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Evaluation & Assessment of Removal Technology for Specific Organic Contaminants in NJ Drinking Water

Prepared for

NJ Corporation for Advanced Technology

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Section 1. Introduction

New Jersey's standard setting process was established within the 1983 amendments to the New Jersey Safe Drinking Water Act. In 1987, the Drinking Water Quality Institute (DWQI) recommended Maximum Contaminant Levels (MCLs) for 16 of the 22 hazardous contaminants listed in the 1983 amendments, which were adopted by New Jersey Department of Environmental Protection (NJDEP) in 1989. In 1994, the DWQI recommended six additional contaminants for regulation in drinking water and MCLs for these contaminants based on their presence in New Jersey waters and the frequency of occurrence. These recommendations were adopted by NJDEP in 1996.

In 2005, NJDEP requested that the DWQI reevaluate the contaminants provided in the legislation (also known as A280 chemicals) to determine if existing MCLs are appropriate or if modification is warranted. As a result of the reevaluation, some MCLs will not change, some will become less stringent, and others may become more stringent. Therefore, NJDEP sought a review of the available literature on selected removal technologies, specifically for New Jersey public water systems to determine if there is treatment feasibility to address the anticipated MCLs. The assessment focused on removal technologies for fifteen contaminants that New Jersey may regulate, either in addition to or more stringent than existing USEPA regulatory limits. Evaluation was conducted for both surface water sources and groundwater sources. For the remainder of this document, "contaminants" will refer to the fifteen (15) contaminants provided in Table 1-1 below.

As one of the most heavily populated states in the nation and one where manufacturing and refining industries were significant employers until recent decades, New Jersey has already dealt with a number of contaminated water supplies. In 2003, 54 community water systems, nearly 9% of the 600 community water systems in the State, had organic removal systems to remove or reduce the levels of regulated volatile or synthetic organic chemicals from the water supply (NJDEP, 2003). In many cases, non-regulated organic chemicals were found in the source waters in addition to the regulated organic chemicals that required treatment, and there are some data regarding the removal of these non-regulated contaminants of concern by air stripping and granular activated processes installed as best available treatment for the regulated organic contaminants.

A major goal of this literature review is to determine if air stripping and granular activated carbon (GAC) adsorption are still the best available treatment methods for the majority of the fifteen contaminants, considering that great advances have been made in the availability and cost effectiveness of membrane treatments, addition of ozone – alone or followed by biological processes, advanced oxidation processes, and specialized adsorptive media.

The report generated as a result of this literature review and evaluation will be used to support the deliberations of the DWQI Treatment Subcommittee and therefore the NJDEP's future MCL setting decisions.

1.1 Contaminants of Concern

Table 1-1 presents a listing of the contaminants as well as their health based levels, and proposed practical quantitation levels for this study currently regulated by USEPA, while others are included in the Drinking Water Health Advisory List (USEPA, 2006b) or in the USEPA Notice of Draft Candidate Contaminant List 3 (USEPA, 2008) for possible future regulation. Drinking water health advisories are non-enforceable concentration of drinking water contaminants. Health advisories provide an estimate of acceptable drinking water levels for a chemical substance based on health effects information (USEPA, 2006b).

Table 1-1 New Jersey Contaminants of Concern (March 3, 2008)

Contaminant	**Existing MCL**	**Health Based Levels**	**Proposed PQL**
Benzene	1 µg/l	0.1 µg/l	0.8 µg/l
1,3 Dichlorobenzene	600 µg/l	6 µg/l	1 µg/l
1,4 Dichlorobenzene	75 µg/l	14 µg/l	1 µg/l
1,1 Dichloroethane	50 µg/l	23 µg/l	1 µg/l
1,1,2 Trichloroethane	3 µg/l	0.6 µg/l	1 µg/l
2,4,6 Trichlorophenol	None	3 µg/l	Under Review (1) (20 µg/l)
1,2,3 Trichloropropane	None	0.005 µg/l	Under Review (1) (0.03 µg/l)
Vinyl Chloride (1 chloroethene)	2 µg/l	0.024 µg/l	1 µg/l
Ethylene glycol	None	10 mg/l	10 mg/l
Formaldehyde	None	100 µg/l	5 µg/l
Methyl Ethyl Ketone (2-Butanone)	None	4000 µg/l	Under Review (1) (2 µg/l)
Methylene chloride (Dichloromethane)	3 µg/l	2.5 µg/l	1 µg/l
n-Hexane	None	33 µg/l	3 µg/l
Tertiary Butyl Alcohol	None	Under Review	Under Review (1) (2 µg/l)
DCPA and Degradates (mono- and di-acid)	None	28 µg/l	Under Review (1) (1 µg/l)

(1) Contaminants described as "under review" may assume proposed PQLs in parentheses

MCL is defined by USEPA as “the maximum permissible level of a contaminant in water which is delivered to any user of a public water system” (40CFR Part141.2). In the preamble to a November 13, 1985 rulemaking (USEPA, 1985, 50 FR 46906), the practical quantitation limit (PQL) was defined as "the lowest concentration of an analyte that can be reliably measured within specified limits of precision and accuracy during routine laboratory operating conditions." The Agency has used the PQL to estimate or evaluate the minimum concentration at which most laboratories can be expected to reliably measure a specific chemical contaminant during day-to-day analyses of drinking water samples.

Table 1-2 presents currently regulated or accepted analytical methods with detection limits for the compounds of concern. The EPA accepted methods and detection limits are as presented in the National Environmental Methods Index (www.nemi.gov).

Table 1-2 Current Analytical Methods

Contaminant	**Analytical Method**	**Detection Limit, µg/l**	**Notes**
Benzene	EPA 502.2 EPA 524.2	0.01 0.03	In reagent water
1,3 Dichlorobenzene	EPA 502.2 EPA 524.2	0.02 0.05	In reagent water
1,4 Dichlorobenzene	EPA 502.2 EPA 524.2	0.01 0.04	In reagent water
1,1 Dichloroethane	EPA 502.2 EPA 524.2	0.07 0.03	In reagent water
1,1,2 Trichloroethane	EPA 502.2 EPA 524.2 EPA 555.1	0.03 0.04 0.005	In reagent water
1,2,3 Trichloropropane	EPA 504.1 EPA 524.2 EPA 555.1	0.02 0.03 0.008	In reagent water
Methylene chloride (Dichloromethane)	EPA 502.2 EPA 524.2	0.02 0.09	In reagent water
Vinyl Chloride (1 Chloroethene)	EPA 502.2 EPA 524.2	0.02 0.04	In reagent water
Ethylene glycol	EPA 8015C	NA	In groundwater
2,4,6 Trichlorophenol	EPA 526 EPA 528	0.01 0.046	Cartridge extract Reagent water

Contaminant	Analytical Method	Detection Limit, µg/l	Notes
Formaldehyde	SM 6252 EPA 556 EPA 556.1	0.09	In reagent water
Methyl Ethyl Ketone (2-Butanone)	EPA 524.2	0.48	In reagent water
n-Hexane	EPA 524.2	0.1	In reagent water
Tertiary Butyl Alcohol	EPA 5031/8015C	7	In groundwater
DCPA	EPA 508 EPA 508.1 EPA 525.2	0.0032 0.009 0.094	In reagent water In reagent water In reagent water
DCPA Degradates (mono- and di-acid)	EPA 515.1 EPA 515.2 EPA 515.3 EPA 515.4	0.067 0.13 0.63 0.113	Estimated detection limits, reagent and groundwater

* MIQ is defined as the minimum quantity that must be injected to result in a spectral match that has the correct compound identification in the top 5 spectral matches. The MIQ will vary depending on instrument sensitivity and sample matrix effects.

A number of the compounds for this study are not currently regulated as drinking water contaminants by USEPA though some do show up on the USEPA Drinking Water Health Advisory List and others have recently been listed in the Notice of Draft Contaminant Candidate List 3, published February 21, 2008. Thus, for a number of these contaminants, analytical methods and quantitation limits in water have been established by the USEPA or other regulatory agencies.

Benzene (molecular weight 78) is a natural component of coal tars and petroleum. Once refined, it is a major component of gasoline and thus is ubiquitous. It is a component of the group of volatile petroleum based hydrocarbons known as BTEX (benzene, toluene, ethylbenzene, and xylenes). Benzene is in the top 20 in industrial chemical production volume in the United States. Benzene has a lower specific gravity than water – it floats to the surface of a water body or an aquifer. Benzene has been detected in surface water and groundwater throughout the United States (ATSDR, August 2007). Benzene in drinking water has been regulated by USEPA since the 1987 Phase 1 (VOC) Rule.

1,3 Dichlorobenzene (molecular weight 147) is used to make pesticides, dyes, and some medical products. It is not a naturally occurring chemical. It is a dense liquid that sinks when added to water. 1,3 Dichlorobenzene does not currently have a drinking water standard under USEPA, but is regulated by the NJDEP with a MCL of 600 µg/l.

1,4 Dichlorobenzene (molecular weight 147) is used as insect repellent (mothballs or flakes) and a deodorizer in garbage cans and restrooms. It is a solid at ambient temperatures but sublimates into the atmosphere. 1,4 Dichlorobenzene currently has a USEPA drinking water MCL of 75 µg/l and a NJDEP MCL of 75 µg/l.

1,1 Dichloroethane (molecular weight 97.5) is a solvent and used as an intermediate in the production of other organic chemicals. 1,1 Dichloroethane is considered a volatile chemical by EPA and it has not been detected in surface water sources (ATSDR, September 1990). However, this compound is regulated in New Jersey at a MCL of 50 µg/l.

1,1,2 Trichloroethane (molecular weight 133) is a solvent and intermediate in the production of other chemicals. It is used primarily in the timber products industry, plastics manufacture, and laundries, often detected with 1,1 dichloroethene (ATSDR, 1989). In a New Jersey survey conducted in 1981, 6.7% of wells contained detectable levels of 1,1,2 trichloroethane (Greenberg et al, 1982). The USEPA MCL is 5 µg/l and NJDEP MCL is 3 µg/l.

1,2,3 Trichloropropane (molecular weight 147) is a dense liquid formed as a by-product of a number of chlorinated solvent reactions and as the by-product from the production of epichlorhydrin. The compound is present on the 2006 USEPA Drinking Water Health Advisory List with a Drinking Water Equivalent level of 0.2 mg/l (200 µg/l) and a lifetime health advisory level of 0.04 mg/l (40 µg/l). It also shows up on the USEPA Notice of Draft Candidate Contaminant List 3. The current NJDEP health based MCL is 0.005 µg/l, which is being re-evaluated by the DWQI Health Effects Subcommittee.

Methylene chloride, otherwise known as dichloromethane, (molecular weight 85), is an industrial solvent and paint stripper and has been detected as a disinfection by-product. Dichloromethane currently has a New Jersey drinking water regulated MCL of 3 µg/l.

Vinyl chloride, otherwise known as chloroethene, (molecular weight 62.5), is a manufactured monomer used to make plastics, in particular, polyvinyl chloride. Polyvinyl chloride is used in potable water piping, wire and cable coatings, automobile upholstery, wall coverings and houseware items. Vinyl chloride is regulated at a MCL of 2 µg/l under the Phase I Rule, and is on the Drinking Water Health Advisory List with a Drinking Water Equivalent Level of 0.1 mg/l (ATSDR, 2006).

There are several unregulated contaminants in the current New Jersey List of Contaminants of Concern (NJDEP, March 2008). Each of these are listed below along with a description of the source of the contaminant and the current lifetime health advisory status established by USEPA. The basis for determining if a particular contaminant will be regulated considers available occurrence data, toxicity data, and the effectiveness of available treatment technologies. The USEPA has published numerous documents providing information on screening of contaminants and the basis for inclusion on the CCL list. These documents can be found on the

USEPA Office of Groundwater and Drinking Water website, http://www.epa.gov/OGWDW/ccl/index.html.

Ethylene glycol, otherwise known as 1,2 dihydroxyethane (molecular weight 62) is used as an antifreeze agent in automobiles and a deicing agent for aircraft. It is also used in the manufacture of polyester fibers and polyethylene teraphthalate (PET) bottles. Even though ethylene glycol does not have an MCL, it shows up on the 2006 USEPA Drinking Water Health Advisory List with a Drinking Water Equivalent level of 70 mg/l and a lifetime health advisory level of 14 mg/l (ATSDR, 2007). Ethylene glycol also shows up on the USEPA Notice of Draft Candidate Contaminant List 3 so may be regulated by USEPA in the future.

2,4,6 Trichlorophenol (molecular weight 197) is used in the manufacture of pesticides and has shown up as a disinfection by-product in chlorinated water. It is included on the 2006 USEPA Drinking Water Health Advisory List with a Drinking Water Equivalent level of 0.01 mg/l (10 µg/l). There is no lifetime health advisory level, however, there is an estimate of 10^{-4} excess estimated lifetime cancer risk at 0.3 mg/l (300 µg/l) (ATSDR, 1999).

Formaldehyde (molecular weight 30) is both naturally occurring and produced and used by humans. Formaldehyde is an ingredient of antiseptics, medicines, cosmetics, cleaning agents, glues and adhesives, plywood and urea-formaldehyde resins. It can be created in water as a result of ozonation. Formaldehyde is included on the 2006 USEPA Drinking Water Health Advisory List with a Drinking Water Equivalent level of 7 mg/l (ATSDR, 1999) and a lifetime health advisory level of 1 mg/l. It also shows up on the USEPA Notice of Draft Candidate Contaminant List 3 so may be regulated by USEPA in the future.

Methyl ethyl ketone (2 Butanone, molecular weight 72) is manufactured in large amounts for use in paints, glues, and other finishes because it rapidly evaporates and will dissolve many substances (ATSDR, 1992). Methyl ethyl ketone is less dense than water. It is on the 2006 USEPA Drinking Water Health Advisory List with a Drinking Water Equivalent level of 20 mg/l and a lifetime health advisory level of 4 mg/l.

n-Hexane (molecular weight 86) is a constituent of the paraffin fraction of crude oil and natural gas and is found in heating oils and fuels. Gasoline is 1 to 3% hexane. Refined hexane is used as a solvent for processing of oils from grains or soybeans. It is included on the 2006 USEPA Drinking Water Health Advisory List with a one day health advisory limit of 10 mg/l and a one week health advisory limit of 4 mg/l for a 10 kg (22 pound) child.

Tertiary butyl alcohol, otherwise known as 2-methyl-2-propanol (molecular weight 74) is used directly as an additive to gasoline as an oxygenate and is a degradation product of methyl tert-butyl-ether (MTBE), an oxygenate that was used in gasoline. The two compounds are often found together in the residues from a gasoline spill or leak. Tertiary butyl alcohol is also a component of paint removers and an intermediate in perfumes. Tertiary butyl alcohol is not currently regulated by USEPA as a drinking water contaminant, nor has a health advisory been established through USEPA. The National Toxicology Program under the National Institutes of Health established a drinking water interim assessment concentration of 12 µg/l, based on toxicology studies they conducted (NPT, 1994).

DCPA (Dacthal or dimethyl 2,3,5,6-tetrachlorobenzene-1,4 dicarboxylate, molecular weight 332) is a phthalate type pre-emergent herbicide. The majority of the herbicide is used at turf sod farms, on golf courses, and for residential lawns and gardens. It is included on the 2006 USEPA Drinking Water Health Advisory List with a Drinking Water Equivalent level of 0.35 mg/l (350 µg/l) and a lifetime health advisory level of 0.07 mg/l (70 µg/l). In the environment, it is metabolized into two degradation products. The major degradation product is the di-acid tetrachloroterephthalic acid (CAS 2136-79-0) while the minor degradation product is the mono-acid monomethyl tetrachloroterephthalic acid (CAS 887-54-7). New Jersey is one of the four states that reported 15 to 40 % of the public water supplies required to monitor for DCPA and the two degradates under the first Unregulated Contaminants Candidate List monitoring program, detected these compounds at or above the minimum reporting level of 1 µg/l (USEPA, 2006). Health based level of 28 µg/l has been developed.

Section 2. Treatment Technologies

2.1 Chemical Properties

The chemical properties of the contaminants govern to a degree what treatment options will be effective for their removal from a drinking water source. Thus, the first step in determining which treatment steps may be possible requires evaluating known properties of the contaminants. Molecular weight data were presented in Section 1 within the description of each contaminant. The solubility of the compound as defined by solubility constants indicate the extent to which the compound will dissolve in water. The volatility of the compound as defined by the Henry's Constant indicates how well a contaminant will be removed by air stripping. Partition coefficients and adsorption isotherm data are available for many compounds and adsorbent combinations to provide guidance about which remain in solution when other solvent or adsorbent options are available. Table 2-1 presents critical chemical data for the fifteen contaminants.

Table 2-1 Critical Chemical Data for Contaminants of Concern

	Solubility, mg/l	**Henry's Constant, atm-m^3/mole, 25°C**	**Octanol/water coefficient, log K_{ow}**
Benzene	1,750	0.0055	2.13
1,3 Dichlorobenzene	125	0.0028	3.53
1,4 Dichlorobenzene	80	0.00241	3.44
1,1 Dichloroethane	5,500	0.0042	1.79
1,1,2 Trichloroethane	4,400	0.00091	2.42
1,2,3 Trichloropropane	1,750	0.000317	1.98
Methylene chloride (dichloromethane)	20,000	0.00203	1.3
Vinyl Chloride (1 chloroethene)	2,763	0.0278	1.36
Ethylene glycol	miscible	0.00000006	-1.36
2,4,6 Trichlorophenol	434	0.0000057	3.69
Formaldehyde	550,000	0.000000327	0.35
Methyl Ethyl Ketone (2-butanone)	136,000	0.0000577	0.29
n-Hexane	9.5	1.69	3.29
Tertiary Butyl Alcohol	miscible	0.0000118	0.35
DCPA	0.5	0.00000218	4.19
DCPA Degradates (mono- and di-acid)	ND	ND	ND

ND means that accurate chemical constants – Solubility, Henry's Constant, and Octanol/Water Coefficient – have not been determined.

The molecular weight of a compound provides indirect information about the size and chemical complexity of a compound. Membrane processes such as nanofiltration

(NF) and reverse osmosis (RO) are rated in their ability to remove compounds above a certain molecular weight. There are NF membranes that have molecular weight cutoffs at 10 to 50 Angstrom units (0.001 to 0.005 µm), while RO is capable of removing compounds and ions greater than 5 to 20 Angstrom units (0.0005 to 0.002 µm) in size. This corresponds to molecular weights of about 100 units for RO and low hundreds of units for NF.

Solubility is the amount of a chemical that can dissolve in a fluid. For the purposes of water quality and treatment, solubility is the amount of a contaminant that can dissolve in water at near ambient temperatures (25^{o}C). Most organic substances become more soluble as the water temperature increases, unless the organic compound is volatile. Solubility of organic compounds in water is controlled primarily by the polarity of the compound. Nonpolar organic compounds do not dissolve well in the polar solvent water. Solubility values less than 1 mg/l (1000 µg/l) are considered insoluble – allowing the compound to be easily removed from water (ASTM, 2008). The higher the solubility value, the greater the amount of the substance that can dissolve in water. Highly soluble compounds, such as ethylene glycol or tertiary butyl alcohol which are soluble in all proportions with water (miscible), are very difficult to remove from water. Very soluble compounds do not transfer to other solvents or adsorbents, nor will they bind to soils or activated carbon.

The equilibrium concentration of a solute or contaminant in air is directly proportional to the concentration of the solute in water at a given temperature. This is supported by Henry’s Constant which states that the amount of gas that dissolves in a given quantity of liquid, at constant temperature and total pressure, is directly proportional to the partial pressure of the gas above the solution. Therefore, the Henry’s Constant describes the tendency of a given compound to separate between a gas and a liquid and is a special case of solubility as the compound is soluble in both water and in air.

The Henry’s Constant can be used to give a preliminary indication of how well an organic chemical can be removed from water. Chemicals with a Henry’s Constant greater than 0.001 are considered volatile and can easily be air stripped. Chemicals with a Henry’s Constant between 0.00001 and 0.001 are semi-volatile, meaning that transfer to air can be a significant removal mechanism but that higher air to water ratios may be needed for adequate removal. Chemicals with Henry’s Constant less than 0.00001 are not considered volatile. Groundwater sources require air stripping treatment once the water is pumped from the well to expose the water to the atmosphere and to promote the transfer of volatile compounds from water to air.

The octanol/water coefficient (log K_{ow}) is the ratio of the concentration of a chemical in octanol and in water at equilibrium at a specified temperature, normally 25^{o}C. Octanol is an organic solvent that is used as a surrogate for natural organic matter and provides information about how well a compound will adsorb to activated carbon. Compounds which are neutral in water, that is that they have no charge at water pH values from 6 to 8, and have a high log K_{ow}, defined as greater than 2, adsorb well to activated carbons or transfer to non-polar solvents. However, the adsorptive removal of compounds which have either a positive or negative charge in water can be greatly affected by the pH of the water, so both octanol/water coefficient and the charge or lack of charge of a specific compound at pH values from 6 to 8 are important.

2.2 Basic Treatment Requirements for Surface Waters and Groundwaters in New Jersey

New Jersey Safe Drinking Water Act Regulations (N.J.A.C. 7:10-4.1(b)) require that all community water systems with groundwater supplies serving 100 dwellings or more must disinfect the water. All surface water (including GWUDI) public water systems must apply filtration treatment and disinfection as described in N.J.A.C. 7:10-9.2 and the Federal Surface Water Treatment Rule. These treatments, designed to provide microbiologically safe water, are the baseline treatments for all public water supplies in New Jersey.

However, municipal water filtration plants using conventional filtration processes have not been effective at removing many volatile and semi-volatile contaminants from raw water (USEPA, 1985), so alternative or additional processes have been developed to accomplish removal of these contaminants of interest. USEPA has published Best Available Treatment techniques for those contaminants for which it has established Maximum Contaminant Levels. It is not required to do so for those contaminants for which it has not established MCLs.

Table 2-2 presents what USEPA has established as Best Available Treatment (BAT) for the contaminants that are regulated at the Federal level.

Table 2-2 USEPA Best Available Treatment for Regulated Contaminants

Contaminant	Activated Carbon	Air Stripping
Benzene	Yes	Yes
1,3 Dichlorobenzene	Yes	Yes
1,4 Dichlorobenzene	Yes	Yes
1,1,2 Trichloroethane	Yes	Yes
Vinyl chloride	No	Yes
Methylene chloride	Yes, with Air Stripping	Yes, with Activated Carbon

2.3 Adsorption Processes using Activated Carbon

Adsorption is the collection and condensation of a substance or substances from the water phase to the solid surface of an adsorbent. Both GAC and powdered activated carbon (PAC) adsorption have been used in drinking water treatment for both surface and groundwater sources. Activated carbon has a large surface area (important because adsorption is a surface phenomenon), different pore sizes that can physically help remove various sizes of molecules, and surface chemistry that varies from non-polar to very oxidized and polar (McGuire and Suffet, 1978). The principle mechanisms that affect the transfer of contaminants from the aqueous phase to the GAC or PAC adsorbent are transport across the hydrodynamic layer around each activated carbon particle, intra-particle transport through the activated carbon bed, and chemical equilibrium (Mathews and Zayas, 1989).

There are different types of GAC and PAC that have been developed from source compounds as diverse as bituminous coal and coconut shells. The different types of GAC and PAC can exhibit greater affinities for some contaminants; therefore the selection of an optimal activated carbon can significantly improve the efficiency of the process for a specific water and particular contaminant. Isotherm tests are conducted to determine if an activated carbon can remove a contaminant or mixture of contaminants from a water source. Suppliers often make both powdered and granular forms of activated carbon from the same source materials so that the two forms may be used in different applications.

Water is passed through a contact bed of GAC in a manner similar to passing water through a filter. Adsorbed compounds adhere to the carbon, competing for bonding sites; therefore, the adsorptive capacity of the carbon will become exhausted and it must be regenerated or replaced to continue removal of the desired compounds from the water. GAC contactors or beds may be open to the atmosphere and operate much like multi-media filters or the carbon may be placed in closed vessels and operate in a pressurized system. Surface water GAC contactors are typically designed like granular media filters but are placed AFTER traditional granular media filters, so that much of the natural organic matter (NOM) which should be incorporated into the floc and could compete for activated carbon sites, is removed by the filters. Organics remaining in the filtered water can then be removed more effectively by the GAC contactors.

PAC has been used in conjunction with settling processes in conventional treatment where the PAC is added to coagulated water before settling. PAC has been added prior to rapid mix or prior to settling so that it contacts raw water or freshly coagulated water. The chance for competing reactions is higher with this form of activated carbon contact than with post-filtration GAC contactors but the capital cost of PAC feed equipment is far less than constructing GAC contactors and the activated carbon dosage can be varied as needed to respond to changing water quality. Contact times of 1 to 3 hours is provided for the PAC in the settling basins, as the PAC settles out in the basins, or is removed by the filters, and it is disposed with other water treatment plant residuals. For water treatment plants that use alternatives to traditional settling basins, such as floc-blanket reactors or solids contact clarifiers, the contact time between the PAC and the contaminants can be increased, typically resulting in improved removal compared to conventional processes (Najm et al., 1991). As ultrafiltration and microfiltration membranes have replaced traditional filters, PAC has been applied as a pretreatment ahead of these membranes (Pirbazari et al, 1992; Jack and Clark, 1998).

In making a determination about which form of activated carbon to use to treat a specific source, two major considerations are the capacity of an optimal carbon for the contaminant or contaminants in the water source and the contact time necessary for adequate removal. As the same carbon type can be supplied either in granular or powdered form, the effectiveness of the activated carbon is often controlled by where in the process it is added. PACs are typically added early in the treatment process, while GAC is usually reserved until after filtration or pretreatment. Mixtures of organic compounds reduce the capacity of any activated carbon to remove any one compound because of competition for bonding sites, so PAC added early in a treatment process may not demonstrate the same removal as GAC after filtration. On the other hand, the powdered form of carbon has a higher surface area, so may effect better removal if there is little competition for adsorption sites.

In addition to the mix of organic contaminants, the efficiency of activated carbon adsorption is affected by:

- The properties of the activated carbon itself
- The contact time of the water with the activated carbon (in the GAC bed or in the process for PAC)
- PAC dosage
- Water temperature
- pH
- The concentration of inorganic substances in the water
- The concentration of natural organic matter in the water which competes for adsorption sites, thereby reducing the adsorption capacity for the target organic chemicals to be removed (surface waters versus most groundwaters)
- The presence or absence of chlorine in the water

Activated carbon reacts with chlorine (or other oxidants) in a reduction-oxidation reaction, which may change the surface characteristics of the activated carbon. Also, the loss of chlorine through GAC may result in additional costs for re-chlorination post-GAC. Over time, GAC could become colonized by bacteria that metabolize adsorbed compounds, enhancing the capacity of the activated carbon and prolonging its life (Clark and Lykins, 1989; Servais et al, 1994; Aizpura et al, 2003).

Activated carbon has been found to be capable of removing a broad range of organic chemicals. Tests conducted by USEPA have indicated that 38 of the organic chemicals on the Candidate Contaminant List (CCL) published in 1998 can be removed using GAC. A literature survey conducted by Najm et al. (1991) resulted in determining the required PAC dosages to reduce 44 organic chemicals from 100 µg/l to 1 µg/l. No reference to the NJDEP proposed limit of 0.8 µg/l was referenced as the federal regulated levels were no lower than 1 µg/l at the time of the study. Among the organics were benzene and dichlorobenzene. Table 2-3 presents these data.

Table 2-3 PAC Dosages required to treat Selected Organics

Compound	**Water**	**PAC Dose, mg/l**	**Time**
Benzene	Distilled water	>100,000	1 hour
Dichlorobenzene	Surface water	12	10 days

An important factor in determining the applicability of GAC for organic chemical removal is the carbon usage rate – the rate at which the GAC will become exhausted and must be replaced. This can only be determined by bench or pilot scale testing at an individual site to determine how the mix of organic contaminants and natural organic matter and inorganic species interact and are removed over long periods of time.

2.4 Air Stripping

Air stripping is a treatment technique in which air is brought into contact with water in a controlled manner to permit the transport of volatile contaminants from the water into the air. The goal is to transfer the contaminant from the water to the air at the gas-liquid interface as efficiently as possible (Montgomery, 1985). Air stripping has been used in water treatment to reduce the concentrations of taste and odor producing compounds, carbon dioxide, hydrogen sulfide and volatile organic chemicals. This process also has been used to oxidize iron and manganese by adding air to the water – referred to as aeration or gas absorption. Regardless of the source of the water, surface or ground, air stripping is often the first treatment process applied as the transfer of volatiles from water to air does not interfere with later coagulation processes, actively promotes oxidation of dissolved iron and, to a lesser degree manganese, and removes volatile compounds from the water stream before advanced oxidation or adsorption using activated carbon is used to further treat the water source. In air stripping, excess carbon is removed resulting in raised pH and lowered dissolved inorganic carbonate – this is a corrosion benefit. The only gas to be increased is typically dissolved oxygen which may have implications for iron and copper corrosion (Lytle et al, 1998). Air stripping processes that have been used most frequently in water treatment include:

- Diffused bubble aerators where a blower adds fine bubbles of air to a chamber of flowing water,

- Packed towers where the water is pumped to the top of a chamber filled with materials that separate the water flow so that introduced air can contact thin films of water, and
- Shallow tray aeration where water is introduced to a top layer of stacked trays filled with coal or a similar medium that facilitates air and water contact.

Each of these techniques has been used extensively in treating groundwater supplies. Packed tower systems provide the greatest flexibility with regard to air:water ratios, contact times, and available area for mass transfer. The driving force for mass transfer is the difference between the existing and equilibrium concentrations of the waterborne contaminant in air and water (Montgomery, 1985). Factors that affect this transfer include:

- The temperature of both water and air
- The physical chemistry of the contaminant (Henry's Constant)
- Concentration of the contaminant
- The ratio of air to water in the process
- Contact time
- Available area for mass transfer
- The pressure of the system

The latter four factors can be controlled in the design of the air stripping system, while the concentration of contaminants are a function of the specific groundwater supply and the nature of the organic chemicals in that supply. Temperature effects can and should be taken into account in the design of air stripping facilities as should the rise in pH that occurs as carbon dioxide is stripped from a super saturated well. Low temperatures are the worse case because diffusion of chemicals through water and air slows in colder waters and the solubility of gases and volatile compounds is also at a maximum at colder temperatures.

Chemicals with Henry's Constant values greater than 0.001 ($1\text{x}10^{-3}$ atm-m^3/mole) are considered volatile and amenable to air stripping. This would include the following from the list of contaminants:

- n-hexane;
- vinyl chloride;
- benzene;
- methylene chloride;
- 1,3 dichlorobenzene;
- 1,4 dichlorobenzene; and
- 1,1 dichloroethane

When more than one volatile chemical is found in a supply, air stripping is designed to treat the least volatile to a target level below the regulatory contaminant concentration. There is no competition between the volatile constituents as the partial pressure of each chemical provides the driving force for volatilization.

Little research has been conducted on air stripping in the past fifteen years as the USEPA regulatory framework has shifted from the removal of volatile organic contaminants from water to regulating semi-volatile organics, contaminants such as pesticides and herbicides, pharmaceuticals, and complex synthetic compounds such as endocrine disruptors. The mechanics of air stripping are understood, the technology is considered mature, and, as long as accurate volatile contaminant concentrations are known, facilities can be designed to remove the contaminant to less than detectable levels. Thus, the volatile contaminants listed above can be removed to less than the current detection limit with properly designed and operated air stripping facilities. Confounding factors, such as the presence of dissolved iron and manganese, addition of oxygen from air, and the rise in pH resulting from concurrent stripping of carbon dioxide in the groundwater, must be considered in design. Dissolved iron and manganese or increases in pH do not interfere with volatile removal, but iron and manganese are regulated as secondary contaminants and unaesthetic to customers and the higher pH of the treated water may favor precipitation of calcium and magnesium carbonates from the water.

2.5 Advanced Oxidation Processes

Oxidation processes have been used in drinking water treatment to accomplish several objectives: disinfection, iron/manganese oxidation, oxidation of organic compounds (particularly taste and odor compounds), and color removal. The mechanism for removal of organic chemicals by oxidation is either the conversion of the chemical into an intermediate reaction product or into carbon dioxide and water (mineralization). Complete destruction is rarely achieved, as intermediates formed can be resistant to further oxidation.

Advanced oxidation has been defined by Glaze (Glaze, 1987) and his associates as “near ambient temperature and pressure water treatment processes which involve the generation of hydroxyl radicals in sufficient quantity to effect water purification.” Advanced oxidation processes are available for removing organic chemicals from drinking water:

- Ozone including ozone with peroxides or catalysts
- Ultraviolet (UV) light with hydrogen peroxide addition or the presence of catalysts such as titanium dioxide
- Combinations of ozone and ultraviolet light

Ozone - Ozone is the most powerful chemical oxidant available for water treatment and therefore has a greater capacity to oxidize organic chemicals as compared to other oxidants used as disinfectants. Ozone can react in aqueous solutions by two mechanisms: direct reaction of the ozone molecule and indirect reaction through decomposition of the ozone to hydroxyl free radicals that in turn react directly with the organic chemicals. The actual oxidation of organic chemicals in an ozone treatment process occurs by a combination of direct and indirect reactions.

The direct molecular ozone reaction pathway is relatively fast as compared to chlorine or chloramines, with most reactions completed within a few seconds to a few minutes. The ozone molecule is a rather selective oxidizing agent, seeking electron-rich centers for oxidative attack. When used alone, the ozone process generally involves an ozone contact basin to provide sufficient time for oxidation to occur. Typically, where ozone is used in drinking water treatment, the theoretical contact time can range from several minutes to greater than 20 minutes. Ozone dosages often range from 1 to 5 milligrams per liter (mg/l), depending upon the ozone demand and water temperature. Ozone doses for contaminant removal will depend on the organic contaminant and the amount of natural organic matter (NOM) in the water. Since the NOM typically is at much higher concentrations than the contaminants of concern, NOM levels will tend to drive the ozone dosage. Ozone is generated on-site from oxygen gas, thus oxygen must be supplied to the treatment plant, or generated on site. Where bromide is found in the raw water, the by-product, bromate, is formed through oxidation with ozone. Ozone remaining at the end of the ozone contactor must be treated through ozone destruct units to prevent release of the ozone into ambient air.

In contrast to the direct reaction pathway, the indirect reaction pathway (via the OH radical) is faster, occurring on the order of microseconds. The OH radical is a more powerful oxidant (oxidation potential of 2.8 V) than ozone itself (oxidation potential of 2.07 V). The OH radical is less selective with respect to oxidation of micro-pollutants. Oxidation processes that utilize the highly reactive OH radical are called advanced oxidation processes (AOPs). Advanced oxidation can be accomplished in several ways including:

- Ozonation at high pH
- Ozonation with addition of hydrogen peroxide
- Ozonation followed by ultraviolet (UV) light
- UV light followed by ozone
- Ozone with titanium oxide catalysts
- UV with titanium catalysts

The UV processes are described below. By utilizing the OH radical, contact times required for effective organic chemical removal can be reduced, or higher removals can be achieved at equivalent design conditions of dosage and contact time compared to ozone alone. Drinking water treatment plants do not receive disinfection credit for ozone/AOP, since ozone residuals in the presence of peroxide are not possible. Furthermore, hydroxyl radicals are a weaker disinfectant as compared to molecular ozone.

UV Light - UV light has become a rather attractive treatment technology for disinfection of drinking water to achieve high inactivation of Giardia and Cryptosporidium. Typical dosages that are used for disinfection range from 30-60 millijoules per square centimeter (mJ/cm^2). At these dosages, direct photolysis of organic contaminants is poor, if at all. Studies have shown that dosages as high as 1,000 mJ/cm^2 are needed to achieve reasonable removals of organic chemicals that are oxidizable. Removal efficiencies can be improved by combining high-energy UV with hydrogen peroxide, titanium dioxide, or ozone, as indicated previously. These advanced oxidation processes can achieve more reasonable removal efficiencies compared to UV alone; however, UV doses of several hundred mJ/cm^2 and often excess hydrogen peroxide are required.

Based on various bench, pilot and full-scale studies on the removal of organic chemicals through oxidation or advanced oxidation processes, the following results have been observed:

- Ozone is rather selective and reacts with amines, phenols and double bonds in aliphatic compounds. Under conditions found in water treatment systems, only those compounds with ozone rate constants greater than 50 M^{-1} S^{-1} (per molar per second) will be removed to an appreciable degree (>50 percent) through direct reactions with ozone.
- Greater removals can be achieved by promoting OH radical formation through the use of advanced oxidation.
- USEPA funded studies of oxidation of organic candidate contaminants by ozone and hydrogen peroxide/ozone revealed that aromatic compounds such as 1,2,4 trimethylbenzene and bromobenzene reacted within minutes for good removal, but that aliphatic compounds such as 1,1 dichloroethane and 2,2 dichloropropane did not react well with ozone or hydrogen peroxide/ozone (Chen et al, 2006)
- Extremely high doses of UV light are required to oxidize most organic contaminants. The use of high-energy UV in combination with ozone or hydrogen peroxide will provide greater removals.
- UV with a titanium dioxide catalyst, applied as a thin film or attached to glass or plastic media, has shown great promise as an advanced oxidation method. No full scale applications have yet been constructed in the United States, but pilot scale trials have demonstrated oxidation of 14 of the 15 contaminants - benzene; 1,1,2 trichloroethane;1,1 dichloroethane; 1,2,3 trichloropropane; 1,3 dichlorobenzene; 1,4 dichlorobenzene; 2,4,6 trichlorophenol; 2 butanone (methyl ethyl ketone); ethylene glycol; formaldehyde; n-hexane; methylene chloride; tertiary butyl alcohol; and vinyl chloride; from water and air (Blake, 2001). The

minimum quantitation levels were not provided and therefore the ability to achieve PQLs or MCLs can not be determined from this study.

2.6 Membranes – NF and RO Membranes

NF and RO membranes are not characterized by pores, though size exclusion criteria are typically provided by manufacturers. Rather they are considered as a dense membrane phase. The primary separation mechanism is selective diffusion of water through the membrane phase. However, some investigators have reported some pore structure in NF membranes with pore sizes in the range of nanometers. Due to the lack of discrete pore structure, the rejection capability of these membranes is characterized by nominal molecular weight cut off (MWCO). It is defined as the size of a macromolecule (such as some proteins or sugars) for which the membrane achieves certain rejection (typically 90%). It is typically assumed that for macromolecules larger than the MWCO, efficient rejection is possible and for macromolecules smaller than MWCO, rejection would be lower. However, the rejection of a given contaminant is dependent on molecular weight as well as degree of dissociation of the species, polarity, molecular structure, membrane chemistry and chemistry of the feed water. In order to accomplish the passage of water and those few ions, gases, and compounds that pass through the membranes, pressures of 300 to 400 psi must be employed for RO and 115 to 175 for NF.

Composition of the membrane materials also affects the ability of the membrane to remove both organic and inorganic contaminants. Cellulose acetate membranes show the least overall rejection of contaminants, while polyamide and thin film composite membranes demonstrate better rejection of both organic and inorganic chemicals (Lykins et al, 1988).

Membrane feed water needs to be low in turbidity, which necessitates conventional processes as pretreatment of most surface waters. Cartridge filtration using 5 micron (5 µm) filters is standard practice. Some membrane polymers are sensitive to strong oxidants so the feed water must be dechlorinated prior to membrane treatment and depending on the scaling potential of the feed water, antiscalents may be necessary to reduce scale formation on the membranes. Membranes require periodic cleaning to remove fouling deposits – often there is weekly to biweekly maintenance cleaning and restorative in-depth cleaning events every few months to restore membrane capacity. The membrane materials are more fragile than granular media filters – replacement is required every three to ten years depending on the quality of the feed water and the membrane materials.

RO membranes are capable of removing a number of organic contaminants as well as most inorganic ions. Microfiltration and ultrafiltration membranes have been shown to assist in the removal of natural organic matter and some synthetic organic contaminants if they are used with PAC addition (Pirbazari et al, 1992). Membrane filtration has become more common in the past ten to fifteen years as membrane capital and operating costs have decreased dramatically. New membrane materials, configurations that permit lower pressures and energy recovery, and staging to improve efficiency have all contributed to the lowered capital and operational costs of membrane treatment. However, costs are still typically higher than other treatments for the removal of synthetic organic contaminants because RO membranes are seldom used as the only treatment – they tend to be integrated into a multiple step process to remove both particulates and organics from a water source.

As the molecular weight of the contaminant increases, the rejection by RO increases. RO is capable of removing larger or more hydrophobic molecules but does not reject small polar or hydrophilic molecules well – thus formaldehyde and alcohols have passed through RO, low pressure RO and NF membranes with rejections of less than 20% (Yoon and Lueptow, 2005). Although the study did not include ethylene glycol, the low molecular weight and miscible characteristics of this alcohol would be likely to enable it to pass though RO membranes.

2.7 Summary

Since a number of VOC's were identified as contaminants in air and in drinking water in the late 1980's, there has been a concerted effort to reduce the levels of volatile organics used in many household and industrial products such as cleansers and paints, degreasers, and solvents. Industrial pretreatment requirements for dry cleaning establishments have also reduced the opportunity for contamination of drinking water with organic solvents.

All of the treatment processes described above have been used for public water supplies and, to a lesser extent, for private homes. For certain contaminants the USEPA has permitted point of entry or point of use treatment systems that were determined to be more cost effective than centralized treatment systems. The latest guidance (USEPA, 2006a) lists which contaminants may be treated via point of use or point of entry systems, describes critical features of the appropriate technologies and provides cost estimates for activated alumina and ion exchange as well as GAC and RO membranes.

With an understanding of the chemical characteristics of the contaminants and available treatment options, it was possible to identify potential treatment options for achieving the proposed regulated MCLs of contaminants. That is not to say that each feasible process is cost effective, only that each contaminant may be treated or removed by a number of different treatment processes. Selection of the best available treatment in each case depends on the water source (surface water or groundwater), the presence of other interfering or competing contaminants, and comparison of the capital and operational costs of the various possible treatment options.

Table 2-4 presents a summary of feasible treatment options for each contaminant. These treatment alternatives can achieve high levels of removals for each of the contaminants stated, with the possible exception of advanced oxidation technologies and biological degradation, unless indicated otherwise. With the exception of advanced oxidation technologies and biological degradation, and based on water quality characteristics, the MCL and proposed PQL could potentially be achieved by employing the treatment options. The advanced oxidation technologies partially convert the contaminants and therefore may not necessarily achieve acceptable removal levels. Biological degradation can occur if the GAC is biologically active, and can be an added benefit to the activated carbon process. Insufficient data on the performance of biological degradation is available as it typically does not occur by design. Therefore we cannot assess the ability of biological degradation to achieve high levels of removal on a consistent basis. In all cases, the treatment performance will be dictated by actual raw water characteristics, basis of design, and facility operations.

The next section presents treatment processes that have been tested or used in New Jersey and approximate costs for these treatment processes for different utility capacities.

Table 2-4 Summary of Treatment Options for the NJDEP Contaminant List

Contaminant	**Air Stripping**	**Activated Carbon Adsorption**	**AOP Ozone/ H_2O_2**	**AOP H_2O_2**	**UV/Ozone**	**Biological Degradation**	**NF Membranes**	**RO Membranes**
n-Hexane	**Yes**	**Yes**	**Partial**	**Partial**	**No**	**Yes**	**NA**	**Yes**
Benzene	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**No**
1,3 Dichlorobenzene	**Yes**	**Yes**	**Yes**	**Yes**	**Slow**	**Partial**	**No**	**Up to 64%**
1,4 Dichlorobenzene	**Yes**	**Yes**	**Yes**	**Yes**	**Slow**	**Yes**	**No**	**No**
1,1 Dichloroethane	**Yes**	**Yes**	**Yes**	**Yes**	**Slow**	**Yes**	**No**	**Up to 71%**
1,1,2 Trichloroethane	**Partial**	**Yes**	**Yes**	**Partial**	**Yes**	**Partial**	**No**	**Partial**
1,2,3 Trichloropropane	**Partial**	**Partial**	**Yes**	**Yes**	**Partial**	**Slow**	**No**	**Up to 85%**
Vinyl chloride	**Yes**	**Partial**	**Yes**	**Yes**	**Yes**	**NA**	**NA**	**NA**
Methylene Chloride	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**Partial**
Methyl Ethyl Ketone	**Partial**	**No**	**Yes**	**Yes**	**Yes**	**Yes**	**NA**	**NA**
2,4,6 Trichlorophenol	**No**	**Yes**	**Yes**	**Yes**	**Yes**	**NA**	**NA**	**NA**
Formaldehyde	**No**	**No**	**No**	**Partial**	**No**	**Yes**	**No**	**No**
Ethylene Glycol	**No**	**No**	**No**	**Partial**	**No**	**Yes**	**No**	**No**
Tertiary Butyl Alcohol	**No**	**No**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**No**
DCPA (Dacthal)	**No**	**Partial**	**Partial**	**Partial**	**No**	**Partial**	**Yes**	**Yes**
DCPA degradates (mono and di-acids)	**No**	**NA**	**No**	**No**	**No**	**No**	**Yes**	**Yes**

NA – information not available

Partial – removals at less than 50% demonstrated

AOP – advanced oxidation processes

Section 3. Status of Technologies in New Jersey

The following provides a summary of some of the applicable treatment technologies which have been installed in New Jersey.

3.1 Adsorption with Activated Carbon

Adsorption with activated carbon is used at a number of New Jersey surface water and groundwater facilities for adsorption of a number of contaminants. A number of groundwater sources have installed air stripping followed by GAC to remove any traces of organic contaminants that may not be adequately removed by air stripping. Activated carbon has also been used to concentrate contaminants from the air used for air stripping as a vapor phase capture. Table 3-2 lists utilities that currently have activated carbon treatment of groundwater for regulated organic contaminants.

The larger surface water systems in New Jersey that use GAC utilize gravity contactors as filter-adsorbers. Two of the surface water GAC facilities in New Jersey use pressure contactors in a post-filter adsorber mode of operation. Both of these plants are small to medium size: 5 – 10 mgd. The use of pressure vs. gravity and filter-adsorber vs. post-filter adsorber for organic chemical removal at surface water plants in New Jersey probably will depend for the most part on the size of the treatment plant and some other factors, such as the depth of media that can be placed in existing filters, etc. Five of the surface water treatment systems in New Jersey that use GAC also use ozone ahead of GAC.

The US Army Corps of Engineers operated a pilot trial of GAC to treat groundwater contaminated with trichlorethene, HMX (octahydro-1,3,5,7 tetranitro-1,3,5,7 tetrazocine), nitrocellulose, and RDX (hexahydro-1,3,5 trinitro-1,3,5 triazine) at the Picatinny Arsenal near Dover, New Jersey (Bricka and Fleming, 1995). This research led to a full scale design of activated carbon treatment for this source.

Table 3-1 presents estimates of costs associated with installation of GAC for smaller systems. As most small systems are served by groundwater rather than surface water, these estimates were based on pressure type activated carbon contactors. Specific design criteria are presented in Appendix A.

Table 3-1 Costs of GAC Small-System Facilities

Plant Size	Capital Costs	O & M Costs (Annual)
< 10,000 gallons/day	NA	NA
< 100,000 gallons/day	$200,000 - $300,000	$10,000 - $15,000
0.1 to 0.5 mgd	$300,000 - $500,000	$20,000 - $75,000
0.5 to 1 mgd	$600,000 - $1,200,000	$50,000 - $100,000

NA-Not Available

3.2 Air Stripping

Air stripping is currently in use in New Jersey at a number of municipal well sites as well as individual residential sites. The 2003 NJDEP TIC report cites 19 public water supplies with aeration systems for the removal of regulated organic contaminants from groundwater. Air stripping has proven effective for removal of the volatile compounds and some of the less volatile or semi-volatile compounds from groundwater. Table 3-2 presents a summary of the water systems cited in the 2003 report. A few case studies are presented in the following text.

Table 3-2 New Jersey Water Supplies with Air Stripping & GAC Treatments

Water System	Type of Treatment	Contaminants
Fairlawn Water Dept	Packed Tower Aeration	MTBE, Trichloroethene, Tetrachloroethene
Garfield Water Dept	Packed Tower Aeration	1,2 dichloroethene, MTBE
Rahway Water Dept	Packed Tower Aeration and GAC	Trichloroethylene, Tetrachloroethylene
Merchantville Pensauken	Packed Tower Aeration	NA
Rockaway Borough and Township Water Co.s	Packed Tower Aeration and GAC	Trichloroethene, 1,1 Dichloroethane
Perth Amboy – Old Bridge Water Dept	Packed Tower Aeration	NA
New Jersey American Water Co	Packed Tower Aeration	NA
Park Ridge Water Dept	Diffused and Packed Tower Aeration, GAC	NA
Flemington Water Dept	Slat Tray Aeration	NA
Waldwick Water Dept	Packed Tower Aeration	NA

Water System	Type of Treatment	Contaminants
Rocky Hill Water Dept.	Packed Tower Aeration	NA
Sea Girt Water Dept.	Tray Aeration	NA
Elizabethtown Water Co.	Packed Tower and Slat Tray Aeration	NA
Salem Water Dept	Aeration, Carbon Injection	NA
Ridgewood Water Dept	Packed Tower Aeration	Tetrachloroethene, MTBE
Newton Water and Sewer Utilities	Packed Tower Aeration	NA
United Water, Toms River	Carbon, Packed Tower Aeration	NA

NA-Not Available

Two municipal wells in Ridgewood, New Jersey use packed tower air strippers to remove perchloroethylene (tetrachloroethene) and methyl tertiary butyl ether (MTBE) to levels below the MTBE goal of 15 µg/l. The average raw water concentration of MTBE was 90 µg/l and the required air/water ratio to achieve 75% removal of this semi-volatile contaminant is 250:1. The Henry's Constant for MTBE is 0.000587 (5.87 x 10-4), therefore benzene, both dichlorobenzenes, 1,1 dichloroethane, 1,1,2 trichloroethane, methylene chloride, vinyl chloride, and n-hexane from the New Jersey Contaminants of Concern List are MORE volatile than MTBE and would be removed to a greater extent under the same aeration conditions.

Rockaway Township has operated packed tower air stripping and GAC contact units in two stages since 1982 to treat wells with trichloroethene, tetrachloroethene, trans-1,2 dichloroethene, 1,1 dichloroethene, di-isopropyl ether, 1,1 dichloroethane, 1,1,1 trichloroethane, carbon tetrachloride and MTBE contamination. The air stripping was originally designed to treat the trichloroethene, the contaminant in the highest concentration with the greatest removal requirement (National Water Research Institute, 2006).

The Omega Drive Wells 1 and 2 are sources for a public water system operated by the United Water Company. The wells are located on Theta Drive in Vernon Township, Sussex County. In 1989, NJDEP determined that both Omega Drive Wells were contaminated with volatile organic compounds. The main contaminants were benzene, toluene, xylenes, methyl tertiary butyl ether (MTBE) and 1,1,1 trichloroethane. An air stripper was installed at the well field in 1994 to remove the contaminants from the water.

Costs of air stripping systems vary depending on the capacity of the water source to be treated, the required air to water ratio of the least volatile contaminant or the contaminant that requires the highest air to water ratio to bring the contaminants to below the regulated levels, and the type of air stripper considered for use. Water quality factors that can affect treatment are the presence of iron or, to a lesser extent, manganese that can be oxidized with exposure to air, with the result that unaesthetic water would be served to customers. Often, groundwaters with iron or manganese require additional sequestering treatment or filtration to remove the oxidized iron and manganese before distribution. Re-pumping of groundwater systems must be added to both capital and operating cost estimates. Design assumptions underlying the cost estimates are presented in Appendix A.

Table 3-3 Capital and Operating Costs for Aeration System

Plant Size	Capital Costs	O & M Costs (Annual)
< 10,000 gallons/day	NA	NA
< 100,000 gallons/day	\$100,000 - \$200,000	\$15,000 - \$30,000
0.1 to 0.5 mgd	\$150,000 - \$300,000	\$25,000 - \$45,000
0.5 to 1 mgd	\$250,000 - \$450,000	\$25,000 - \$50,000

NA – Not Available

3.3 Advanced Oxidation

In 1995, both pilot scale and full scale trials of in-situ oxidation of groundwater contaminated with MTBE, benzene, toluene, ethylbenzene, and xylenes (BTEX) were conducted at a warehousing facility in Union County, New Jersey (USEPA, 1998). Raw water samples from the most contaminated wells revealed BTEX concentrations in excess of 25,000 µg/l and MTBE concentrations in excess of 6,000 µg/l. Injection of hydrogen peroxide solution and a proprietary iron based catalyst into the groundwater at the site of the highest contamination proved promising, so full scale injection of peroxide solution and catalyst was conducted at six locations within the project site. Post treatment samples, collected four months after the treatment regime was completed, demonstrated that the total BTEX concentration was reduced to less than 25 µg/l and that the MTBE was no longer detectable. The cost of the trial was \$220,000. This same process was also tested for oxidation of trichloroethane and other unidentified volatile organics at an industrial site in Clifton, New Jersey. Average total VOC concentrations dropped from the original average level of 44 mg/l to 15 mg/l.

The AwwaRF Study "In-line Ozone and Hydrogen Peroxide Treatment for Removal of Organic Chemicals", published in 1992, presents pilot scale work conducted at Ridgewood, NJ and Spring Valley, NY groundwater sources. Both wells contained trichloroethylene (TCE) and tetrachloroethylene (PCE), and the Ridgewood well also contained methyl tertiary butyl ether (MTBE), a gasoline-related compound that is very difficult to strip from water and very poorly adsorbed using GAC. The tests conducted to evaluate process issues indicated poor removals of TCE, PCE, and MTBE using only ozone as an oxidant. The addition of hydrogen peroxide in conjunction with ozone significantly improved the removals of each of these compounds. Removals of greater than 90 percent of TCE and PCE were achieved using ozone dosages of about 6.0 mg/l, contact times of 3 to 6 minutes, and a hydrogen peroxide-to-ozone ratio of 0.5. Nondetectable levels of MTBE were recorded using an ozone dosage of 8 mg/l, similar contact times, and a similar ozone-to-hydrogen peroxide ratio. The preliminary cost comparison indicated that the in-line ozone and hydrogen peroxide process was more cost effective for TCE and PCE removal than GAC adsorption or packed tower air stripping with vapor phase treatment, particularly at flow rates greater than about 400 gpm for the water tested. At lower flow rates, the cost advantage of the in-line process did not appear to be as great, although overall costs were still lower than for the other two processes. Packed tower air stripping alone was the most cost-effective process for all flow rates.

Camden, NJ has installed ultraviolet light, though for disinfection purposes rather than for synthetic chemical oxidation. The difference in irradiance between the two uses is significant with typical disinfection “doses” on the order of 40 mJ/cm2, while advanced oxidation requires “doses” closer to 1000 mJ/cm2.

The Lucerne Water Treatment Project was considering the use of UV advanced oxidation system to provide 95 percent removal of geosmin. The equipment cost for the system which included the UV reactors and the hydrogen peroxide system was about $275,000 - $300,000. The estimated operating cost was $36,000 to $65,000, which was based on the assumption that the advanced oxidation mode would only be utilized a third of the year.

Table 3-4 Capital and Operating Costs for Ozone System

Plant Size	Capital Costs	O & M Costs (Annual)
< 10,000 gallons/day	NA	NA
< 100,000 gallons/day	$380,000 - $460,000	$70,000
0.1 to 0.5 mgd	$418,000 - $700,000	$75,000
0.5 to 1 mgd	$720,000 - $1,200,000	$80,000

NA-Not Available

Table 3-5 Capital and Operating Costs for UV H_2O_2 System

Plant Size	Capital Costs	O & M Costs (Annual)
< 10,000 gallons/day	NA	NA
< 100,000 gallons/day	\$35,000 - \$40,000	\$5,000
0.1 to 0.5 mgd	\$40,000 - \$140,000	\$5,000 - \$15,000
0.5 to 1 mgd	\$280,000 - \$3,500,000	\$25,000 - \$50,000

NA-Not Available

3.4 Membranes

The City of Cape May completed a 2 mgd RO water treatment plant in 1998 to provide drinking water from the brackish Cohansey aquifer and Atlantic City 800 Foot Sands aquifer.

Southeast Morris County MUA (SMCMUA) replaced their membrane facility approximately 4 years ago. Project costs to construct a new 2.5 mgd Zenon (submerged membranes) plant, including GAC polishing, was $7 million. Plant was primarily designed for turbidity removal and taste and odor control.

Depending on the level of pre-treatment required ahead of the process, RO membrane operational costs vary widely. Pretreatment can be as extensive as complete conventional processes consisting of coagulation, flocculation, clarification processes, filtration either through granular media or through microfiltration or ultrafiltration membranes to remove particulates and foulants as much as possible. RO is also energy intensive, primarily as a result of the high pressures at which it must be operated. Energy recovery systems have been developed to reduce operating costs.

Table 3-6 Capital and Operating Costs for RO Membrane Systems

Plant Size	Capital Costs	O & M Costs (Annual)
< 10,000 gallons/day	\$100,000	\$15,000
< 100,000 gallons/day	\$300,000	\$30,000 - \$120,000
0.1 to 0.5 mgd	\$500,000 - \$1,000,000	\$50,000 - \$300,000
0.5 to 1 mgd	\$1,000,000 - \$2,000,000	\$100,000 - \$600,000

Section 4. Status of Technologies not currently in use in New Jersey

The following provides a brief overview of technologies not currently in use in New Jersey, but have been installed elsewhere.

4.1 Advanced Oxidation

USEPA and Applied Process Technology, Inc. (APT) undertook a demonstration study of ozone and hydrogen peroxide (HiPOx) for destruction of methyl-tertiary-butyl-ether (MTBE), tertiary butyl alcohol which is a degradation product of MTBE, and acetone which is also a degradation product of MTBE. The demonstration project was carried out on a high alkalinity groundwater with approximately 750 µg/l of MTBE at Ventura County Naval Base in Port Hueneme, California. The average ozone dose was 119 mg/l with concurrent hydrogen peroxide doses of 121 mg/l. Resultant MTBE levels were less than 1 µg/l. Tertiary butyl alcohol was reduced from 40 µg/l to an average of 14 µg/l. However, acetone levels increased to an average of 135 µg/l from less than 40 µg/l, indicating that the MTBE was not completely oxidized by the advanced oxidation process (Speth and Swanson, 2002).

Another HiPOx demonstration study was undertaken for destruction of 1,2,3 trichloropropane and dibromochloropropane from a municipal well in the San Joaquin Valley of California. The trials were conducted at bench scale. Raw water concentration of the two contaminants were 0.95 µg/l for 1,2,3 trichloropropane and 0.059 µg/l for dibromochloropropane respectively. The 1,2,3 trichloropropane was reduced to a target level of 0.005 µg/l at an ozone dose of 53 mg/l and a peroxide to ozone mole ratio of 0.7 (Dombeck and Borg, 2005).

4.2 Membrane Processes including RO

PAC with ultrafiltration membranes has been used on a pilot scale to evaluate total organic carbon as well as atrazine and cyanazine pesticide removal from a river source in Illinois (Jack and Clark, 1998). Average removals of the pesticides exceeded 50% but unresolved operational difficulties rendered the process unfeasible for this source.

USEPA undertook bench scale and pilot scale studies to determine removal of regulated synthetic organics using cellulose acetate, polyamide, and three types of thin film composite RO membranes. The pilot scale studies were conducted in Suffolk County, NY. Influent concentrations of contaminants ranged from 6 to 153 mg/l and all of the pilot scale trials reflect steady state, one pass operating conditions. Table 4-1 presents the removal data (Lykins et al., 1988).

Table 4-1 Percent Removal of Organic Contaminants by Various RO Membranes

Compound	Cellulose Acetate	Polyamide	Composite A	Composite B	Composite C
1,2 Dichloroethane	NC	NC	15	38	71
1,2 Dichloropropane	10	61	90	NC	NC
Trichloromethane	0	33	47	55	82
1,1,1 Trichloroethane	15	88	100	97	97
Tetrachloromethane	NC	NC	NC	NC	96
Bromodichloromethane	7	44	79	NC	NC
Dibromochloromethane	0	32	78	NC	NC
Tribromomethane	16	38	81	NC	NC
c1,2 Dichloroethene	0	19	14	12	12
t1,2 Dichloroethene	20	0	0	NC	NC
Trichloroethene	0	31	37	41	75
Tetrachloroethene	NC	NC	NC	71	92
Benzene	2	18	16	NC	NC
Toluene	10	NC	NC	NC	NC
Ethylbenzene	34	NC	NC	NC	NC
oXylene	9	NC	NC	NC	NC
pXylene	22	NC	NC	NC	NC
Chlorobenzene	NC	NC	50	54	87
1,2 Dichlorobenzene	NC	NC	65	NC	NC
1,3 Dichlorobenzene	NC	NC	64	NC	NC
1,4 Dichlorobenzene	10	NC	0	NC	NC
Bromobenzene	11	0	NC	NC	NC
1,2,4 Trichlorobenzene	17	NC	NC	NC	NC

*NC indicates that testing was not conducted with that membrance with the contaminant

Organic compounds on the NJDEP Contaminants of Concern list are shown in **bold** text.

Section 5. Summary of Best Available Treatment Options

In the past ten years, the performance and understanding of the capabilities of some of the newer technologies such as advanced oxidation have improved and capital costs have decreased. This is particularly the case for membrane processes. The new technologies are used as unit processes by themselves, but have also been paired with older technologies such as activated carbon to obtain the synergistic benefits of both treatment techniques. Examples of such synergies include advanced oxidation followed by GAC beds which are designed to act both as adsorbers as well as supports for biological growth. The oxidized organics created sustain the microbiological communities and the microbes utilize the oxidized organics more effectively than the original parent compound.

Table 5-1 presents a summary of the 15 NJDEP Contaminants with the best available treatment recommendation for each contaminant. The best available treatment was determined according to the following criteria:

- Feasibility or treatment effectiveness. The best available treatment (or treatment sequence) must be able to remove the contaminant down to or below the proposed MCL.
- Cost. If two or more process or treatment techniques are equally effective at removal, utilities will prefer to install and operate the least expensive process as long as it can be integrated into existing treatment processes.
- Versatility. If a feasible treatment process has benefits for removal of multiple contaminants or can improve finished water quality, either to improve compliance with existing Safe Drinking Water Act regulations or the aesthetic quality of the finished water, then it would be preferred to a process that lacked such versatility.

Table 5-1 Current Best Available Treatment(1) for NJDEP Contaminants

Contaminant	Best Available Treatment(1)	Second Best
Benzene	Air Stripping	GAC
1,3 Dichlorobenzene	Activated Carbon	Air Stripping
1,4 Dichlorobenzene	Activated Carbon	Air Stripping
1,1 Dichloroethane	Air Stripping	Advanced Oxidation
1,1,2 Trichloroethane	Air Stripping	Activated Carbon
1,2,3 Trichloropropane	Activated Carbon	Advanced Oxidation
2,4,6 Trichlorophenol	Activated Carbon	Advanced Oxidation
Vinyl Chloride	Air Stripping	Activated Carbon
Ethylene glycol	Biological Degradation	Advanced Oxidation
Formaldehyde	Biological Degradation	Advanced Oxidation
Methyl Ethyl Ketone	Advanced Oxidation	Biological Degradation
Methylene Chloride	Air Stripping	Activated Carbon
n-Hexane	Air Stripping	Activated Carbon
Tertiary Butyl Alcohol	Biological Degradation	Advanced Oxidation
DCPA	Membranes	Biological Degradation
DCPA degradates	Membranes	Biological Degradation

(1) Based on engineering judgement; insufficient quantified data are available to determine if target levels can be consistently achieved.

It is clear that no single treatment technique is the best available treatment or even applicable for all of the contaminants of interest to the NJDEP. As presented in Table 5-1, air stripping is the best available treatment for 6 of the 15 and the second choice for 2 more contaminants. Activated carbon adsorption is the next most widely applicable treatment technology. It is the first choice for 4 compounds and a second choice for 5 more. In addition, it could be used as a support for the growth of microbial communities and thus, its use extends to biological degradation processes, making it useful in the removal of 3 difficult to treat contaminants. These are 1,1,2 trichloroethane, formaldehyde, ethylene glycol. Advanced oxidation processes, particularly ultraviolet light supplemented by hydrogen peroxide or used with a catalyst such as titanium dioxide, has shown great promise for the oxidation of contaminants that are not volatile and do not adsorb to non-polar activated carbon.

These include methyl ethyl ketone, tertiary butyl alcohol, ethylene glycol and formaldehyde.

Only the herbicide Dacthal and its degradates elude removal by adsorption, air stripping, or advanced oxidation. Biological degradation is very slow, particularly once the di-acid has been formed.

In accordance with Table 5-1, the stated Best Available Treatment (BAT) should be the method considered first. As stated in the preface to the table, this is based on treatment effectiveness, cost and versatility. As is illustrated in Table 5-1, air stripping and GAC are the preferred methods of treatment for all but 6 contaminants. For these 6 contaminants (ethylene glycol, formaldehyde, methyl ethyl ketone, tertiary butyl alcohol, DCPA and DCPA degradates), the stated primary mode of treatment may not be sufficient to achieve necessary removals and multiple processes may be required. In all cases, the treatment performance will be dictated by actual raw water characteristics, basis of design and facility operations.

Section 6. References

Aizpura, A, L. Malhautier, J.C. Roux, and J.L. Fanlo, 2003, *“Biofiltration of a Mixture of Volatile Organic Compounds on Granular Activated Carbon”*, Biotechnology and Bioengineering, Vol. 83, No. 4, New York, New York

Agency for Toxic Substances and Disease Registry (ATSDR), December, 1990; Toxicological Profile for 1,1 Dichloroethane, Atlanta, GA

Agency for Toxic Substances and Disease Registry (ATSDR), July, 1992; Toxicological Profile for 2 Butanone, Atlanta, GA

Agency for Toxic Substances and Disease Registry (ATSDR), September, 1992; Toxicological Profile for 1,2,3 Trichloropropane, Atlanta, GA

Agency for Toxic Substances and Disease Registry (ATSDR), July, 1999; Toxicological Profile for n-Hexane, Atlanta, GA

Agency for Toxic Substances and Disease Registry (ATSDR), July, 1999; Toxicological Profile for Formaldehyde, Atlanta, GA

Agency for Toxic Substances and Disease Registry (ATSDR), July, 1999; Toxicological Profile for Chlorophenols, Atlanta, GA

Agency for Toxic Substances and Disease Registry (ATSDR), December, 1999; Toxicological Profile for 1,1,1 Trichloroethane, Atlanta, GA

Agency for Toxic Substances and Disease Registry (ATSDR), September, 2000, Toxicological Profile for Methylene Chloride, Atlanta, GA

Agency for Toxic Substances and Disease Registry (ATSDR), July, 2006, Toxicological Profile for Vinyl Chloride, Atlanta, GA

Agency for Toxic Substances and Disease Registry (ATSDR), August, 2006, Toxicological Profile for Chlorobenzenes, Atlanta, GA

Agency for Toxic Substances and Disease Registry (ATSDR), August, 2007; Toxicological Profile for Benzene, Atlanta, GA

Agency for Toxic Substances and Disease Registry (ATSDR), September, 2007; Draft Toxicological Profile for Ethylene Glycol, Atlanta, GA

Blake, Daniel M. "Bibliography of Work on the Photocatalytic Removal of Hazardous *“Compounds From Water and Air Update Number 3 to January, 1999.”* 162 pp. Golden, CO: National Renewable Energy Laboratory, 1999.

Bricka, R.M. and E.C. Fleming, 1995 *"Use of Activated Carbon for the Treatment of Explosives Contaminated Groundwater at the Pickatinny Arsenal,"* Technical Report EL-95-31, US Army Engineer Waterways Experiment Station, Vicksburg, MS

Browlowski, A., 2006 *"Super-oxidation Ozone Systems for Aquifer Restoration – A Michigan State Superfund Site"*, The Annual International Conference on Soils, Sediments, and Water, University of Massachusetts, Amherst, MA

Chen, W.R.; C.M. Sharpless; K.G. Linden; I.H. Suffet, 2006 *"Treatment of Volatile Organic Chemicals on the EPA Contaminant Candidate List Using Ozonation and the O3/H2O2 Advanced Oxidation Process"*, Environ Sci Technol. 40 (8): 2734 - 2739

Dilling, W.L., N.B. Tefertiler, & G.J. Kallos. 1975. *"Evaporation rates and reactivities of methylene chloride, chloroform, 1,1,1 trichloroethane, trochloroethylene, tetrachloroethylene, and other chlorinated compounds in dilute aqueous solutions,"* Environ Sci Technol. 9(9):833-837.

Dixon, K.L., Ramon G. Lee, J. Smith, and P Zielinski, 1991, *"Evaluating Aeration Technologies for Radon Removal"*, JAWWA Vol 83.(4), 141-148

Dombeck, G and C. Borg, 2005, *"Multi-Contaminant Treatment for 1,2,3 Trichloropropane Destruction Using the HiPOX Reactor"*, Proceedings of the 2005 NGWA Conference on MTBE and Perchlorate:Assessment Remediation and Public Policy

Esposito, K; B. Stinson; R Jarnis; T. Bradley; and G. Whalen, 2007, *"Contaminants of Potential Concern in a Pilot Water Reclamation System for Groundwater Replenishment,"* Proceedings, IOA-IUVA Joint World Congress, Los Angeles, CA, August 27-29, 2007

Glaze, W. H., Kang, J. W. & Chapin, D. H. *"The chemistry of water treatment processes"*. *"Involving ozone, hydrogen peroxide and UV-radiation"*. Ozone: Sci. Eng., 1987, 9, 335–352.

Jack, A. M. and M. M. Clark, 1998, *"Using PAC-UF to Treat a Low Quality Surface Water,"* JAWWA Vol. 90 (11), 83-95

Jang, W and R.E. Speece, 1990, Cascade Air-Stripping System for Removal of Semi-volatile Organic Contaminants: Feasibility Study, AwwaRF and AWWA, Denver, CO

Lykins, B.W., Jr., Clark, R.M. and Fronk, C.A. (1988) RO for removing synthetic organics from drinking water: a cost and performance evaluation. In: AWWA 1988 Annual Conference Proceedings, Orlando, FL. American Water Works Association, Denver, CO. pp. 1433-1457.

Lytle, D.A.; Schock, M. R.; Clement, J.A.; Spencer, C. M.; 1989 *"Using Aeration for Corrosion Control"*, JAWWA, Vol. 90, Issue 3, pp 74-88.

Mathews, A. P. and I. Zayas, 1989, *"Particle Size and Shape Effects on Adsorption Rate Parameters"*, Journal of Environmental Engineering, ASCE, Vol 115, No. 1, February, 41-55.

NTP,1994, *"Toxicology and Carcinogenesis Studies of t-Butyl Alcohol (CAS No. 75-65-0) in F344/N Rats and B6C3F1 Mice"*, National Toxicology Program, Technical Report No. 436, National Institutes of Health, Public Health Service, U.S. Department of Health and Human Services, Research Triangle Park, NC.

Najm, Issam N.; Snoeyink, Vernon L.; Lykins, Benjamin W. Jr.; Admans, Jeffrey Q., 1991 *"Using Powdered Activated Carbon: A Critical Review"*, JAWWA, Vol. 83 Iss. 1, January 1991, pp 65–76.

National Water Research Institute, 2006 Removal of MTBE from Drinking Water Using Air Stripping: Case Studies, Fountain Valley, CA

New Jersey Department of Environmental Protection, Division of Science, Research, and Technology, 2003, *"The Characterization of Tentatively Identified Compounds (TICs) in Samples from Public Water Systems in New Jersey"*, Trenton, NJ

Pirbazari, M., B.N. Badriyha, and V. Ravindran, 1992, *"MF-PAC for Treating Waters Contaminated with natural and Synthetic Organics"*, JAWWA Vol. 84 (12), 95-103

Servais, P, G. Billen, and P. Bouillot, 1994, *"Biological Colonization of Granular Activated Carbon Filters in Drinking Water Treatment,"* Jour. of Environmental Engineering, ASCE, Vol. 120, No.4, July/August, Reston, VA, United States

Speth, T.F. and G Swanson, 2002, Demonstration of the HiPOx Advanced Oxidation Technology for the Treatment of MTBE-Contaminated Groundwater, EPA/600/R-02/094, Cincinnati, OH

Stackelberg, P.E., J. Gibs, E.T. Furlong, M.T. Meyer, S.D. Zaugg, and R.L. Lippincott, 2007, Efficiency of conventional drinking-water-treatment processes in removal of pharmaceuticals and other organic compounds, US Geological Survey, Received 11 July 2006; revised 23 January 2007; accepted 28 January 2007. Available online 23 March 2007.

USEPA National Primary Drinking Water Regulations: Volatile Synthetic Organic Chemicals, Federal Register Vol. 50, No.219, p 46902, Nov. 13, 1985

USEPA Center for Environmental Research Information, 1995, Manual: Groundwater and Leachate Treatment Systems, EPA 625/R-94/005, Cincinnati, OH

USEPA Office of Solid Waste and Emergency Response, 1998, Field Applications of In-Situ Remediation Technologies, EPA/542-R-98-008, Washington DC

USEPA Office of Groundwater and Drinking Water, 2006, Regulatory Determinations Support Document for CCL2- DRAFT, EPA Report 815-D-06-007, Washington DC

USEPA, 2006a, Point of Use or Point of Entry Treatment Options for Small Drinking Water Systems, EPA Report 815-R-06-010, Washington DC

USEPA Office of Water, 2006b, 2006 Edition of the Drinking Water Standards and Health Advisories, EPA 822-R-06-013, Washington DC

USEPA Notice- Drinking Water Contaminant Candidate List 3 – Draft, 2008, Federal Register Vol. 73, No.35, p 9628, February 21, 2008

Yoon, Y and R.M. Lueptow, 2005, *“Removal of Organic Contaminants by RO and NF Membranes”*, Journal of Membrane Science, 261 (April).

Appendix A

A.1 Important Design Features and Assumptions

A.1.1 Activated Carbon

The key process design parameters for a GAC system include:

- Contactor Configuration
- Empty Bed Contact Time
- Loading Rate
- Pretreatment
- GAC Regeneration

Contactor Configuration – Contactors can be configured in a variety of ways for different applications. Downflow contactors, which operate similarly to rapid sand filters, can be categorized into gravity flow contactors and pressure contactors. In addition, GAC contactors can be designed and operated as filter-adsorbers or post-filter adsorbers. When operating as filter-adsorbers, the GAC contactor removes both turbidity and organic chemicals in the same bed. When operated as post-filter adsorbers, the GAC contactor is placed after the filters and is used solely for organic chemical removal. USEPA recommends post filter adsorbers for removal of regulated contaminants to reduce competition for adsorption sites on the activated carbon.

The reason for using gravity contactors in surface water plants is to reduce the construction cost and the footprint required to install GAC. Also, the use of pressure contactors would require an extra pumping step (which may not be required in every instance for gravity contactors) that would increase construction and operating costs. Filter-adsorbers tend to be used over post-filter adsorbers to reduce both construction and operating costs.

The larger surface water systems in New Jersey that use GAC utilize gravity contactors as filter-adsorbers. Two of the surface water GAC facilities in New Jersey use pressure contactors in a post-filter adsorber mode of operation. Both of these plants are small to medium size: 5 – 10 mgd. The use of pressure vs. gravity and filter-adsorber vs. post-filter adsorber for organic chemical removal at surface water plants in New Jersey probably will depend for the most part on the size of the treatment plant.

Empty Bed Contact Time (EBCT) – The adsorption of dissolved organic compounds from the water phase to the solid GAC requires time for the transport and attachment of the compound to the surface of the activated carbon. Determination of an optimal contact time of the water to the activated carbon bed is a critical design parameter as contact time has a major impact on carbon usage (EPA, 1991). Researchers have found that a minimum EBCT of 7.5 minutes is needed to achieve any measurable organic chemical removal. Typically, EBCTs of 10 to 30 minutes have been used in evaluating GAC for synthetic organic chemical removal. In the GAC systems that have been installed in New Jersey, the EBCT varies depending on the contactor configuration. Those used in a filter-adsorber mode generally provide between 3 and 10 minutes of EBCT depending on the plant flow. Those used in a post-filter adsorber mode generally provide additional EBCT – 10 to 20 minutes. An EBCT of 10 to 15 minutes at the average plant flow should be provided. For systems treating less than 10 mgd, this contact time probably would be accomplished using pressure contactors in a post-filter adsorber mode of operation. For larger plant flows, gravity contactors operating in a filter-adsorber configuration probably would be more reasonable from a cost standpoint. Note that NJDEP regulatory requirement is an EBCT of 20 minutes.

Loading Rate – Once the EBCT is established, a combination of hydraulic loading rate and carbon bed depth can be determined. Hydraulic loading rates used in practice have ranged from 2 to 10 gallons per minute per square foot (gpm/ft2). A moderate hydraulic loading rate of about 5 gpm/ft2 (at maximum plant flow) was selected for the design basis and for determining cost estimates that are presented later in this section.

Pretreatment - All surface water systems have undesirable levels of suspended solids or turbidity that can blind the pores of the activated carbon and create premature headloss. Therefore surface waters require at least particle removal pretreatment to extend the life of the carbon contactors, and so the GAC contactors must be located after sedimentation. The carbon contactors should also have backwash capability to reduce headloss and keep the activated carbon clean during operation. While groundwater systems typically have far lower levels of particulates, the ability to backwash activated carbon contactors would be very useful. As a minimum, the carbon must be backwashed after initial installation to remove the carbon fines. Backwash capability is included in the cost estimates for the activated carbon adsorption contactors.

GAC Regeneration – Over time, all of the available sites on the carbon become filled with adsorbents resulting in breakthrough of some of the contaminants. At that point, the contactor must be taken off line and the GAC must be replaced. The spent carbon can be regenerated either off-site or on-site, although off-site regeneration will likely be more cost effective than on-site regeneration. The USEPA estimated that carbon usage in the range of 500 to 2,000 lbs per day is most compatible with off-site regeneration. Often, the carbon supplier will remove and regenerate the spent carbon and provide new or regenerated carbon as part of an operations contract. On-site regeneration is very costly and requires carbon transport and storage facilities in addition to a regeneration furnace which is used to “burn” the organic chemicals off the carbon. All of the GAC systems in New Jersey use off-site regeneration. For the purpose of this study, off-site GAC regeneration is assumed.

A.1.2 Operational/Regulatory Considerations

There are three operational and regulatory issues that must be considered relative to activated carbon adsorption processes:

- Impacts on Carbon Usage Rate
- Spent Carbon Disposal

Carbon Usage Rate - Carbon usage rate for a single contaminant is typically derived by performing isotherms to determine the capacity of the specific activated carbon for the contaminant. For complex mixtures of contaminants, it is more difficult to determine the carbon usage rate for several reasons:

- Various organic chemicals with different adsorptive characteristics - some contaminants will adsorb more strongly than others.
- Competition among the various organic chemicals for adsorption sites.
- Desorption (displacement) of compounds as more adsorbable compounds take up sites - there may be displacement reactions as the compounds that adsorb more strongly replace less strongly adsorbed contaminants.
- Changing organic chemical concentrations, especially with very low concentrations.
- Type of GAC - activated carbon can be made from source materials as varied as bituminous coal to coconut hulls. Bituminous coal based activated carbons are some of the most commonly used in water treatment.
- Biological activity on the GAC - discussed further under Oxidation/Biological Treatment.

Spent Carbon Disposal - In all GAC installations treating New Jersey waters, the method of GAC regeneration is off-site by the carbon supplier. As a result, there are no disposal issues. Off-site carbon regeneration is assumed for purpose of this study.

A.1.3 Cost Estimates

Capital and operating cost estimates were developed for the installation of GAC contactors to remove the organic chemicals that have been detected in New Jersey surface waters.

Equipment and Facility Assumptions - Although the design of a GAC system will vary depending on the local conditions (types and levels of organic chemicals present in the water and the location of the facility), the major components of any GAC treatment system are:

- Carbon Contactors
- Carbon Charge
- Backwash Capabilities
- GAC Contactor Building: It is necessary to house the GAC contactors to protect them from freezing.
- Repumping: Additional head will be introduced with the installation of the GAC contactors and intermediate pumping may be needed to compensate for the additional head.

For the GAC contactors, the following design criteria have been used for the purpose of developing cost estimates based on the process description presented previously:

- EBCT - 15 minutes at the design flow. Note that NJDEP regulatory requirement is an EBCT of 20 minutes.
- Contactor configuration - pressure, downflow type
- Liquid loading rate - 5 gpm/sf
- Backwash - taken from finished water
- Regeneration - off-site
- Pretreatment - existing coagulation/sedimentation processes if applied to surface waters

Operating costs will include:

- Carbon replacement
- Labor
- Power
- Maintenance

The majority of the cost will be for replacement of the carbon. Considering the number and variety of organic chemicals that may be in a given surface or groundwater supply, it is very difficult to estimate the carbon replacement frequency. For purposes of this report, it is estimated that the replacement frequency may be 6-12 months.

A.1.4 Air Stripping

Groundwaters are often under pressure and not in equilibrium with the various gases in air. Contaminants in groundwater are unable to escape into the atmosphere. Thus, groundwaters are frequently supersaturated with carbon dioxide, and potentially, radon, methane and a number of organic contaminants that can be transferred to air if adequate contact time and volumes of air are introduced to the water. The driving force for mass transfer is the difference between the existing and equilibrium concentrations of the waterborne contaminant in air (Montgomery, 1985). Packed tower air stripping is considered the most efficient type of aeration process, especially for achieving high removals of both volatile and semi-volatile compounds. Therefore, packed tower air stripping is considered the most applicable aeration process for removing the organic chemicals that are addressed as part of this study.

A.1.5 Process Description

Packed tower air stripping is a relatively simple process where water is pumped to the top of the packed tower and flows down through random packing material. At the same time, air is blown up through the tower to provide a countercurrent flow of air and water. Water is distributed evenly over the packing material using an orifice-type distribution plate located at the top of the tower. Redistribution plates may be located at certain intervals along the depth of the packing material to maintain a balanced flow through the entire depth of the tower. The packing material is designed to provide a high surface area per cubic foot of packing to maximize the transfer of the organic chemicals from the water to the air. Disinfection of the treated water is required before pumping into the distribution system.

The efficiency of a packed tower for removing volatile or semi-volatile organic chemicals depends on several factors:

- Contact time between the air and the water
- The ratio of the volume of air to the volume of water passing through the tower
- Available surface area for mass transfer to occur
- Liquid loading rate
- Temperature of the water and the air
- Chemistry of the organic chemical

The first three factors can be controlled in the selection of design criteria of the packed tower. The other two factors are set for a given water supply.

Contact Time - The contact time is a function of the depth of the packing material – the greater the packing depth, the longer the contact time. A longer contact time results in greater organic chemical removals for those chemicals that are volatile. Also, the packing depth is a design parameter that has one of the greatest effects on the capital cost of the packed tower. For relatively volatile compounds like TCE and PCE, packing depths of 15-25 feet have been used to achieve greater than 90 percent removal. For more difficult to strip compounds like MTBE, packing depths of 30-40 feet have been used to achieve high removal efficiencies. The volatile compounds that have been detected in New Jersey groundwaters and addressed in this study include semi-volatile compounds as well as compounds that are rather easily stripped. Therefore, for purposes of this study, a packing depth of 30 feet has been selected and has been used for determining opinion of probable costs that are presented later in this section.

Air:Water Ratio - The air:water ratio is an important design parameter that also affects the removal efficiency of the packed tower. The greater the air:water ratio, the greater the removal efficiency. The air:water ratio impacts the operating cost, as higher air:water ratios result in higher power costs. For relatively volatile compounds like TCE and PCE, air:water ratios of 20:1 to 30:1 have been used to achieve greater than 90 percent removal. For more difficult to strip compounds like MTBE, air:water ratios of 100:1 to 200:1 have been used to achieve high removal efficiencies. The volatile compounds that have been detected in New Jersey groundwaters and addressed in this study include semi-volatile compounds as well as compounds that are rather easily stripped. Therefore, for purposes of this study, an air:water ratio of 30:1 has been selected and has been used for determining opinion of probable costs that are presented later in this section.

Packing Material - The available area for mass transfer is a function of the packing material. Various sizes and types of packing material have been developed to maximize the surface area and yet minimize the air pressure drop across the packing.

Liquid Loading Rate - The liquid loading rate dictates the diameter of the packed tower. It is determined based on minimizing the liquid pressure drop across the packing material. For relatively volatile compounds like TCE and PCE, loading rates of 20-30 gpm/sf have been used to achieve greater than 90 percent removal. For more difficult to strip compounds like MTBE, loading rates of 15-20 gpm/sf have been used to achieve high removal efficiencies. The volatile compounds that have been detected in New Jersey groundwaters and addressed in this study include semi-volatile compounds as well as compounds that are rather easily stripped. Therefore, for purposes of this study, a loading rate of 20 gpm/sf has been selected and has been used for determining opinion of probable costs that are presented later in this section.

A.1.6 Operational/Regulatory Considerations

The installation of packed tower air stripping at a typical groundwater supply in New Jersey involves the consideration of several operational and regulatory issues including:

- Repumping
- Corrosion Control
- Disinfection
- Air Discharge

Repumping - A typical groundwater system involves pumping the water from the well directly into the distribution system. The installation of a packed tower will alter the pumping and piping of the system whereby the water from the well will be pumped to the top of the packed tower and then fall by gravity through the tower. Therefore, it will be necessary to repump the treated water to the distribution system.

Typically, this is accomplished by restaging the well pump using low head pumps and installing new high head pumps after the packed tower. Also, a clearwell of some type is needed to collect the treated water and to act as the sump for the treated water pumps. The modification of the well pumps, along with the installation of a clearwell and new high lift pumps, have been included in the costs.

Corrosion Control - The use of packed tower air stripping will raise the dissolved oxygen level and typically decrease the dissolved carbon dioxide of the treated water. The presence of dissolved oxygen could increase the corrosiveness of the water while the decrease in carbon dioxide with the resultant increase in pH typically decreases the corrosiveness of the water. However, experience with packed towers in New Jersey and across the country has indicated that the increase in pH is often more important than the addition of oxygen, particularly if the groundwater has been chlorinated. Therefore, it is not anticipated that additional corrosion control measures would have to be implemented when using a packed tower.

Disinfection - It is important that the treated water from a packed tower be adequately disinfected because of the exposure to the air. Although no evidence has been found of air contamination of treated water from packed towers, the treated water must be disinfected to meet current state regulations and to meet upcoming requirements of the Groundwater Rule.

Air Discharge - Some concern has been expressed for the potential contamination of the air surrounding a packed tower because the organic chemicals removed from the water are transferred to the atmosphere. The concentration of a compound in the air immediately exiting the tower depends on the mass of compound removed from the water and the volume of air used in the process. The discharge of organic chemicals into the atmosphere is regulated by NJDEP under the New Jersey Administrative Code, Title 7, Chapter 27, Subchapter 17. The NJDEP air emission limit is 0.1 pounds per hour for each organic chemical.

For the majority of packed towers that have been installed in New Jersey for VOC removal, the air discharge limit is easily met and no air treatment is needed. Where air treatment has been required, activated carbon has been used to treat the air stream. Alternatively, the top of the packed tower can be modified so that the air exiting the tower is discharged as high as possible thereby reducing the organic chemical concentration in the air by the time the air reaches ground level. Considering the very low levels of the organic chemicals considered in this study, treatment of the air is not expected to be required to meet the NJDEP air discharge regulation.

A.1.7 Opinion of Probable Costs

Equipment and Facility Assumptions - The equipment required for a typical packed tower installation consists of the following:

- Packed Tower: Metal (aluminum or steel), plastic, fiberglass, or concrete can be used for the shell. Aluminum has been assumed for this study. Internals (packing, supports, distribution plates, mist eliminator) are either plastic or metal.
- Blower: Typically, centrifugal type blowers are used. Two blowers are recommended in the event that one is out of service. Noise attenuation may be required depending on the size and location.
- Clearwell: A clearwell is generally provided immediately below the packed tower to store the treated water.
- High Head Pumping: Required to repump the water into the distribution system. Vertical turbine pumps are typically used and are mounted over the clearwell.
- Building: It is not necessary to house the packed tower, but is usually is necessary to house the blowers and the high head pumps to minimize the noise levels and to protect this equipment.

For the packed tower, the following design criteria have been used for the purpose of developing cost estimates based on the process description presented previously:

- Packing depth - 30 feet
- Air:Water ratio - 30:1
- Liquid loading rate - 20 gpm/sf
- Pretreatment - none
- Air treatment - none

It should be noted that the actual design criteria and equipment/facility requirements will be dictated by local conditions - types and levels of organic chemicals present in the water and the location of the facility.