOP
- H_2O_2/O_3
- H_2O_2/MP-UV

The final analysis prior to selection and implementation of a specific technology is a detailed comparison between the most promising alternatives. The following sections compare the technologies with respect to their ease of permitting, reliability, flexibility, adaptability, potential for modifications, and cost effectiveness.

6.2.1 Permitting

While a detailed evaluation of permitting requirements for the four technologies was beyond the scope this report, it is possible to perform a cursory analysis of permitting for the various technologies. For each technology, permitting issues can be divided into two categories: 1) start-up requirements and 2) steady-state operational requirements. As discussed in the DHS extremely impaired source water policy, permitting for start-up usually requires several months of pilot-scale demonstration with consistent contaminant removal prior to regulatory acceptance of treated effluent water as drinking water. Steady-state operational requirements encompass all the permits related to by-product formation, off-gas discharges, and regeneration issues.

Air stripping has been proposed by DHS as the BAT for MTBE removal from drinking water and, thus, is expected to require the least amount of pilot-scale demonstration prior to being permitted. However, an air stripper will require an off-gas treatment or discharge permit, which may dramatically increase the permitting difficulty. In addition, the height of packed towers may increase the permitting difficulty, especially in residential neighborhoods or near schools. For example, due to the regulatory difficulty of obtaining an off-gas treatment permit and the political challenges of installing a packed tower within 1,000 feet of a school, the use air stripping for MTBE removal from drinking water was not pursued in Santa

Monica, California. Alternatively, GAC was not originally considered by DHS as a BAT, but is now being evaluated in the selection of a BAT for early 2000. GAC is expected to be easier to permit once operational because it creates no by-products or secondary contamination (e.g., air) and has been used extensively for organic contaminant removal in drinking water applications.

Resin sorption and AOPs are expected to be relatively difficult to permit due to the limited use of these technologies in drinking water treatment. There are no full-scale drinking water applications using resins for MTBE removal from drinking water, nor are there systems where full-scale regeneration of resins has been performed in a drinking water application. AOPs have been used in limited cases for drinking water treatment, although no applications are for MTBE removal. Consequently, extended start-up pilot-scale testing will be required to demonstrate consistent MTBE removal before either of these technologies will be approved for delivery of potable water to consumers. Once permitted for operation, AOP steady-state operational permitting is expected to be difficult due to the formation of oxidation by-products and the presence of residual oxidant concentrations. Similarly, the use and operation of on-site steam regeneration for resins and the treatment of the regenerant are expected to incur strict regulatory scrutiny for large-scale resin applications.

6.2.2 Reliability

The reliability of a technology can be divided into two components: mechanical reliability and process reliability. Technologies with fewer moving parts are considered to be more mechanically reliable because they have fewer parts subject to wear and tear and, thus, are less susceptible to mechanical failures and require less frequent maintenance work (e.g., lubrication, replacements of seals, etc.). Minimizing the number of other parts required for operation (e.g., monitoring and control systems) also improves system mechanical reliability.

GAC involves no moving parts other than a pump and, therefore, is expected to be the most mechanically reliable of the technologies evaluated. Air stripping (both low profile and packed tower) is also highly mechanically reliable because it relies only on a pump and blower for MTBE removal. Air stripping may also necessitate off-gas treatment; however, even with this ancillary treatment step, it still involves fewer moving parts than resins or AOPs. Resin sorption and AOPs are the least mechanically reliable due to the large number of additional parts (e.g., steam generators, ozone diffusers), chemical additions (e.g., ozone, peroxide), and ancillary technologies (e.g., super-adsorber columns, regenerant disposal equipment, ozone off-gas destruction equipment) required for MTBE removal. However, it should be noted that within each of these general classes of technologies, such as AOPs, specific technologies can vary in their degree of mechanical reliability. For example, APT's H_2O_2/O_3 process is expected to be as mechanically reliable as a low profile air stripper.

Process reliability is evaluated based on the ability of a technology to consistently produce effluent that meets the necessary drinking water standards. Sorption technologies, such as GAC and resins, are expected to be highly reliable for achieving consistently high removal efficiencies of MTBE since these technologies are typically designed to remove contaminants to non-detectable levels. A single packed tower air stripper has been demonstrated to consistently achieve greater than 95 percent MTBE removal at higher flows (i.e., 600 to 6,000 gpm), while a single low profile air stripper is capable of high removal efficiencies for MTBE at lower flows (<100 gpm). Bench-scale testing suggests that AOPs will also be reliable; however, further studies at higher flow rates need to be conducted for verification of consistent MTBE removal.

6.2.3 Flexibility

Occasionally during the operation of a treatment process, the influent flow rates increase or decrease significantly compared to the design flow rate. A flexible technology is able to handle these fluctuations with no major impact on the treatment process outcome. Each of the selected treatment technologies can handle a fluctuating flow rate, both higher flow rates or lower flow rates than expected, while maintaining process reliability. However, some modifications or adjustments may be necessary.

Thus, to compare technologies, one can look at the relative decreased costs when the flow rate falls and increased costs as the flow rate raises. For example, as the flow rate decreases, adsorption technologies can be operated longer prior to regeneration or carbon change-out, thereby reducing the O&M cost of these technologies. Similarly, decreasing the amount of chemical additions during lower flow rate periods can reduce the cost for AOPs. For an air stripper, costs can be lowered by maintaining a constant AWR (i.e., as the water flow rate falls the air flow rate can also be decreased to maintain a constant AWR). However, not all air stripper blowers are capable of turn down, (e.g., low profile units have minimal turndown) and, thus, air stripping represents the technology for the lowest potential cost savings with decreasing flow rates. As the flow rate increases, operation of each technology will require modification or adjustment to maintain constant removal efficiencies. Sorption technologies will experience faster breakthrough and, thus, require more rapid carbon or resin regeneration. AOPs will require more chemical additions. Air stripping will require an increase in the air flow rate by either turning up the blower or installing a larger blower. If the flow rate increase beyond the design flow rate, each technology will require additional units operated in parallel.

6.2.4 Adaptability

Adaptability of a technology is defined as its ability to handle fluctuations in water quality conditions, such as influent contaminant concentrations, hardness, alkalinity, and turbidity. Based on the literature review, the performance of air stripping and resins are least affected by background water quality. While air stripping can be adversely affected by the presence of scaling agents, both of these technologies are unaffected by the presence of other contaminants or changing background water quality to achieve consistent MTBE removal from drinking water. Alternatively, the presence of other contaminants or NOM can significantly reduce MTBE removal efficiencies for GAC due to the competitive desorption of target contaminants. Similarly, high concentrations of alkalinity, bromide, and TOC in source water, among other factors, can decrease the effectiveness of AOPs.

If influent contaminant concentrations change and the effluent goal remains unchanged, treatment costs will rise and fall proportionally to the influent concentration. For increasing influent concentrations, the carbon or resin usage rate will increase, the AOP chemical dose will increase, and the AWR for an air stripper will increase. In general, sorption and AOPs can handle fluctuating contaminant concentrations better than air stripping because of the difficulty in turning up the blower power. Similarly, if contaminant concentrations decrease, air stripping is probably the most difficult technology to turn-down, for the same reasons discussed in Section 6.2.3 for a decrease in flow rates.

6.2.5 Potential for Modifications

The potential for modifications is defined as the operator's ability to alter the installed system, including addition of any necessary pre- and post-treatment systems, to accommodate changes in the design criteria and conditions. To comply with regulations, each of the technologies discussed in the report requires a redundant treatment system prior to drinking water distribution. This redundant treatment system is effectively a post-treatment polishing system. All of the technologies can handle this system or any pre-treatment systems with similar ease. However, some of the systems may require pre- or post-treatment systems prior to regulatory acceptance and, thus, these technologies should be rated lower than those technologies which can stand alone.

GAC is the only stand-alone technology, requiring no pre- or post-treatment systems for drinking water applications, other than the redundant carbon vessel. Air stripping may require an off-gas treatment unit, depending on local air quality restrictions. AOPs will require ozone off-gas treatment units, hydrogen peroxide catalytic oxidizers, and/or a polishing filter to remove oxidation by-products. Finally, resin systems require regeneration units, super-adsorber columns, and other equipment for on-site regeneration and re-use of the resins.

6.2.6 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. Furthermore, it may be difficult to compare costs between technologies due to differences in vendor assumptions and technology effectiveness. For example, all technologies can remove MTBE concentrations to below drinking water standards; however, AOPs create oxidation by-products, which may cause effluent water quality to exceed regulatory thresholds. Keeping these complicating factors in mind, a summary of the total amortized costs ($/1,000 gallons; in 1999 $) for the various treatment technologies is presented in Table 6-6. A detailed description of assumptions used is provided in each respective chapter.

A direct comparison of these costs indicate that, under the assumptions stated for the cost analysis of each technology, packed tower aeration with off-gas treatment (when required) is generally the most cost-effective treatment option. However, packed tower aeration is expected to be ineffective for cases where very high removal rates are required. In these cases, H_2O_2/O_3 systems become the most cost-effective option for small and medium-sized systems (60 and 600 gpm, 2,000 μg/L to 0.5 μg/L, 99.98 percent removal). For large systems (6,000 gpm), resin sorbent systems appear to be the most cost-effective option for both low (20 μg/L) and high (2,000 μg/L) concentrations. For medium concentrations (200 μg/L), H_2O_2/O_3 systems are most cost-effective for lower removal efficiencies (90 percent) while packed towers are most cost-effective for higher removal efficiencies (97.50 and 99.75 percent). However, it is important to note that the differences in unit costs amongst 6,000 gpm systems for these technologies (packed tower aeration with off-gas treatment, H_2O_2/O_3 systems, and resin sorbent systems) are generally in the order of a few cents per thousand gallons. Considering the uncertainty in these cost estimates, all three technologies can be considered equivalent in costs for a large-scale system.

Table 6-6

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.

6.3 Recommendations for Future Research

In general, there are only a few full-scale installations of MTBE treatment systems for drinking water treatment. Therefore, for each technology, there are a number of areas that are still lacking information critical for effective implementation in MTBE applications. Recommendations for further research to address these areas of uncertainty are discussed below.

6.3.1 Air Stripping

Air stripping is a well-understood technology with many full-scale installations across the country. However, other than the packed tower air strippers at LaCrosse, 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.

6.3.2 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 these water quality parameters. The evaluation criteria must include MTBE removal efficiency, oxidation by-product formation, disinfection by-product (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, MP, pulsed) 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.

6.3.3 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-based carbon and coal-based carbon.

2) *Dynamic GAC Adsorption Capacities.* Dynamic column tests should be performed to determine GAC usage rates, optimum 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 the California MTBE Research Partnership with financial and performance data from pilot-scale testing.

6.3.4 Resins

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 report should be investigated.