



and



New Jersey Department of Environmental Protection
Division of Science, Research & Technology



**EVALUATION AND ASSESSMENT
OF
ORGANIC CHEMICAL REMOVAL TECHNOLOGIES
FOR
NEW JERSEY DRINKING WATER
GROUND WATER REPORT**

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CHAPTER 1 - INTRODUCTION

BACKGROUND

Numerous organic chemicals are used every day in New Jersey (NJ) for industrial, commercial and household purposes. A number of these chemicals have found their way into the State's wastewater treatment facilities, receiving waters, aquifers and drinking water treatment facilities. This situation is not unique to NJ as occurrence studies conducted around the country indicate similar findings. A recent report (dated December 20, 2005) completed by the Environmental Working Group (a nonprofit organization based in Washington, DC) indicated that 141 unregulated organic chemicals (UOCs) were detected in tap waters from 42 states.

The various types of UOCs that have been detected include:

- Pesticides
- Volatile organic chemicals (VOCs)
- Endocrine-disrupting compounds (EDCs)
- Pharmaceuticals and personal care products (PPCPs)
- Petroleum-related compounds
- Other industrial organic chemicals

Also, some naturally-occurring organic chemicals have been detected.

State and Federal agencies, environmental groups and the public are raising concerns regarding these chemicals as emerging contaminants of interest even though many of the chemicals have only been found at trace concentrations and only sparse data are available regarding their health and/or environmental effects. The fact that organic chemicals are being detected in drinking water supplies and that there is a concern regarding their health effects raises a fundamental question – what are the best available treatment technologies for removing these organic chemicals from drinking water supplies? And more specific to NJ, which technologies are most applicable to the State's ground water systems, and to what level should these compounds be removed? As answers to these questions are developed, it should be noted that the ability to detect these compounds is simply a function of the analytical method, and that removal efficiency is, in reality, a reflection of the

detection limits. Verification of complete removal of the compounds is not possible; one can simply document that concentrations are below the detection limits of the current analytical methods.

The New Jersey Department of Environmental Protection (NJDEP), in conjunction with the Drinking Water Quality Institute (DWQI), is considering potential options for addressing these contaminants in NJ drinking waters, and is seeking information on the effectiveness of various treatment technologies to assist in their evaluations. Treatability data are available for some of the organic chemicals that have been detected, but very little to no information on treatment removal efficiencies at the low UOC concentrations present in ground water is available for the vast majority of the chemicals.

PURPOSE AND SCOPE

This project is designed to review and summarize existing information on the effectiveness of various treatment technologies for removing UOCs and to identify the best available technologies for removing the organic chemicals found in NJ drinking waters. This report specifically addresses organic chemicals detected in ground waters in the State. For the purpose of this report, the synthetic organic chemicals are referred to as UOCs. It should be noted that the scope of this study does not include disinfection by-products or the “common” volatile organic chemicals that have been detected in ground waters. An extensive literature review was completed to document existing information on the removal of organic chemicals from drinking water. The available treatment techniques were reviewed and summarized to determine the most applicable technologies for NJ ground water supplies. The most applicable technologies are described relative to performance, reliability, treatment issues, and approximate (or relative) costs. The results of this project will be used by NJDEP to determine the need for and extent of demonstration testing that may be conducted to further evaluate the most feasible technologies as they apply to NJ ground water supplies.

LITERATURE REVIEW

The Project Team conducted a comprehensive literature review to evaluate the state of knowledge of treatment technologies for removing organic chemicals. Much of the information has been

assembled from literature searches that Black & Veatch (B&V) and the Project Team members have performed for several recent American Water Works Association Research Foundation (AwwaRF) projects and other research projects. Appendix A includes a list of references that have been developed by the Project Team. A significant amount of information on the removal of EDCs and PPCPs during water treatment is now available. The following are examples of AwwaRF studies that have provided important information on the treatment of organic chemicals:

- Project #2897 - Impact of UV and UV - Advanced Oxidation Processes on Toxicity of Endocrine-Disrupting Compounds in Water
- Project #2902 - Evaluation of Triclosan Reactivity in Chlorinated and Monochloraminated Waters
- Project #2758 - Evaluation of Conventional and Advanced Treatment Processes to Remove Endocrine Disruptors and Pharmaceutically Active Compounds
- Pharmaceuticals and Personal Care Products: Occurrence and Fate in Drinking Water Treatment (2004)

B&V and/or the Project Team members have been involved in these projects.

The literature review has focused on two major areas: (1) identification of treatment processes that definitively have been reported to definitively remove specific organic chemicals, and (2) relating the removal of well-studied compounds (*e.g.*, lindane, atrazine, geosmin, inorganic metals and oxoanions, natural organic matter (NOM) surrogate compounds) by conventional and advanced processes to the physical and chemical properties of compounds like EDCs and PPCPs, and other industrial organic chemicals. It should be noted that EDCs are unique in that they are not a list or type of compound – they are a class of compounds that produce a toxicological effect. Most EDCs are industrial organic chemicals and PPCPs. The review has included emerging organic EDCs and PPCPs, as well as treatability of other micropollutants where more extensive work has been conducted, providing a framework for understanding and predicting removal of emerging compounds. The findings have been utilized from the perspective of identifying trends in treatability based upon the physical structure of the compounds (molecular size/ polarity/functionality). The results of the literature review were used to determine which organic chemicals might be removed by the available treatment techniques as discussed in Chapter 3 - Available Treatment Techniques.

CHAPTER 2 - OCCURRENCE OF UOCs IN NJ GROUND WATERS

NJDEP STUDIES

In 1997, the NJDEP's Division of Science, Research and Technology began a multi-year project funded through the NJ A-280 Safe Drinking Water Research Fund to assess the occurrence of UOCs in NJ's ground water supplies (Murphy, 2003). More specifically, this project investigated the occurrence of Tentatively Identified Compounds (TICs) in water samples collected from NJ ground water systems. A TIC is a compound that can be seen by an analytical method but its identity and concentration cannot be confirmed without further investigation. TICs were detected using both standard and non-standard analytical methods.

There were three related objectives to this multi-year project:

1. Tentatively identify and possibly quantify chemicals present in raw and treated water samples collected from water supply systems impacted by hazardous waste sites.
2. In instances where chemicals are present in the raw water, determine if existing water treatment is effective at removing them.
3. Characterize the types of unregulated compounds present in water samples due to sampling and laboratory contamination.

The criteria used to select the sample locations included existing organic chemical contamination and/or proximity to known hazardous waste sites and thus a potential for raw water impacts. In several instances, the contaminated site influencing the water wells had been identified and the responsible party has paid for installation and maintenance of the treatment technology at the water system.

Twenty one (21) water systems from around the state were sampled in this study. With one exception, each of the water systems used ground water as their source of supply. Also, most of the systems had treatment (air stripping and/or granular activated carbon) in place for UOC removal. The sampling was conducted in 1997, 1998, 1999, and 2000.

All water samples were sent to the New Jersey Department of Health and Senior Services (NJDHSS) laboratory for analysis by standard USEPA Methods 524.2 (84 target volatile chemical analytes) and

525.2 (42 target semi-volatile chemical analytes). Both USEPA methods are designed specifically for the analysis of drinking water samples. The NJDHSS laboratory also had available and used for this study a sensitive analytical adaptation of Method 525.2 for the detection of styrene-acrylonitrile trimer (a compound which is the sum of four isomers and had been detected in the United Water Toms River water supply in November 1996). Non-standard analytical methods were developed at the NJ Environmental and Occupational Health Sciences Institute (EOHSI) and the NJ Center for Advanced Food Technology (CAFT) at Rutgers University. The EOHSI method utilized gas chromatography to analyze for semi-volatile and a small subset of volatile compounds. The CAFT method utilized high pressure liquid chromatography to analyze for non-volatile compounds.

Details of the project including the sampling locations and results are presented in a report entitled “The Characterization of Tentatively Identified Compounds (TICs) in Samples from Public Water Systems in New Jersey” dated March 2003. The TICs identified in the March 2003 report were used in this study for the purpose of determining appropriate treatment technologies.

ORGANIC CHEMICALS DETECTED IN NJ GROUND WATERS

Some 600 TICs were detected in the NJDEP project – in either a blank, or a raw water sample, or a finished water sample. Of these TICs, 338 were detected in raw water samples and not in the blanks, leading to the presumption that the TICs were actually present in the water supply and were not a sampling or analytical artifact. Of these 338, 266 were detected only in raw water samples, and not in finished water samples or any other category of sample. Semi-volatile compounds were present in the raw water samples, as these samples also contained the highest numbers of VOCs of the groups. As expected, these samples also contained the highest concentrations of VOCs of the sampling groups. The most frequently detected TICs in raw water samples included: bromacil, 1-eicosanol, a naphthalene derivative and a benzene derivative. These and other TICs detected (at least twice) in raw water samples and not in blanks (or detected infrequently in blanks) are listed in Table 2-1.

Table 2-1 Number of Times TICs found in Raw Water Samples Only (21 Systems Studied)

<u>Organic Chemical</u>	<u>Number of Times Detected</u>
Bromacil	11
1-eicosanol	6
1,2,5,6-tetramethylacenaphthylene	6
Benzene,(1,1-dimethylnonyl)-	5
Hexadecanoic acid, octadecylester	5
Acridine, 9,10-dihydro-9,9,10-trimethyl-	4
Cyclotetradecane,1,7,11-trimethyl-4-(1-methylethyl)	4
2-propenal,3-(2,2,6-trimethyl-7-oxabicyclo[4,1,0]hept-1-yl)	4
Unknown 21.8	4
2-propenoic acid, 3-(4-methoxyphenyl)-2-ethylhexyl ester	4
Cyclodecanol	3
Cyclododecanemethanol	3
7-hydroxy-7,8,9,10-tetramethyl-7,8-dihydrocyclohepta [d,e]naphthalene	3
3-methoxy-2-methyl-cyclohex-2-enone	3
2H-pyran,tetrahydro-2-(12pentadecynyloxy)-	3
Toluene,3-(2-cyano-2-phenylethenyl)	3
Benzene,1-isocyanato-2-methyl-	3
1,2-benzenedicarboxylic acid, 3-nitro	3
Phenol, 3-(1,1-dimethylethyl)-4-methoxy-	3
Hexanoic acid, 3,5,5-trimethyl-,1,2,3-propanetriyl ester	3
Isothiazole,4-methyl	2
Mepivacaine	2
Methanone,phenyl(5,6,7,8-tetrahydro-2-naphthalenyl)-	2
Metolachlor	2
1-naphthalenamine	2
2-naphthalenamide	2
1,3,2-oxazaborolidine,3,4-dimethyl-2,5-diphenyl	2
Pentadecane, 4-methyl-	2
Phenanthrene	2
2-phenyl-4,6-di(2-hydroxyphenyl)pyrimidine	2
6H-purine-6-thione,1,7-dihydro-1-methyl	2
triindenol[2,3,3',3',2'',3'']benzene	2
2,3,4-trimethyl hexane	2
Undecanone,2-methyl oxime	2
Bis (2-methoxyethyl)phthalate	2
Benzamide, N-(4-hydroxyphenyl)-2-methyl	2
Benzene, (1,1-dimethylbutyl)-	2
Benzene (1-methyldecyl)-	2
Benzene, 1,3,5-tri-tert-butyl	2
Benzene, 1-ethyl-3-methyl	2
Ethanone, 1-(5,6,7,8-tetrahydro-2,8,8)	2
1H-indene, 2,3-dihydro-4,5,7-trimethyl	2

Table 2-1 continued

<u>Organic Chemical</u>	<u>Number of Times Detected</u>
2-isopropenyl-3,6-dimethylpyrazine	2
5-hexadecenoic acid, 2-methoxy-,methyl ester	2
9,12-octadecadienoic acid (Z,Z)-	2
Unknown 12	2
Unknown 21.6	2
Unknown 24.38	2
Unknown 25.1	2

CATEGORIZATION OF DETECTED UOCs

For the purpose of determining appropriate treatment technologies for NJ's ground water supplies, the list of UOCs from the two most affected well sites (Camden and Fair Lawn) were selected. The total number of UOCs detected in these two water systems was 221 as compared to the total of 338 compounds detected in the raw water samples. Added to this list were any of the most frequently detected TICs from Table 2-1 that were not detected in the Camden or Fair Lawn wells. The final list that was used for purposes of this study amounts to about 250 organic chemicals, which represents over 90 percent of the TICS found in the raw water supplies.

The total list of organic chemicals was broken down in to 3 major classes of compounds:

- Aliphatics
- Cyclics which are defined as saturated ring compounds without aromatic characteristics
- Aromatics which are ring compounds that are unsaturated, and thus more reactive than cyclic compounds

Within each class, the organic chemicals were further broken down into several categories as follows:

- Petroleum Components
- Flavoring agents/Fragrances
- Pharmaceuticals
- Surfactants/Personal Care Products
- Lubricants/Emulsifiers
- Polymers/Plastics
- Phthalates
- Polycyclic Aromatic Hydrocarbons (PAHs)
- Pesticides/Herbicides

- Other Consumer Products not directly used as personal care products
- Other Industrial Chemicals – compounds that are manufacturing intermediates for a variety of end products but do not fit into the other categories; for example, corrosion inhibitors for metals
- Natural Compounds
- Unknown Compounds

The number of organic compounds that fell into the three classes and various categories are shown in Table 2-2. Approximately 100 of the compounds fall into the categories of either petroleum components, flavors/fragrances, pharmaceuticals, surfactants/personal care products, or other industrial chemicals. The categorization of 79 of the compounds is unknown.

The specific compounds in the three classes (aliphatics, cyclics, and aromatics) and various categories are listed in Tables B-1, B-2, and B-3, respectively, which are included in Appendix B. For most of the compounds, the Chemical Abstracts Service number (CAS#), class, molecular weight, and uses of the compound, if known, are included in the tables. Classification and categorization of the organic chemicals also were used to determine appropriate treatment techniques which are described in Chapter 3.

Table 2-2
Classes and Categories of UOCs Detected

<u>Class - Categories</u>	<u>Aliphatics</u>	<u>Cyclics</u>	<u>Aromatics</u>	<u>Totals</u>
Petroleum Components	5	6	11	22
Flavoring AgentsFragrances	5	10	2	17
Pharmaceuticals	4	5	19	28
Surfactants/Personal Care Products	13	0	3	16
Lubricants/Emulsifiers	6	0	0	6
Polymers/Plastics	9	0	8	17
Other Industrial Chemicals	1	0	18	19
Phthalates	0	0	5	5
Polycyclic Aromatic Hydrocarbons (PAHs)	0	0	12	12
Pesticides/Herbicides	5	1	5	11
Other Consumer Products	0	1	1	2
Natural Compounds	0	2	2	4
Unknown	22	17	38	77
TOTALS	70	42	124	236

CHAPTER 3 - AVAILABLE TREATMENT TECHNIQUES

INTRODUCTION

Various treatment techniques have been evaluated, tested, and applied to remove UOCs from ground water supplies. These techniques generally may be categorized as follows:

- Adsorption processes
- Oxidation processes
- Air stripping processes
- Membrane processes
- Biological processes

Each of these categories of processes is discussed in the following sections of this chapter with respect to general process description, factors affecting process efficiency and applicability to organic chemical removal. As a general note, the presence of natural organic matter (NOM) in water can interfere with the performance of many of the listed treatment techniques. Fortunately, levels of NOM generally are very low in northeastern ground water, especially in the bedrock aquifers in northern NJ. As such, NOM should not impact treatment to any significant degree.

Information on the removal of organic chemicals from drinking water varies largely on the molecular structure of the chemicals. For instance, much work has been done on the removal of many VOCs and petroleum-related contaminants found in ground water supplies, while much less has been done and is known about the removal of EDCs and PPCPs and other industrial organic chemicals. Information on the removal of unregulated chemicals (unregulated from the perspective that no drinking water limits or advisories have been established) is somewhat limited because the analytical procedures associated with these compounds are complex and are not generally available to commercial/utility laboratories. Therefore, analyses for these compounds are rare, and when detected, they are present at fluctuating concentrations near analytical method detection limits. Most of the knowledge about the removal of these TICs is derived from laboratory or bench-scale studies. When treatment data are not available, removal predictions can be made based on the research on contaminants with similar chemical properties.

For some of the more frequently occurring chemicals, bench, pilot and even full-scale data are available to determine the efficiency of certain treatment techniques. However, for the vast majority of the organic chemicals that have been detected in NJ ground waters, no treatability data are available, and estimates of removal efficiencies must be made based on previous research with organic chemicals exhibiting similar chemical characteristics or in similar classes or categories.

It should be noted that much of the information on the removal of the UOCs from drinking water was obtained from previous research work performed by either Dr. Shane Snyder of the Southern Nevada Water Authority or Dr. Karl Linden of Duke University. References to their work are indicated throughout the text and are shown in the various documents listed in Appendix A.

ADSORPTION PROCESSES

General Process Description

Adsorption is the collection and condensation of a substance or substances from the water phase to the solid surface of an adsorbent. For the purpose of this study, granular activated carbon (GAC) adsorption is the process of choice because GAC typically is used in drinking water treatment for ground water 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). Water to be treated is passed through a 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 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. Groundwater applications are typically closed systems. Also, in a number of ground water treatment systems, air stripping has been applied for removal of volatiles before the adsorption process to reduce the organic load on the carbon and extend its effective life.

Factors Affecting Process Efficiency

The principle mechanisms that affect the transfer of contaminants from the aqueous phase to the GAC adsorbent are transport across the hydrodynamic layer around each GAC particle, intra-particle transport through the activated carbon bed, and chemical equilibrium. Typically, contaminants that are water soluble will not adsorb well to GAC and mixtures of compounds reduce the capacity of the activated carbon to remove any one compound because of competition for bonding sites. In addition to the mix of organics, the efficiency of GAC adsorption is affected by:

- The properties of the carbon itself
- The contact time of the water in the GAC bed
- Water temperature
- pH
- The concentration of inorganic substances in the water
- Natural organic matter in the water which competes for adsorption sites, thereby reducing the adsorption capacity for the target organic chemicals to be removed
- The presence or absence of chlorine in the water

GAC reacts with chlorine (or other oxidants) in a reduction-oxidation reaction, but at the cost of oxidation of some of the surface characteristics of the activated carbon. Over time, the GAC can become colonized by bacteria that metabolize adsorbed compounds, enhancing the capacity of the activated carbon and prolonging its life.

There are different types of GAC that have been developed from source compounds as diverse as bituminous coal and coconut shells. The different types of GAC can exhibit greater affinities for some contaminants so selection of an optimal activated carbon can significantly improve the efficiency of the process for a specific water source. Isotherm tests are conducted to determine if an activated carbon can remove a contaminant or mixture of contaminants from a water source.

Applicability to UOC Removal

GAC adsorption already has widespread use in the drinking water industry for removal of regulated organic chemicals as well as taste and odor compounds. GAC 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. 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. Organic chemicals exhibiting high carbon usage rates may not be amenable to treatment using GAC. This factor is discussed further in Chapter 4.

Since the discovery of halogenated disinfection by-products in the early 1970s, a number of studies have been conducted to determine the relative amenability of different organic compounds and classes of compounds to activated carbon adsorption. Some of the readily adsorbed classes of organic compounds are:

- Aromatic solvents and fuels, non-polar solvents such as benzene, toluene, xylene, gasoline, kerosene
- Polynuclear aromatic hydrocarbons such as phenanthrene and fluoranthene
- Aliphatic hydrocarbons with more than six carbons, because the smaller hydrocarbons are volatile. Some of the larger hydrocarbons are hexane, octane, nonane, decane.
- Halogenated organic compounds, aliphatic and aromatic, ranging from carbon tetrachloride and dichloroacetonitrile to the pesticide chlordane and polychlorinated biphenyls (PCBs)

There has also been some experience with adsorption of aromatic alcohols (phenols), humic substances, dyes, surfactants such as long chain fatty acids and fatty acid esters as the long chain is non-polar, and organic compounds containing nitrogen (EPA, 2000). Work by Snyder indicated that GAC was very effective for removal of 31 specific EDCs and pharmaceuticals, but regeneration frequencies can be high. The presence of NOM in the water resulted in reduced efficiencies.

The more polar, water soluble compounds are not well adsorbed by GAC. These include:

- Alcohols
- Aldehydes and ketones, particularly low molecular weight molecules
- Carboxylic acids
- Carbohydrates – both sugars and starches

Very large or high molecular weight organics such as tannins are not well adsorbed either and these should be removed by other processes before the activated carbon.

OXIDATION PROCESSES

General Process Description

Chemical oxidation processes have been used in drinking water treatment to accomplish several objectives: disinfection, iron/manganese oxidation, oxidation of taste and odor producing compounds, and color removal. They also have been used for treatment of waters containing organic chemicals. The mechanism for organic chemical removal by oxidation is the conversion of the organic chemical into either intermediate reaction products or into carbon dioxide and water, which are the final oxidation products. Complete destruction is rarely achieved as the intermediates which are formed may be more resistant to further oxidation than the original organic chemical.

Several oxidants are available for removing organic chemicals from drinking water:

- Ozone
- Chlorine
- Chlorine dioxide
- Ultraviolet (UV) light

Each of these is discussed briefly below.

Ozone - Ozone is the most powerful oxidant available for water treatment and therefore has a greater capacity to oxidize organic chemicals than the other oxidants. Ozone can react in aqueous solutions by two mechanisms: direct reaction of the ozone molecule and indirect reaction through decomposition of the ozone to primarily hydroxyl free radicals (OH[•]) 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 radical reactions.

The direct reaction pathway, via the ozone molecule, is relatively slow, occurring on the order of seconds to minutes depending on the organic chemical. 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 as high as 20 minutes. Ozone dosages generally range from 1 to 5 milligrams per liter (mg/L). For organic chemical removal, contact times of 5 to 20 minutes should be sufficient to achieve high removal efficiencies for many organic chemicals. Required ozone

dosages will depend on the organic chemical and the amount of NOM in the water. Since the NOM typically is at much higher concentrations than the contaminants of concern, the NOM levels will tend to drive the ozone dosage. Ozone must be generated on-site, so the facility must include ozone generating equipment.

In contrast to the direct reaction pathway, the indirect reaction pathway (via the OH radical) is relatively fast, 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 nonselective with respect to oxidation of micropollutants. Oxidation processes that utilize the highly reactive OH radical are called advanced oxidation processes. Advanced oxidation can be accomplished in several ways including:

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

The UV processes are described later in this chapter. By utilizing the OH radical, ozone 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 using ozone alone.

Chlorine - Chlorine is commonly used for disinfection of drinking water and also has been evaluated for oxidation of organic chemicals. Of the available oxidants, chlorine is the least powerful. Therefore, higher chlorine dosages and contact times, compared to ozone oxidation, are needed to achieve effective removal of organic chemicals. High dosages of chlorine could result in unacceptable levels of disinfection by-products. Therefore, the typical use of chlorine for disinfection may provide some removal of a limited number of organic chemicals, but its use for significant removals of a broad range of organic chemicals probably is not practical.

Chlorine Dioxide - Chlorine dioxide is a strong oxidant – stronger than chlorine but not as strong as ozone. Therefore, in general, the dosages and contact times required for effective removal are lower

compared to chlorine but higher compared to ozone. At typical chlorine dioxide dosages (1 to 1.5 mg/L) and contact times (10 minutes) used in drinking water treatment, removals of certain organic chemicals have been reported to be less than 50 percent. Higher dosages may not be practical because of the concern for producing the by-products chlorite and chlorate. Higher contact times also may not be practical.

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 UOCs is extremely poor, if at all. Studies have shown that dosages as high as $1,000 \text{ mJ}/\text{cm}^2$ are needed to achieve reasonable removals of UOCs that are oxidizable. Removal efficiencies can be improved by combining UV with hydrogen peroxide or ozone, as indicated previously (Linden, 2006). Both of these advanced oxidation processes can achieve more reasonable removal efficiencies compared to UV alone; however, UV doses of several hundred mJ/cm^2 are still required.

Factors Affecting Process Efficiency

The important factors that affect the removal efficiencies that may be achieved with oxidation or advanced oxidation processes include:

- Characteristics of the organic chemical – discussed further below
- pH of the water - at pH ranges below 7.0, molecular ozone predominates over the OH radical; above pH 8.0, the ozone molecule decomposes very rapidly to form OH radicals. Lower pH also has been found to provide higher removals with chlorine.
- Alkalinity of the water - the presence of bicarbonate and carbonate ions may slow down the decomposition of ozone to OH radicals.
- Presence of humic substances in the water - humic substances may function as an initiator or promoter of the decomposition of ozone to the OH radical.
- Contact time - the longer the contact time, the more time for oxidation to occur provided an oxidant is present.
- Oxidant dosage - the higher the oxidant dosage, the greater the removals. Lower dosages generally can be used with advanced oxidation processes.
- Oxidant demand of the water - sufficient oxidant must be added to the water to overcome the demand exerted by such things as natural organic matter or iron and manganese that may be present in the water.

For ground waters in NJ, pH and alkalinity may affect oxidation. Typically, levels of natural organic matter are very low in ground water, especially in the bedrock aquifers in northern NJ, and so the impact on oxidation should be minimal.

Applicability to UOC Removal

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

General Observations

- Dissociated acidic compounds are more reactive than protonated forms (i.e., reactivity increases with pH), but non-dissociated bases are more reactive when not protonated.
- General order of reactivity from highest to lowest for aromatic or aliphatic compounds - thiols > amines > hydroxyl > carboxyl.
- Aromatic compounds are more reactive than aliphatic compounds.

Ozone

- 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 reciprocal molar seconds ($M^{-1}s^{-1}$) 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.
- Work conducted by Linden indicated that most of the CCL (1998) compounds are not very reactive with ozone. One exception was 1,2,4-trimethylbenzene which has been found in NJ ground water.
- Work by Snyder indicated that a 0.1 to 0.3 mg/L ozone residual at 5 minutes contact time provided greater than 70 percent removal of many EDCs and pharmaceuticals. About 80 percent removal of metolachlor, one of the UOCs found in NJ ground water, was achieved under these conditions.
- Snyder also found that the addition of hydrogen peroxide does not significantly increase removal and concluded that hydrogen peroxide is rarely, if ever, needed in addition to ozone for removal of most organic chemicals.

Chlorine

- Free chlorine reacts rapidly with phenolic compounds.
- The transformation of several amine-containing antibiotics, diclofenac, and caffeine was observed in some laboratory studies.
- Snyder reported that tests with free chlorine at a residual dosage of 0.5 mg/L after 24 hours yielded varying results. Of the 31 pharmaceuticals and EDCs tested, about half

were removed by less than 30 percent and another half were removed by over 70 percent. Metolachlor was removed by about 30 percent. Reducing the pH to 5.5 provided somewhat better removals.

Chlorine Dioxide

- Chlorine dioxide can oxidize herbicides, pesticides, and PAHs, but removal efficiencies have been reported to be below 50 percent and contact times can be very long – hours. It is anticipated that compounds containing phenolic amino and thiol functional groups will react with chlorine dioxide.

UV Light

- Extremely high doses of UV light are required to oxidize UOCs. The use of UV in combination with ozone or hydrogen peroxide is likely to provide greater removals at lower doses.
- Work conducted by Snyder indicated that UV doses of 40 mJ/cm² (typical of disinfection) provided no removal to less than 30 percent for the 31 EDCs and pharmaceuticals that were tested. At a UV dose of 1,000 mJ/cm², removals of some compounds increased to over 80 percent, but removal of many compounds still was less than 20 percent. At 40 mJ/cm², metolachlor was removed by about 10 percent, and at 1,000 mJ/cm² removal increased to about 70 percent.
- Snyder also reported that with the addition of 4 and 8 mg/L of hydrogen peroxide and a UV dose of 1,000 mJ/cm², removals of many compounds increased to greater than 80 percent, including metolachlor.
- Work conducted by Linden using both low pressure (LP) and medium pressure (MP) UV lamps (at energies 10 to 50 times disinfection doses) to oxidize 6 pharmaceuticals indicated the following orders of removal:

LP: iohexol > clofibric acid > naproxen ~ carbamazepine

MP: chlofibric acid > naproxen ~ iohexal > carbamazepine

The tests were conducted at UV doses of 300 to 1,800 mJ/cm².

- Linden's work showed that removals were less than 40 percent at 100 mJ/cm² for naproxen, carbamazepine, clofibric acid and iohexol. About 80 percent removal was achieved for ketoprofen and ciprofloxacin. For the poorly removed compounds, the addition of hydrogen peroxide increased removals to 20-50 percent.
- Linden reported that for all 6 compounds, to achieve about 90 percent removal required UV doses greater than 300 mJ/cm² and 10 mg/L of hydrogen peroxide.

Overall, for the oxidation processes, it would appear that the use of chlorine or chlorine dioxide is not feasible for treating NJ ground waters as the dosages and/or contact times required for greater than 30 percent removal are unreasonably high. Incidental removal by existing chlorine processes

used for disinfection might provide some removal of certain compounds. The use of ozone or high energy UV alone may provide reasonable removal efficiencies for a number of the UOCs found in NJ ground waters. However, combinations of ozone and UV or hydrogen peroxide and UV and hydrogen peroxide would provide greater removal efficiencies for a greater number of organic chemicals by promoting the indirect reaction with OH radical reactions.

AIR STRIPPING PROCESSES

General Process Description

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 certain (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. 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,
- 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 ground water supplies. Packed towers have been used more frequently for removing SOCs because of the superior efficiency of this process.

Factors Affecting Process Efficiency

Ground waters are often under pressure and not in equilibrium with the various gases in air. As a result, contaminants in ground water are unable to escape into the atmosphere. Thus, ground waters

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).

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, according to the Henry's Law 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 Law Coefficient describes the tendency of a given compound to separate between gas and liquid. The Henry's Law Coefficient can be used to give a preliminary indication of how well an organic chemical can be removed from water, as discussed further below.

Factors that affect this transfer include:

- The temperature of both water and air
- The physical chemistry of the contaminant
- 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 last four factors can be controlled in the design of the air stripping system, while the first two factors are a function of the specific ground water supply and the nature of the organic chemicals in that supply.

Applicability to UOC Removal

The contaminants that can be removed by aeration are those that are gases or that become vapors at ambient temperatures and pressures. Aliphatic compounds of 4 carbons or less are gases and aliphatic compounds with 5 to 6 carbons are volatile. Many of the smaller cyclic and aromatic

compounds are also volatile. Figure 3-1 illustrates the types of UOCs that may be volatile and removed using air stripping techniques based on polarity and molecular weight.

	Volatile	Semivolatile	Nonvolatile
Polar	Alcohols	Alcohols	Polyelectrolytes
	Ketones	Ketones	Carbohydrates
	Carboxylic Acids	Carboxylic Acids	Fulvic Acids
		Phenols	
Semipolar	Ethers	Ethers	Proteins
	Esters	Esters	Carbohydrates
	Aldehydes	Aldehydes	Humic Acids
		Epoxides	
		Heterocyclics	
Nonpolar	Aliphatic hydrocarbons	Aliphatics	Non-ionic polymers
	Aromatic hydrocarbons	Aromatics	Lignins
		Alicyclics	Hymatomelanolic acid
		Arenes	
	Low Molecular Weight	Medium Molecular Weight	High Molecular Weight

Figure 3-1 Volatility of Classes of Organic Chemicals

The Henry's Law Coefficient of a compound indicates how well a compound can be removed from water via air stripping. A higher Henry's Law Coefficient indicates good removal from the water phase to the air phase. Figure 3-2 presents Henry's Law Coefficients for selected organic chemicals. Generally, the more soluble the gas, the lower the value of the Henry's Law Coefficient. The polarity and molecular weight of a gas strongly affect its solubility – with more polar and higher molecular-weight gases being more soluble. This information can be used to provide a preliminary indication of the applicability of air stripping to remove the organic chemicals that have been detected in NJ ground waters.

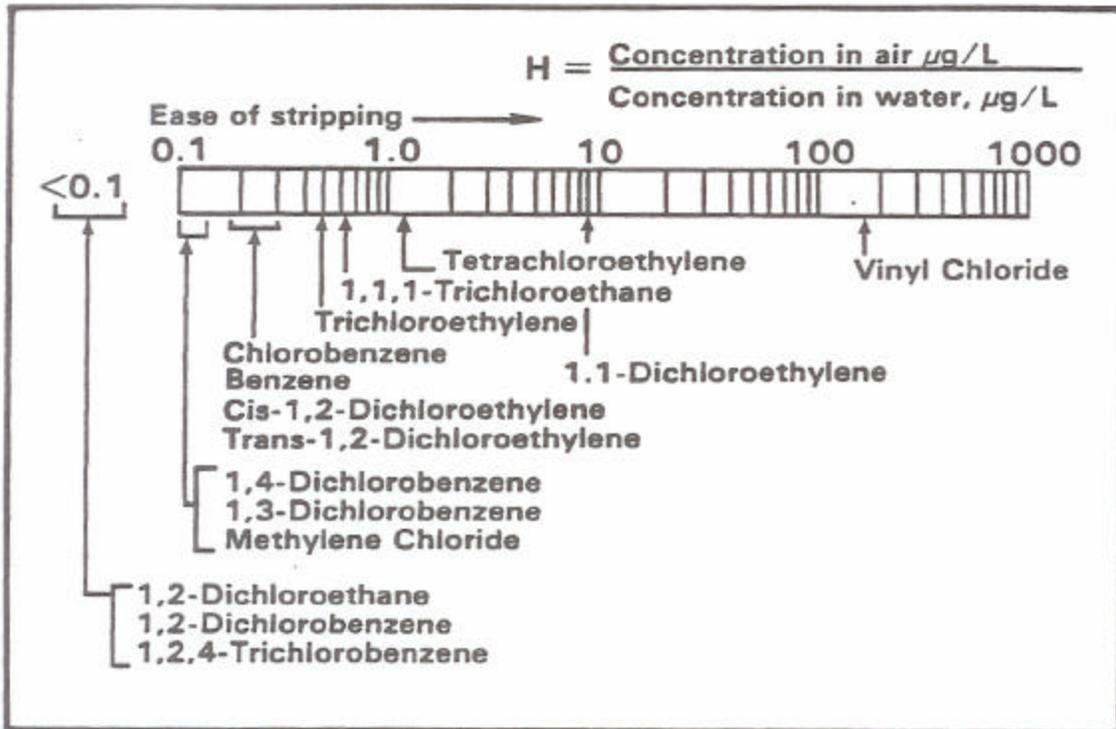


Figure 3-2 Henry's Law Coefficients for Various Organic Chemicals

MEMBRANE PROCESSES

General Process Description

Increasingly, utilities are using membrane technology to solve a wide array of water treatment problems, including the following:

- Surface water treatment with microfiltration or ultrafiltration.
- Water reclamation with microfiltration or ultrafiltration followed by reverse osmosis.
- Desalination with reverse osmosis.
- Softening with reverse osmosis or nanofiltration.
- Removal of nitrate (and other ions) with reverse osmosis.
- Removal of color, total organic carbon (TOC), and DBP precursors with reverse osmosis or nanofiltration and ultrafiltration with coagulation.
- Treatment and recovery of filter backwash water with ultrafiltration or nanofiltration.
- Industrial processing for ultrapure water and reuse with reverse osmosis.

Membranes used in water treatment may be defined as a thin film barrier that selectively removes some of the constituents in the water. The constituents removed include particles, colloidal species,

and dissolved organic and inorganic constituents. The major membrane types used in water treatment that are discussed in this report include:

- microfiltration (MF),
- ultrafiltration (UF),
- nanofiltration (NF),
- reverse osmosis (RO)

These membranes differ from each other in several aspects including driving force, materials, configurations, removal mechanism and rejection ability as listed in Table 3-1.

MF, UF, NF and RO membrane processes use pressure to induce transport of water across the membrane. Pressure is applied on the feed side of the membrane to separate the feed stream into a permeate (or filtrate) stream that passes through the membrane, and a reject or concentrate stream that does not pass through the membrane and contains the rejected constituents in the feed water. For submerged MF and UF membranes, suction is used instead of pressure to move the water through the membrane.

**Table 3-1
General Description of Membrane Systems Commonly Used
in Water Treatment**

Membrane type	Driving force	Mechanism of separation	Membrane structure
Microfiltration (MF)	Pressure	Physical sieving	Macropores
Ultrafiltration (UF)	Pressure	Physical sieving	Macropores
Nanofiltration (NF)	Pressure	Physical sieving + diffusion + exclusion	Dense membrane phase & nanopores
Reverse Osmosis (RO)	Pressure	Physical sieving + diffusion + exclusion	Dense membrane phase

MF and UF membranes are porous in nature and the removal mechanism is primarily one of sieving. Under applied pressure or vacuum (negative pressure), water is transported across the membrane, while all contaminants larger than the size of the membrane pores are retained. RO and NF

membranes are semipermeable membranes allowing transport of water across the *membrane phase* through diffusion, and limiting the diffusive transport of solutes. The transport of water across the membrane occurs by convection under the applied pressure gradient.

Factors Affecting Process Efficiency

The ability of the membrane processes to reject various contaminants in water is highly dependent on the removal mechanism and membrane structure. Based on that, the membrane processes listed above could be grouped into two categories:

- MF and UF membranes: Pressure or suction driven process; removal through sieving
- NF and RO membranes: Pressure driven process; removal through diffusion and sieving
- All - removal by electrostatic repulsion based on zeta potential and contaminant charge (both dependent on pH)

MF and UF Membranes - The surface of these membranes consists of macropores which allows passage of water, while retaining all constituents larger than the pore size. The main difference between MF and UF membranes is the nominal pore size. The commercially available MF and UF membranes are characterized by nominal pore sizes of approximately 0.1 μm and 0.01 μm , respectively. Due to their pore sizes, these membranes effectively remove all contaminants larger than their pore size. Of particular interest to the water treatment industry is their ability to reject pathogens such as *Cryptosporidium* oocysts and *Giardia lamblia*. UF membranes, depending on their pore size, could achieve significant removal of viruses also as discussed later. The molecular weight cut off for UF membranes is generally around 10,000, which is much higher than any of the organic chemicals.

NF and RO Membranes - NF and RO membranes are not characterized by pores. 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 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, higher 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.

The main distinction between RO and NF membranes is their rejection ability. Typically RO membranes achieve high rejection of many dissolved substances including monovalent ions. The rejection of nanofiltration membranes is lower, particularly for the monovalent ions. NF systems are sometimes referred to as 'loose' RO membranes, as their pressure requirement as well as rejection ability is lower.

Applicability to UOC Removal

Based on bench and pilot scale testing of membranes for removal of organic chemicals, the following results have been reported:

- Typically, compounds associated with particles or colloidal matter in the water would be removed by microfiltration or ultrafiltration.
- Both RO and tight nanofiltration systems would be more effective in removing organic chemicals.
- Polar compounds and charged compounds that interact with membrane surfaces will be better removed than less polar or neutral compounds.
- Overall, membrane separation provides an excellent barrier for most EDCs and PPCPs, except lower molecular weight uncharged compounds.
- Work by Linden indicated that the CCL (1998) compounds could be removed by as much as 80 percent and higher with the use of RO.

In general, MF and UF membrane systems have been shown to remove less than 20 percent of organic chemicals, while NF and RO membrane systems can achieve as high as 100 percent removal.

BIOLOGICAL PROCESSES

General Process Description

Biological processes have been used in water treatment for removal of iron, manganese, and ammonia. Also, biological treatment has been used in conventional surface water treatment plants to provide a greater barrier for microbiological control. Typically, biological treatment is accomplished in combination with a filtration process using sand, anthracite or GAC media, or with an adsorption process using GAC. In some instances where GAC has been used for removal of VOCs from ground water, bacterial growth has been shown to occur on the GAC. This occurred in Rockaway Township, NJ where both air stripping and GAC has been used for VOC and methyl tertiary butyl ether (MTBE) removal. Apparently, the air stripping process adds oxygen to the water to promote biological growth. GAC preceded by ozonation can produce an even greater impact on biological growth as the water is saturated with oxygen.

Generally, an initial start-up period is required for the process to establish the biomass in the filter or adsorber. This can be significant depending on the nature of the compounds to be removed. Once the system is operating, it is better to run it continuously to avoid a reduction in the biomass and a resultant reduction in removal efficiency. This could be a problem for ground water systems where a well or wells are operated intermittently. Depending on the nature of the water, a nutrient may have to be added to the water before biological filtration to provide sufficient food for the microorganisms to grow.

Factors Affecting Process Efficiency

The key factors that would impact the removal efficiency of a biological process for organic chemical removal are:

- Biodegradability of the compound to be removed
- Amount and nature of food supply in the raw water.
- pH of the water
- Operating scenario - continuous vs. intermittent
- Contact time
- Presence and concentration of dissolved oxygen in the water

Applicability to UOC Removal

Very little work has been done to determine the removal efficiency of biological processes on organic chemicals in drinking water. More work has been done on wastewater treatment, however, the nature of the water is obviously much different especially regarding the food supply for microorganisms. Also the temperature of the wastewater is generally warmer than that found in ground waters, promoting greater biological growth. If GAC were used for organic chemical removal from a ground water supply, it is likely that some biological growth would occur. This may be especially true for GAC adsorbers preceded by air stripping as oxygen tends to be added to the water enhancing microbiological growth. Microbiological growth was seen in the Rockaway Township GAC adsorbers as evidenced by higher HPC levels in the GAC effluent after air stripping was added ahead of the process. The organic chemical removal that would take place in a GAC adsorber would depend on the nature of the water and the biodegradability of the organic chemicals.

SUMMARY OF AVAILABLE TREATMENT TECHNIQUES

The review of available treatment data indicated that data do not exist for most of the individual compounds that have been detected in the NJ ground water systems as summarized in Chapter 2. As a result, the applicability of specific treatment techniques for NJ ground waters was estimated based on treatability data from compounds of similar characteristics. A good example is shown in Table 3-2 which presents a summary of information developed by Snyder on the treatability of various groups and classes of organic chemicals found in water.

Based on the available information, the potential for treatment of the specific organic chemicals by the various treatment techniques is presented in Tables C-1 (alkanes), C-2 (alkenes), and C-3 (aromatics) which are included in Appendix C. Summaries of this information by UOC class and category are presented in Tables 3-3 (cyclics), 3-4 (aliphatics), and 3-5 (aromatics). The information presented in these tables regarding the potential for removal of the 234 UOCs by the available treatment techniques may be summarized as follows:

	<u>Cyclics</u>	<u>Aliphatics</u>	<u>Aromatics</u>	<u>Totals</u>
Oxidation	1	4	48	53
Adsorption	28	49	87	164
Air Stripping	13	13	28	54
Biological Treatment	2	18	17	37

It is estimated that membranes, particularly RO, could be applicable for removal of almost all the organic chemicals. However, RO is not considered a practical alternative for installing at multiple well sites or even at wellfields because of the cost and waste disposal issues.

From the above information, the available treatment techniques have been divided into the following general categories:

Most Applicable Technologies - Adsorption with GAC and AOP

Other Applicable Technologies - Oxidation and Air Stripping

Additional Technologies - Biological Treatment and Membranes

Adsorption appears to be the most applicable technology because of its ability to remove a wide range of compounds, although the type of compound will dictate the GAC replacement frequency. Advanced oxidation processes involving ozone or UV also are considered most applicable to NJ ground waters. Oxidation and air stripping also seem to be applicable because of the number of compounds that appear to be removed. Of the oxidation technologies, ozone and UV are the most applicable. Biological treatment and membranes are not considered as applicable because of the limited available data on their use for UOCs. Also, neither treatment technique is typically used in ground water treatment. They are also considered more costly when compared to the other techniques, especially in the case of RO. Incidental biological treatment might be obtained with the use of adsorption, but the installation of an adsorber solely for biological treatment may not be practical.

It should be noted that based on the various studies that have been completed to date on the fate of organic chemicals in water treatment processes, no one treatment technique can remove all of the UOCs that have been detected in NJ ground waters. In addition, it is unlikely that all of the UOCs could be removed from a given location even using a combination of processes. Third, by-products of oxidation and biological activity are likely to be generated creating other organic chemicals while the original organic chemicals in the ground water are removed to a certain extent.

Table 3-2 Unit Processes and Operations Used for EDCs and PPCPs Removal

Group	Classification	AC	BAC	O ₃ /AOPs	UV	Cl ₂ /ClO ₂	Coagulation/ Flocculation	NF	RO	Degradation {B/P/AS} ^a
EDCs	Pesticides	E	E	L-E	E	P-E	P	G	E	E {P}
	Industrial Chemicals	E	E	F-G	E	P	P-L	E	E	G-E {B}
	Steroids	E	E	E	E	E	P	G	E	L-E {B}
	Metals	G	G	P	P	P	F-G	G	E	P{B},E{AS}
	Inorganics	P-L	F	P	P	P	P	G	E	P-L
	Organometallics	G-E	G-E	L-E	F-G	P-F	P-L	G-E	E	L-E
PhACs	Antibiotics	F-G	E	L-E	F-G	P-G	P-L	E	E	E {B}
	Antidepressants	G-E	G-E	L-E	F-G	P-F	P-L	G-E	E	G-E
	Anti- inflammatory	E	G-E	E	E	P-F	P	G-E	E	E {B}
	Lipid regulators	E	E	E	F-G	P-F	P	G-E	E	P {B}
	X-ray contrast media	G-E	G-E	L-E	F-G	P-F	P-L	G-E	E	E {B and P}
	Psychiatric control	G-E	G-E	L-E	F-G	P-F	P-L	G-E	E	G-E
PCPs	Synthetic musks	G-E	G-E	L-E	E	P-F	P-L	G-E	E	E {B}
	Sunscreens	G-E	G-E	L-E	F-G	P-F	P-L	G-E	E	G-E
	Antimicrobials	G-E	G-E	L-E	F-G	P-F	P-L	G-E	E	L-E {B}
	Surfactants/ detergents	E	E	F-G	F-G	P	P-L	E	E	L-E {B}

^aB, biodegradation; P, photodegradation (solar); AS, activated sludge; E, excellent (>90%); G, good (70–90%); F, fair (40–70%); L, low (20–40%); P, poor (<20%).

Table 3-3
Treatability of Cyclics

<u>Category</u>	<u>Air Stripping</u>		<u>Adsorption</u>		<u>Oxidation</u>		<u>Biological</u>	
	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>
Petroleum Components – 6	2	1	3	3	-	-	-	-
Flavor/Fragrances 10	4	2	-	2	-	-	1	-
Pharmaceuticals 5	-	1	1	4	1	-	-	-
Pesticides/ Herbicides – 1	-	-	-	1	-	-	-	-
Consumer Products – 1	1	-	-	1	-	-	-	-
Natural Compounds – 2	-	-	-	1	-	-	1	-
Unknown- 17	1	2	2	4	-	-	-	-
TOTALS – 40	7	6	7	21	1	-	2	-

Table 3-4
Treatability of Aliphatics

<u>Category</u>	<u>Air Stripping</u>		<u>Adsorption</u>		<u>Oxidation</u>		<u>Biological</u>	
	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>
Petroleum Components - 5	-	3	5	-	-	-	-	-
Flavor/Fragrances 5	-	2	1	1	-	1	1	-
Surfactants/ Personal Care Products – 13	-	-	6	5	-	1	3	-
Pharmaceuticals 4	-	-	1	1	-	-	1	-
Lubricants/ Emulsifiers – 6	-	-	2	4	-	-	2	-
Polymer/ Plastic Manufacture 9	-	-	4	4	-	-	3	1
Industrial Chemicals-1	-	-	1	-	-	-	1	-
Pesticides/ Herbicides - 5	-	4	1	-	1	-	3	-
Unknown- 22	2	2	5	8	1	-	1	2
TOTALS - 70	2	11	26	23	2	2	15	3

Table 3-5
Treatability of Aromatics

<u>Category</u>	<u>Air Stripping</u>		<u>Adsorption</u>		<u>Oxidation</u>		<u>Biological</u>	
	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>	<u>Yes</u>	<u>Possible</u>
Petroleum Components - 11	6	1	9	2	10	-	3	-
Flavor/Fragrances 2	-	2	1	2	1	-	1	-
Pharmaceuticals 19	2	1	-	11	3	-	1	-
Surfactants/PCP 3	-	-	-	1	-	-	1	-
Polymer/Plastic Manufacture – 8	3	-	3	2	3	1	1	-
Industrial Chemicals - 19	2	1	6	6	6	-	4	1
Phthalates – 5	-	-	1	4	4	-	-	-
PAHs – 12	-	-	-	12	7	3	1	-
Pesticides/ Herbicides - 5	-	1	2	1	4	-	2	-
Natural Compounds-2	-	-	-	-	-	-	1	-
Unknown- 38	2	7	9	19	6	-	2	-
TOTALS - 124	15	13	31	56	44	4	17	1

CHAPTER 4 - APPLICABLE TECHNOLOGIES FOR NJ

INTRODUCTION

A variety of treatment techniques were reviewed and evaluated in the previous chapter for removing the UOCs that have been detected in NJ ground water supplies. As indicated in Chapter 3, the techniques that appear to be applicable to NJ ground waters based on available information are:

- Activated carbon adsorption
- Air stripping
- Oxidation and advanced oxidation

Applicable technologies are those technologies that have been demonstrated to remove the UOCs detected in NJ ground waters, or are expected to remove them based on their characteristics. Each of these treatment techniques is discussed in more detail in the following sections of this chapter with respect to general description, process description, and operational/regulatory considerations. In addition, capital and operating cost estimates for a 1.0 mgd system are presented for each technology.

ACTIVATED CARBON ADSORPTION

General

Adsorption of synthetic organic chemicals from water using granular activated carbon is recognized as the best available technology for removal of many regulated organic contaminants. Early studies by the water industry looked at removal of disinfection by-products and removal of naturally occurring taste and odor compounds (Environmental Engineering, 2003). Research expanded to include removal of pesticides and herbicides and a number of synthetic industrial chemicals by activated carbon. It is expected that many of the tentatively identified compounds found by NJDEP in the NJ ground waters will be amenable to activated carbon adsorption. Of the ground water systems included in the NJDEP survey, there were nine granular activated carbon (GAC) facilities in operation to remove organic chemicals.

Process Description

Contaminated water is passed through a bed of GAC in much the same way that settled water is introduced to sand or multimedia filter beds for final polishing. The adsorbable organic compounds transfer from the bulk water to the surfaces of the activated carbon. The key process design parameters for a GAC system include:

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

Each of these parameters is discussed in the following paragraphs.

Empty Bed Contact Time (EBCT) – The adsorption of dissolved compounds from the water phase to the solid granular activated carbon 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. Researchers have found that a minimum EBCT of 7.5 minutes is needed to achieve any appreciable organic chemical removal. Typically, EBCTs of 10 to 20 minutes have been used in full-scale GAC designs. Because of the uncertainty of the adsorbability of many of the organic chemicals found in NJ ground waters, a total EBCT of 20 minutes at the design flow of 1 mgd has been selected for the purpose of this study. This contact time would be accomplished using contactors in series for reasons that are outlined in the contactor configuration below.

Contactor Configuration – Contactors can be configured in a variety of ways for different applications. Upflow contactors have been used more often in wastewater applications where there is the potential to blind the GAC with suspended solids while downflow systems, which are easier to operate, are most often used for drinking water. Downflow contactors can be further categorized into gravity flow contactors and pressure contactors. Most ground water systems use pressure contactor vessels to maintain hydraulic grade if possible.

If there is only one contaminant to be removed, parallel contactors may be used for adsorption. It is the simplest adsorption process to operate. However, with complex mixtures of contaminants, placing contactors in series provides the greatest safety and longest contact between the water and GAC. The contactors are used in a lead/lag mode of operation. The first or lead contactor removes the more adsorbable contaminants. The water then passes to a second or lag contactor where adsorption of the remaining contaminants can take place. When the lead bed is exhausted, it is taken out of service and the GAC regenerated or replaced. The lag contactor then becomes the lead contactor. Given that more than half of the 21 wells tested by NJDEP had more than one tentatively identified contaminant, the preferred contactor configuration would be downflow GAC beds in series. Pressure vessels would be used to maintain the hydraulic grade of the well system.

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 relatively conservative hydraulic loading rate of about 5 gpm/ft² (maximum) was selected for the design basis and for determining estimated costs that are presented later in this section.

Pretreatment - Some ground water systems have undesirable levels of suspended solids or turbidity that can blind the pores of the activated carbon and create premature headloss. These ground waters would benefit from particle removal pretreatment to extend the life of the carbon contactors. The carbon contactors should also have backwash capability to reduce headloss and keep the activated carbon clean during operation. As a minimum, the carbon must be backwashed after initial installation to remove the carbon fines. Backwash capability is included in the estimated costs for the activated carbon adsorption contactors.

Some wells have iron and/or manganese at levels that would interfere with adsorption and create objectionable discolored water in the distribution system. Iron and/or manganese removal prior to GAC will improve contactor performance and extend the life of the activated carbon for these sources. The cost of iron/manganese removal is not included in the estimated costs as it probably would be necessary even if GAC were in place or not; although in some cases iron and/or manganese control may not be needed unless GAC is in use.

Wells that have volatile organic contaminants will benefit from the application of air stripping ahead of the GAC contactors. Air stripping would lessen the organic loading to the GAC contactors and extend the carbon life by removing contaminants that can volatilize as well as adsorb. Five of the treatment systems in the NJDEP survey include packed tower air stripping ahead of GAC. Such combined treatments are discussed further under Combined Treatments for UOC removal.

GAC Regeneration – Over time, the available sites on the carbon become filled with adsorbents resulting in breakthrough 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. For the purpose of this study, off-site GAC regeneration is assumed. On-site regeneration would not be cost effective for the typical ground waters systems in NJ.

Operational/Regulatory Considerations

The installation of GAC at a typical ground water supply in NJ should be a relatively uncomplicated design and operation. However, there are two operational and regulatory issues that must be considered:

- 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.

The concentrations of tentatively identified chemicals from the wells were typically quite low – microgram to nanogram per liter levels – in the sampling conducted by NJDEP. The variability in well water concentrations of these UOCs has not been established but would affect the carbon usage rate of the carbon. If levels remain low, the life of the carbon should be quite long, particularly if some of the compounds are biologically degraded once they are adsorbed to the activated carbon. If concentrations vary, carbon life will be shorter and some of the less sorbable compounds may be driven back into the water, displaced by higher levels of more adsorbable organics.

For the reasons stated above, it is very difficult to accurately estimate the carbon usage rate for any given ground water supply in NJ. Based on the very low levels of UOCs in NJ ground waters and the limited information on treatability, it would appear that the carbon should last from 6-12 months before it must be replaced. Bench scale tests could be conducted rather easily and quickly as part of a preliminary design to more accurately determine the carbon usage rate and life.

Activated carbon can support microbial growth by fixing biodegradable organic compounds on surfaces accessible to the bacteria and by reducing disinfectants such as chlorine. The microbial growth removes some of the adsorbed organic matter, potentially extending the life of the activated carbon. The treated water must be disinfected after activated carbon contact to kill bacteria in the water.

Spent Carbon Disposal - In all GAC installations treating NJ ground 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.

Estimated Costs

Capital and operating cost estimates were developed for the installation of GAC contactors to remove the organic chemicals that have been detected in NJ ground waters. The equipment and facility assumptions that were used to generate these costs and the costs are presented in the following subsections.

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.
- Restaging the Well Pump(s): Additional head will be introduced with the installation of the GAC contactors and the well pump will need to be restaged or replaced 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 - 20 minutes at the design flow
- Contactor configuration - two pressure, downflow contactors in series, each with a 10 minute EBCT
- Liquid loading rate - 5 gpm/sf
- Backwash - taken from finished water
- Regeneration - off-site
- Pretreatment - none

Costs - Capital and operating costs were developed for a 1.0 mgd system, the approximate size of a demonstration facility that is being considered by NJDEP. Based on the facility and design assumptions presented above, it is estimated that the capital cost would be about \$0.8 to 1.2 million, including all facility costs and engineering.

Operating costs will include:

- Carbon replacement
- Labor
- Power
- Maintenance

The majority of the operating cost will be for replacement of the carbon. Considering the number and variety of organic chemicals that may be in a given ground water 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. On this basis, the annual operating cost is estimated to range from \$50,000 to \$100,000.

AIR STRIPPING

General

Air stripping has been used for over 20 years to remove volatile organic chemicals (VOCS) from ground water supplies in NJ. Of the 55 well facilities that were sampled as part of the NJDEP TIC study, 43 employed some type of aeration process – air stripping, diffused aeration, or tray aeration. Of these, 28 are packed towers. All of the aeration facilities were installed to remove VOCs such as trichloroethylene (TCE) and tetrachloroethylene (PCE). Some of the facilities were designed to remove semi-volatile organic chemicals such as methyl tertiary butyl ether (MTBE). 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 UOCs that are addressed as part of this study. Packed air stripping could be used alone or in combination with another technology depending on the levels of UOCs in the water and the desired finished water concentration.

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 packed 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 four 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/semi-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 90-95 percent removal. For more difficult to strip compounds like MTBE, packing depths of 30-40 feet have been used to achieve high removal efficiencies (McKinnon, 1982). The volatile compounds that have been detected in NJ ground waters 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 35 feet has been selected and has been used for determining estimated 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, to

a point. Pilot tests have demonstrated that the packing depth has a greater influence on removal efficiency than air:water ratio. 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 90-95 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 NJ ground waters 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 150:1 has been selected and has been used for determining estimated 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. The most common type of packing material is a plastic, ribbed, spherical-shaped medium, one to two inches in diameter.

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 90-95 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 (McKinnon, 1982). The volatile compounds that have been detected in NJ ground waters 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 estimated costs that are presented later in this section.

Pretreatment - Treatment of the water prior to a packed tower may be needed to remove any particulate or dissolved material that may clog the packing material. For high turbidity waters, at least filtration may be needed to remove particles that could clog the packing. Waters with high hardness, iron, or manganese levels may need to be pretreated as the oxidation of calcium, iron, or manganese can occur in the tower and consequently clog the packing. For NJ ground waters, the hardness does not appear to be sufficiently high to require pretreatment based on the experiences of

packed towers in the state. However, it may be necessary for some systems to include a pretreatment step, like oxidation/filtration to remove iron or manganese. For purposes of this study, we have not included costs for pretreatment.

Operational/Regulatory Considerations

The installation of packed tower air stripping at a typical ground water well in NJ involves the consideration of several operational and regulatory issues including:

- Repumping
- Corrosion Control
- Disinfection
- Air Discharge

Repumping - A typical ground water 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 pump 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 NJ and across the country has indicated that the increase in pH due to a decrease in carbon dioxide is often greater than the decrease in pH due to the increase in dissolved

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 Ground Water 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 NJ 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 NJ 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 diluting 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.

Estimated Costs

Capital and operating cost estimates were developed for the installation of a packed tower facility to remove the volatile and semi-volatile organic chemicals that have been detected in NJ ground waters. The equipment and facility assumptions that were used to generate these costs and the costs are presented in the following subsections.

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 used most often and 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 it 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 - 35 feet
- Air:Water ratio - 150:1
- 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.

Costs - Capital and operating costs were developed for a 1.0 mgd system, the approximate size of a demonstration facility that is being considered by NJDEP. Based on the facility and design assumptions presented above, it is estimated that the capital cost would range from \$350,000 to \$450,000, including all facility costs and engineering.

Operating costs will include:

- Labor
- Power
- Maintenance

The majority of the cost will be for power. The annual operating cost could range from \$25,000 to \$50,000.

OXIDATION PROCESSES

General

Advanced oxidation processes have less history in water treatment than adsorption or air stripping. Ozonation is well known as a disinfectant and a means to reduce taste and odor compounds, but when supplemented by the addition of hydrogen peroxide, can oxidize many organic chemicals. Ultraviolet (UV) light at high irradiance levels supplemented by hydrogen peroxide addition has also been proven able to oxidize organic contaminants. These processes have not been explored to the full extent of their potential capabilities, but look very promising for removal of organic compounds.

Process Description

Ozone and UV both have been demonstrated to achieve some (generally less than 50 %) removal of many of the type of UOCs that have been detected in NJ ground water supplies. In addition, both oxidation processes have been able to achieve higher removal efficiencies in many cases with the use of hydrogen peroxide. Both ozone and UV with the addition of hydrogen peroxide act to generate hydroxyl radicals that enhance the oxidative degradation of organic materials. The hydroxyl radicals are non-selective, though some compounds are oxidized more easily than others. Many compounds are partially oxidized to degradation products that could be as toxic or undesirable as their parent compound; very few react to carbon dioxide and water. Ultraviolet light energy can also be absorbed directly by some organics, depending on the output of the ultraviolet source, the absorbance characteristics of the water and the absorbance characteristics of the organic chemical.

The influent water quality has a direct impact on a system's efficiency to remove organic contaminants. Oxidation is a non-selective process. Therefore, other compounds in the water can react besides the contaminants of concern. This increases the oxidant demand, thus increasing costs. The other reactions may also prevent complete oxidation, resulting in by-products other than carbon dioxide and water. Examples of how water quality can affect the Advanced Oxidation Process (AOP) are the following:

- Alkalinity scavenges hydroxyl free radicals and may require pH reduction to minimize the scavenging effect.
- Nitrate absorbs UV light and is converted to nitrite, which exerts an oxidant demand.
- Turbidity (not generally a problem with groundwater) lowers transmittance of UV light.

Because of these water quality impacts, it is desirable to locate the UV process after iron and manganese removal and after particulate removal if the source has turbidity.

Ozone - There are a number of parameters that must be taken into account in the design of an ozone process including:

- Ozone demand of the water
- Ozone dosage
- Contact or reaction time
- Method of application
- Ozone source
- Hydrogen peroxide dosage (when used for advanced oxidation)

The ozone demand of the water itself must be taken into account during design. Natural organic material present in the raw water and measured as Total Organic Carbon (TOC) will scavenge ozone and must be compensated for when determining an ozone dose. Typically, ground waters in NJ, especially in northern NJ, exhibit very low TOC levels, and so there is a rather low ozone demand in the raw water. Other oxidizable species (As (III), reduced forms of iron, manganese, etc.) exert oxidant demand, especially if they are more easily oxidizable than the target organics. Bromide, if present in sufficient concentrations, can be converted to bromate (which has a Maximum Contaminant Level) by ozone.

Bench and pilot tests of ozonation to oxidize organic chemicals have indicated dosages of between 2 – 5 mg/L are required to achieve good removals. Contact time between the water and the ozone also is important for reaction of the ozone with the organic chemicals to occur. Contact times of 5 – 10 minutes have been used to achieve good removals of organic chemicals.

Although the application of ozone has not changed substantially in the past 7 years, the technology of the generation and application of ozonation has changed. In the past, ozone has been generated from air using drying, cooling and compressor equipment. Ozone system suppliers now are using high purity feed gases (such as liquid oxygen) and more efficient generators with advanced contacting systems to make ozonation a more affordable option. The application of ozone in a pipeline has become more convenient with the use of specially designed injectors (side-stream injectors), nozzles, and static mixers.

Because ozone alone has been found to remove only about 50% or less of the types of organic chemicals found in NJ ground waters, hydrogen peroxide has been used to generate hydroxyl radicals to achieve higher removal efficiencies. The hydrogen peroxide is added ahead of the ozone process, and a dosage of 5 to 10 mg/L has been shown to provide as high as 90% removal of some of the organic chemicals.

UV - The parameters that are important in the design of a UV process for organic chemical removal are:

- UV transmittance of the water
- Type of UV reactor (low pressure vs. medium pressure)
- UV dosage or intensity

For ultraviolet systems, the ultraviolet absorbance characteristics of the water are important – very clear water that transmits the ultraviolet light promotes better oxidation. For typical ground waters, the transmittance is very high – 90 to 95%.

Both medium and low pressure UV devices have been tested for organic chemical removal efficiency. The medium pressure units have exhibited slightly better removals compared to low pressure units.

UV intensities of 40 mJ/cm² to over 1,000 mJ/cm² have been tested for organic chemical removal. The lower intensity is typically used for microbial inactivation, but has been found to provide very low organic chemical removal - less than 30 % for many compounds. A dosage of several hundred mJ/cm² can improve removal efficiencies to about 50 %. To achieve high removal efficiencies such as 90 %, an intensity of 1,000 mJ/cm² and higher is required. The use of hydrogen peroxide has been shown to increase organic chemical removals using UV because of the generation of hydroxyl radicals. The application of 5 to 10 mg/L of hydrogen peroxide in conjunction with UV at an intensity of several hundred mJ/cm² can boost removals to 80 % and higher for some compounds.

Operational/Regulatory Considerations

Although ozone and UV are considered advanced treatment technologies, both are relatively easy to operate, especially at the lower flowrates that are typical of ground water supplies. The use of hydrogen peroxide does have some operational considerations. Hydrogen peroxide is a liquid chemical. It is generally used as an oxidizing agent, though can be a reducer in some reactions. Concentrated solutions can decompose spontaneously to form water and oxygen and release heat. Hydrogen peroxide vapor can detonate above 70°C (158 °F), so it is best to keep solutions cool. The typical hydrogen peroxide solution is provided at 35% and is compatible with stainless steel or polyethylene.

Estimated Costs

Capital and operating cost estimates were developed for the installation of an oxidation facility to remove organic chemicals that have been detected in NJ ground waters. The equipment and facility assumptions that were used to generate these costs and the costs are presented in the following subsections.

Equipment and Facility Assumptions - The equipment required for typical ozone and UV installations consists of the following:

Ozone

- **Contactors:** A stainless steel pipe would be used to provide the necessary contact time.
- **Injection System:** A side-stream injector would be used to apply the ozone to the water. Ozone would be added in a sidestream injection loop that will use an eductor to add the ozone, a small reaction vessel, and a gas separation column to remove the offgas prior to the sidestream being pumped back to the main flow in a pipeline contactor. An ozone destruct unit would be provided to destroy any ozone before it can enter the atmosphere.
- **Ozone Generation:** A liquid oxygen (LOX) system would be used to generate ozone.
- **Building:** A building will be needed to house the equipment listed above.
- **Piping:** Piping modifications will be needed to re-route the water to and from the ozone contactor.
- The well pump may have to be restaged to account for the additional headloss through the ozone contactor.
- For AOP, a hydrogen peroxide storage and feed system will be needed.

A filter would not be needed after ozone for ground water treatment because of the very low levels of organic material typically found in ground water supplies.

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

- **Ozone dosage:** 2-5 mg/L
- **Contact time:** 7 minutes
- **Hydrogen peroxide dosage:** 5-10 mg/L

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.

UV

- **Reactor:** A medium pressure UV device would be used.
- **Building:** A building will be needed to house the equipment listed above.
- **Piping:** Piping modifications will be needed to re-route the water to and from the UV reactor.

- The well pump may have to be restaged to account for the additional headloss through the UV reactor.
- For AOP, a hydrogen peroxide storage and feed system will be needed.

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

- UV transmittance: 95%
- UV intensity: 1,000 mJ/cm²
- No. of Reactors: 1
- Hydrogen peroxide dosage: 5-10 mg/L

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.

Costs - Capital and operating costs were developed for both an ozone system and a UV system, each 1.0 mgd, the approximate size of a demonstration facility that is being considered by NJDEP. Based on the facility and design assumptions presented above, it is estimated that the capital cost would range from \$500,000 to \$600,000 for an ozone system and from \$400,000 to \$500,000 for a UV system. Both cost ranges include the cost for a hydrogen peroxide storage and feed system and all facility costs and engineering.

Operating costs for either system will include:

- Labor
- Power
- LOX (for ozone only)
- Hydrogen peroxide
- Maintenance

Power will be a major part of the operating cost, especially for the UV system. The annual operating cost could range from \$25,000 to \$50,000 for either the ozone or UV system.

COMBINATIONS OF PROCESSES AND SUMMARY

The treatment processes described above can be used alone or in combinations. The use of air stripping alone might not be adequate depending on the types of organic chemicals found in the ground water supply. If only volatile and semi-volatile compounds are present in the supply, air stripping would be adequate to achieve high removals. If non-volatile compounds are present, GAC, ozonation, or UV might be used. Because most of the well sites that were sampled in the NJDEP survey included a mixture of volatile and non-volatile compounds, the use of GAC would be the most appropriate technology.

One of the key considerations in the application and operation of a GAC system is the frequency at which the carbon must be replaced. It is very difficult to estimate with any certainty what the carbon replacement frequency will be if GAC were installed at any one of the ground water supplies in NJ because of the variety and number of UOCs that may be in the water. A carbon replacement frequency of once every month or even up to once every three months could be cost prohibitive, as it would be \$20-30,000 per carbon change. To reduce the cost for carbon replacement, which represents the majority of the operating cost for a GAC system, one would consider using air stripping, ozone, or UV ahead of the GAC to reduce the organic load on the carbon. The following process combinations might be used:

- Air Stripping and GAC - air stripping would be used to remove the volatile and semi-volatile compounds, thereby reducing the load on the carbon to only the non-volatile compounds.
- Air Stripping and Ozone or UV - air stripping would be used to remove the volatile and semi-volatile compounds, and ozone or UV would be used to remove the non-volatile compounds.
- Ozone or UV and GAC - ozone or UV would be used ahead of the GAC to oxidize some of the organic compounds, thereby reducing the load on the carbon. Because complete removal would not be needed through the ozone or UV systems, both systems could be designed for lower removal efficiencies. For example, ozone might be designed for a lower dosage (1-2 mg/L) and a smaller contact time (2-5 minutes). This would reduce the size of the ozone contactor and the generator. For UV, a lower UV intensity might be used - 100-300 mJ/cm². For either ozone or UV, AOP might not be needed so a hydrogen peroxide system would not be included.
- Air Stripping plus Oxidation and GAC - this process combination might be used only for wells with a large number of UOCs at relatively high concentrations. Air stripping would

be use to remove the volatile and semi-volatile compounds. Oxidation using either ozone or UV would be used to reduce the number and levels of remaining UOCs before the water is treated with GAC. This would reduce the loading on the GAC and extend the time for carbon replacement.

It should be noted that with the use of either ozone or UV, the use of GAC following either of these processes might be considered to remove any by-products that might be formed by the incomplete oxidation of the UOCs in the raw water. The use of GAC would remove any by-products that could be more undesirable than the original UOCs.

Another concept that is worth considering is the potential for biological growth to occur on the GAC and the resultant organic chemical removal through bio-degradation. The point of chlorine application must be moved to after the GAC in any process combination because GAC will adsorb the chlorine, thus using adsorption sites and reducing the capacity of the carbon for adsorbing organic compounds. Moving the chlorination point will allow for the growth of microorganisms on the GAC that could use the organic chemicals as a food supply. This phenomenon could help to extend the life of the carbon and provide additional organics removal.

SUMMARY OF APPLICABLE TREATMENT TECHNIQUES

The applicable treatment techniques and their estimated costs are summarized below:

<u>Technique</u>	<u>Capital Cost</u>	<u>Annual Operating Cost</u>
GAC	\$800,000 - \$1,200,000	\$50,000 - \$100,000
Air Stripping	\$350,000 - \$450,000	\$25,000 - \$50,000
Ozone/Hydrogen Peroxide	\$500,000 - \$600,000	\$25,000 - \$50,000
UV/Hydrogen Peroxide	\$400,000 - \$500,000	\$25,000 - \$50,000

If ozone or UV were combined with GAC, the cost for either the ozone or the UV system would be reduced because the hydrogen peroxide storage and feed system would not necessarily be needed.

CHAPTER 5 - SUMMARY OF FINDINGS AND CONCLUSIONS

BACKGROUND

Numerous organic chemicals are used every day in NJ for industrial, commercial and household purposes. A number of these chemicals have been found in the State's wastewater treatment facility discharges and in aquifers and wells that are used for drinking water supplies. The various types of organic chemicals that have been detected include:

- Pesticides
- Volatile organic chemicals (VOCs)
- Endocrine-disrupting compounds (EDCs)
- Pharmaceuticals and personal care products (PPCPs)
- Petroleum-related compounds
- Other industrial organic chemicals

Also, some naturally-occurring organic chemicals have been detected.

The fact that UOCs are being detected in drinking water supplies and that there is a concern regarding their health effects raises a fundamental question – what are the best available treatment technologies for removing these organic chemicals from drinking water supplies? And more specific to NJ, which technologies are most applicable to the State's ground water systems, and to what level should these compounds be removed? As answers to these questions are developed, it should be noted that the ability to detect these compounds is simply a function of the analytical method, and that removal efficiency is, in reality, a reflection of the detection limits. Verification of complete removal of the compounds is not possible; one can simply document that concentrations are below the detection limits of the current analytical methods.

The New Jersey Department of Environmental Protection (NJDEP), in conjunction with the Drinking Water Quality Institute (DWQI), is considering potential options for addressing these contaminants in NJ ground waters, and is seeking information on the effectiveness of various treatment technologies to assist in their evaluations. This report reviews and summarizes existing information on the effectiveness of various treatment technologies for removing organic chemicals

and identifies the best available technologies for removing these chemicals found in NJ ground water supplies.

In 1997, the NJDEP's Division of Science, Research and Technology began a multi-year project funded through the NJ A-280 Safe Drinking Water Research Fund to assess the occurrence of organic chemicals in NJ's ground water supplies. More specifically, this project investigated the occurrence of Tentatively Identified Compounds (TICs) in water samples collected from NJ ground water systems. Twenty one (21) water systems from around the state were sampled in this study over a four year period. With one exception, each of the water systems used ground water as their source of supply. Also, most of the systems had treatment (air stripping and/or granular activated carbon) in place for organics removal.

Some 600 TICs were detected in the NJDEP project – in either a blank, a raw water sample, or a finished water sample. Of these TICs, 338 were detected in raw water samples and not in the blanks, leading to the presumption that the TICs were actually present in the water supply and were not a sampling or analytical artifact. Of these 338, 266 were detected only in raw water samples, and not in finished water samples or any other category of sample. Semi-volatile compounds were present in the raw water samples, as these samples also contained the highest numbers of VOCs of the groups. The most frequently detected TICs in raw water samples included: bromacil, 1-eicosanol, a naphthalene derivative and a benzene derivative.

FINDINGS

Based on the NJDEP survey, the total list of organic chemicals was broken down into 3 major classes of compounds:

- Aliphatics
- Cyclics which are defined as saturated ring compounds without aromatic characteristics
- Aromatics which are ring compounds that are unsaturated, and thus more reactive than cyclic compounds

Within each class, the organic chemicals were further broken down into several categories as follows:

- Petroleum Components
- Flavoring agents/Fragrances
- Pharmaceuticals
- Surfactants/Personal Care Products
- Lubricants/Emulsifiers
- Polymers/Plastics
- Phthalates
- Polycyclic Aromatic Hydrocarbons (PAHs)
- Pesticides/Herbicides
- Other Consumer Products not directly used as personal care products
- Other Industrial Chemicals – compounds that are manufacturing intermediates for a variety of end products but do not fit into the other categories; for example, corrosion inhibitors for metals
- Natural Compounds
- Unknown Compounds

Various treatment techniques have been evaluated, tested, and applied to remove organic chemicals from ground water supplies. These techniques generally may be categorized as follows:

- Adsorption processes
- Oxidation processes
- Air stripping processes
- Membrane processes
- Biological processes

For some of the more frequently occurring chemicals, bench, pilot and even full-scale data are available to determine the efficiency of certain treatment techniques. However, for the vast majority of the organic chemicals that have been detected in NJ ground waters, no treatability data are available, and estimates of removal efficiencies were made based on previous research with organic chemicals exhibiting similar chemical characteristics or in similar classes or categories.

CONCLUSIONS

Based on a review of the available treatment technologies, the potential for removal of the 234 UOCs may be summarized as follows:

	<u>Cyclics</u>	<u>Aliphatics</u>	<u>Aromatics</u>	<u>Totals</u>
Oxidation	1	4	48	53
Adsorption	28	49	87	164
Air Stripping	13	13	28	54
Biological Treatment	2	18	17	37

From the above information, the available treatment techniques were divided into the following general categories of applicability to NJ ground waters:

Most Applicable Technologies - Adsorption with GAC and AOP

Other Applicable Technologies - Oxidation and Air Stripping

Additional Technologies - Biological Treatment and Membranes

The estimated capital cost for these techniques is estimated to range from \$350,000 for an air stripping system to \$1.2 million for a GAC system. Annual operating costs are estimated to range from \$25,000 for air stripping, ozone, or UV to as much as \$100,000 for GAC. These costs must be refined based on the design information that is obtained through the demonstration project.

It should be noted that based on the various studies that have been completed to date on the fate of organic chemicals in water treatment processes, no one treatment technique can remove all of the organic chemicals that have been detected in NJ ground waters. In addition, it is unlikely that all of the organic chemicals could be removed to below detection levels from a given location even using a combination of processes. Third, by-products of oxidation and biological activity are likely to be generated creating other organic chemicals while the original organic chemicals in the ground water are removed to a certain extent.

Although GAC may be the most applicable technology, both air stripping and oxidation might be used ahead of the GAC to reduce the frequency at which the carbon must be replaced. Also, there

may be incidental biological treatment on the GAC because of natural microbial growth on the carbon.

FURTHER RESEARCH

The variety and number of UOCs that have been found in NJ ground waters makes it difficult to establish process design criteria for any of the applicable processes with any degree of certainty. The vast majority of the organic chemicals have not been tested for treatability. Therefore, additional testing is needed to determine the removal efficiencies of the applicable technologies and to develop more certain design criteria.

It is understood that NJDEP plans to conduct demonstration testing at ground water facilities in NJ. It is recommended that GAC be tested because it appears to be the most applicable technology. In addition to testing GAC, it is recommended that the other technologies be tested, even if at a lower flowrate. For example, side streams of the main treatment train could be treated to evaluate oxidation and advanced oxidation processes. Also, the GAC could be preceded by an existing air stripping process. Testing of the various applicable processes will provide valuable information regarding:

- The amount of organic chemicals that can be removed by air stripping which represents the least expensive process.
- The effectiveness of GAC alone to remove organic chemicals and the projected life of the carbon.
- The effect of air stripping on the life of the carbon.
- The effectiveness of both ozone and UV to remove organic chemicals.
- The need for advanced oxidation using hydrogen peroxide in conjunction with either ozone or UV.
- The effect of using either ozone or UV ahead of GAC to reduce the organic load onto the GAC and to prolong the life of the carbon.

This information will not only provide more accurate data for the applicability and design of these processes, but will provide for more accurate cost estimates for these processes.

POTENTIAL FUNDING

NJDEP plans to fund the demonstration testing of the applicable processes. In addition to state funds, NJDEP might consider obtaining funds from:

- USEPA research group in Cincinnati
- AwwaRF tailored collaboration program

It is believed that both of these organizations would be interested in participating in the demonstration project by contributing towards the cost.

APPENDIX A
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APPENDIX B

**LIST OF ORGANIC CHEMICALS
FOUND IN NJ GROUND WATERS**

Table B-1
Aliphatics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
2,3-dimethyl 1-hexene	16746-89-4	Alkene	112	Petroleum component
2,3,4 trimethyl hexane	921-47-1	Alkane	128	Petroleum component
3 methylene undecane		Alkene	168	Kerosene component, diesel fuel
3 methylene tridecane		Alkene	209	Paraffin, jet fuel, paper manufacture
2,3 dimethyl 2 pentanol		Alcohol	116	Fusel oil
1 dodecanol	112-53-8	Alcohol	186	Fragrance for detergents
3,5,5 trimethyl hexanoic acid	3302-10-1	fatty acid	158	Intermediate for flavors, cosmetics, dyes, etc
Hexanoic acid heptyl ester	6976-72-3	Fatty acid ester	214	Naturally occurring pheromone used in flavors
5 methoxy 4 phenylthio pent-4-en-3-one		Alkene		Fragrance compound
verticiol		Alcohol		Essential plant oil
1 tridecanol	112-70-9	Alcohol	200	Lubricants, detergents, HVC*
1 nonadecanol	1454-84-8	Alcohol	284	surfactant
1 eicosanol	629-96-9	Alcohol	298	Skin creams, cosmetics
Hexadecanoic acid	57-10-3	Fatty acid	256	Surfactant, naturally occurring
Octadecanoic acid	57-11-4	Fatty acid	284	Surfactant, naturally occurring
2 methoxy 5 hexadecanoic acid, methyl ester		Fatty acid ester	284	Lipid, naturally occurring
Tetradecanoic acid	544-63-8	Fatty acid	228	Surfactant, naturally occurring
Acetic acid, octadecyl ester	822-23-1	Fatty acid ester	312	Personal care products
Octadecanoic acid, butyl ester	123-95-5	Fatty acid ester	340	Surfactant, emulsifier for foods, paints, inks
Hexadecanoic acid, octadecyl ester	2598-99-4	Fatty acid ester	509	Derivative of palm oil in personal care products
2 buyoxyethanol phosphate 3:1	78-51-3	Phosphate ester	398	Cleaning agents, HVC*
N,N bis (2 hydroxyethyl) dodecanamide	120-40-1	Amide	287	Surfactant, used in cosmetics, personal care products, food wrap
N (2 hydroxyethyl) dodecanamide		Amide	242	Surfactant, used in cosmetics
1,9 nonanediol	3937-56-2	Alcohol	160	Pharmaceutical and polymers
O decylhydroxylamine	29812-79-1	Amine	172	Antihistamine, antioxidant

Table B-1 (continued)
Aliphatics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
N' phenyl N,N dipropyl thiourea		Aromatic alkane	236	Manufacture of pharmaceuticals
13 bromo-tetradecanoic acid		Halogenated fatty acid	307	Antifungal, intermediate in pharmaceuticals
5 octadecene (E)	7206-33-9	Alkene	252	Solvent for computer chips
1,1' oxybis decane	2456-28-2	Ether	298	Lubricant for plastic manufacture
9,12 octadecadienoic acid (Z,Z)	60-33-3	Fatty acid	280	Naturally occurring pheromone, used in paints, HVC*
9 octadecenamide	301-02-0	Alkene amide	281	Lubricant in plastics, paper and textiles
Selenocyanic acid, phenyl ester		Ester w/ selenium	254	Photographic emulsions
N,N dimethyl 9 octadecenamide	2664-42-8	Alkene amide	311	Printing inks and paints
Octadecanoic acid, hexadecyl ester	540-10-3	Fatty acid ester	481	Emulsifier for textiles, paints, inks, foods
Nonanoic acid	112-05-0	Fatty acid	158	Plasticizer, fungicide
10 undecen-1-ol	112-43-6	Alcohol	170	Manufacture of polymers
1,10 decanediol, bis (trimethylsilyl) ether	112-47-0	Alcohol	174	Polymer manufacture, TMS lab artifact
4 methyl pentadecane	2801-87-8	Alkane	226	Manufacture of plastic films
Propanedioic acid, dibutyl ester		Acid ester	227	Plasticizer, solvent carrier
3 (4 methoxyphenyl) 2 ethylhexyl ester 2 propenoic acid		Acid ester	290	Manufacture of acrylics, polymers, paints, dispersants, cleaners
Octadecanoic acid, 2 methylpropyl ester	646-13-9	Fatty acid ester	338	PVC manufacture, HVC*
Dodecanedioic acid, dimethyl ester	1731-79-9	Fatty acid ester	308	Polyamide production, adhesives and coatings
Boric acid, trihexyl ester	5337-36-0	Borate ester	314	Polycarbonate manufacture
dichlovos	62-73-7	Halogenated phosphate	221	Organophosphate pesticide
Ethanedioic acid, bis (trimethylsilyl) ester		Acid ester	136	Naturally occurring acid used in pesticides, ester likely artifact

Table B-1 (continued)
Aliphatics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
1,2 dibromobutane	533-98-2	Halogenated alkane	216	pesticide
Ethyl pyrophosphate	107-49-3	phosphate	290	Insecticide, chlorinesterase inhibitor
Arsenous acid, tris (trimethylsilyl) ester	EDF-221	Organic arsenic		Wood treatment, agricultural chemicals, electronics
2,4 dimethyl 2,3 heptadien-5-yne		Alkene/alkyne	120	
oxyacetic acid, (trimethylsilyl)		Acid ester	125	
1 bromo 3 methylpentane	51116-73-5	Halogenated alkane	165	
N (4 methoxyphenyl) propamide		amide	183	
5 methyl 5 phenyl 2 hexanone		ketone	191	
2 undecanone, methyl oxime		ketone	199	
(Z) 6 pentadecen-1-ol		alcohol	226	
Dodecyl isopropyl ether		ether	228	
2,4 diphenyl 4 methyl 2 (Z) pentene		alkene	236	
3,3,7,7 tetramethyl 11 dodec-5-one		Keto-alkene	240	
Butyl 2 hydroxybutyl methyl phosphate		Alkyl phosphate	240	
3,5,5 trimethyl 1,2,3 propanetriyl hexanoic acid		Acid ester	250	
7 methyl 7 heptadecanol		alcohol	270	
3 amino 3 (4 methylphenyl) 1 phenyl 2 propen-1-one		Keto-alkene	279	
2,5,8,11,14,17 hexaoxaoctadecane	1191-87-3	Ester		
1,2 dibromododecane		Halogenated alkane	328	
Butanediyl bis phosphonic acid, tetraethyl ester	7203-67-0	Phosphate ester	330	
2,2,13,13 tetramethyl 3,12 dioxa 2,13 disila-tetradecane		Alkane w/silica	342	

Table B-1 (continued)
Aliphatics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
Perflouro- 1-heptene		Halogenated alkene	350	
Octadecanoic acid, octadecyl ester	2778-96-3	Acid ester	536	
Octadecanoic acid, eicosyl ester		Acid ester	564	
Triethyl (S) 2 carboxymethoxymethyl oxydiacetate				

*** High Volume Chemical**

Table B-2
Cyclics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
1,2,4 trimethyl cyclopentane	2613-72-1	alkane	114	Gasoline component
1,1,3,3 tetramethyl cyclopentane	50876-33-0	alkane	126	Gasoline component
cyclodecane	293-96-9	alkane	140	Gasoline component
1 hexyl 3 methyl cyclopentane		alkane	168	Gasoline component
1,1'(1,2-dimethyl-1,2-ethanediyl)bis-cyclohexane	54889-87-1	alkane	222	
1,7,11 trimethyl-4-(1-methylethyl) cyclotetradecane		alkane	240	Incomplete combustion of plastics
2 thienyl methanol	636-72-6	alkene	114	Flavor and fragrance
2 methyl 3 methoxy cyclohex-2-enone		Keto-alkene	140	Fragrance compound
{1,1' bicyclopentyl}-1-ol		alcohol	145	Fragrance compound
4a-methyl trans-1(2H)-octahydronaphthalenone		ketone	167	Fragrance derivative
2 (3H) furanone, dihydro 5 octyl	2305-05-7	ester	198	Pheromone from cockroaches
1H-cycloprop[e]azulene, decahydro-1,1,7-trimethyl-4-methylene-, [1aR-1a		alkene		Fragrance derived from plants
5,7a-didehydroindicine petrimethylsilyl ether		Hetero-alkene	299	Pheromone, antitumor properties
2-propenal, 3-(2,2,6-trimethyl-7-oxabicyclo[4.1.0]hept-1-yl)		alkene		Flavoring agent
azulene, 1,2,3,4,5,6,7,8-octahydro-1,4-dimethyl-7-(1-methylethylidene)-		alkene		Extract of desert lavender
thiazolidine	504-78-9	Hetero-cyclic	89	Manufacture of pharmaceuticals, antibiotics
2-cyclohexylpiperidine		piperazine	167	Precursor to PCP
5-tert-butyl-4-phenyl-, cis-2 oxazolidinone		ketone	219	antibiotic
mepivacaine	22801-44-1	amide	282	anaesthetic
3,4-dimethyl-2,5-diphenyl 1,3,2-oxazaborolidine		Hetero-cyclic		catalyst for organic reactions, pharmaceutical base

Table B-2 (continued)
Cyclics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
prometon	1610-18-0	cyclic amine	225	broad spectrum herbicide, Kh 2.3x10 ⁻⁶ mm Hg
1,6-dichloro 1,5-cyclooctadiene		Halogenated alkene	178	Flame retardant
methyl 2,5-di-O-methyl a-D-xylofuranoside		Cyclo-alcohol	178	may be naturally occurring derivative of xylose
2,3,4,4a,5,6,7,8-octahydro-1H-benzocyclohepten-7-ol		cyclic alcohol	199	naturally occurring in red cedar
a-methyl-a-vinyl 2-furanacetaldehyde		Alkene ester	150	
3-methyl-2-(2-oxopropyl)furan		Alkene ester	153	
cyclodecanol	1502-05-2	alcohol	156	
3-(1,1-dimethylpropyl) dihydro-2,5-furandione		Hetero-cyclic ketone	168	
6-butylhexan-6-olide		ester	171	
1-carboxylic acid, 2,6,6-trimethyl 1,3-cyclohexadiene-, ethyl ester		Alkene with acid	194	
1,2-diphenyl cyclopropanecarbonitrile		Aromatic alkyne	197	
cyclododecanemethanol	1892-12-2	Alcohol	198	
4-(1-phenylethyl)-bicyclo[3.2.1]octa-2,6-diene		alkene	211	
1-(phenylthioxomethyl)-2,5-pyrrolidinedione		Hetero-ketone	217	
2,4-diphenyl 1H-pyrrole		Hetero-alkene	219	
5-(4-methylphenyl)-3-phenyl 1,2,4 oxydiazole		heteroalkane	236	
1,3-dioxolane,4-ethyl-5-octyl-2,2-bis(trifluoromethyl)		Halogenated ether	246	
tetrahydro-2-(12pentadecyloxy)-2H-pyran		ether	315	
2-(12pentadecyloxy)-2H pyran		Keto-alkyne	319	
4-ethyl-5-octyl-2,2-bis(trifluoromethyl),trans 1,3 dioxolane		Halogenated alkane	348	

Table B-2 (continued)
Cyclics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
methyl 2-deoxy-3,4,6-tri-o- methyl-2-(N- methylacetamido) cyclohexyl		Hetero- alkane		

Table B-3
Aromatics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
p-xylene (1,4 dimethylbenzene)	106-46-3	Xylene	106	HVC*, solvent, gasoline component, MCGL 10 mg/L
o-xylene (1,2 dimethylbenzene)	95-47-6	Xylene	106	Gasoline component, manufacture of phthalic anhydrides
1,2,3-trimethylbenzene	526-73-8	Benzene	120	HVC*, gasoline component,
1,2,4-trimethylbenzene	95-63-6	Benzene	120	HVC*, gasoline component,
1,3,5-trimethylbenzene	108-67-8	Benzene	120	HVC*, gasoline component, solvent, Kh = .00518 atmm ³ /mol
1-ethyl-3-methyl benzene	620-14-4	Benzene	120	likely component of gasoline
2,5-bis (1,1 dimethylethyl) thiophene		Hetero-aromatic	196	component of petroleum products
2,5-bis(1,1-dimethylethyl)-phenol	5875-45-6	Alkyl-phenol	206	found in crude oils and fuel wastes
3,5-bis(1,1-dimethylethyl)-phenol	1138-52-9	Alkyl-phenol	206	found in crude oils and fuel wastes
2,6-bis(1,1-dimethylethyl)-4-ethyl phenol	4130-42-1	Alkyl-phenol	234	found in crude oils and fuel wastes
1,2,3,4,5,6,7,8-octahydrotriphenylene		fused aromatic	356	component of gasoline, fuel oil
4 methyl isothiazole		Hetero-aromatic	99	Manufacture of pharmaceuticals
1,2,3,4-tetrahydroisoquinoline		fused aromatic	133	intermediate in production of pharmaceuticals
benzothiazole	95-16-9	Hetero-aromatic	139	intermediate in production of dyes, pharmaceuticals
1,2 benzisothiazole	272-16-2	Hetero-aromatic	139	intermediate in the production of antibiotics, pharmaceuticals
N-propylbenzamide	010546-70-0	Amide	163	base for pharmaceuticals and fungicides
1,7-dihydro-1-methyl 6H-purine-6-thione	50-44-2	Hetero-aromatic	168	anticancer agent used to treat leukemia, nucleobase substitute
3-acetamide 1,2-benzisothiazole		Fused hetero-aromatic	178	intermediate in pharmaceuticals
(1,1-dimethylethyl)-2-methoxyphenol	121-00-6	Alkyl-phenol	180	manufacture of pharmaceuticals, plasticizers, stabilizes halogenated hydrocarbons
ampyrone (4 aminoantipyrine)	83-07-8	Cyclic w/ aromatic	203	painkiller, anticonvulsant, manufacture of dyes

Table B-3 (continued)
Aromatics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
4-methyl-2-phenyl pyrrolo[2,3-b]pyridine		Hetero-aromatic	207	Anti-tumor agent
6,11-dihydrodibenz(b,e)loxi- n-11-one		Keto – hetero-aromatic	212	pharmaceutical, antibiotic
2-hydroxybenzoic acid, phenyl ester	118-55-8	acid	214	antiseptic and antipyretic
6-amino-4-oxo 4H-1-benzopyran-2-carboxylic acid, ethyl ester		Acid w/ amine	233	pharmaceutical - beta blocker, treats hypertension
Ergost-14-ene,(5.alpha.)-		Fused aromatic		steroid
2,4-dimethoxy- 917.beta estra-1,3,5(10)-triene- 3,17-diol	50-27-1	Fused aromatic	256	estrogen used for hormone replacement
trimetazidine	5011-34-7	piperazine	266	pharmaceutical, coronary vasodilator, anti-ischemic metabolite
nordextromethorphan	125-71-3	Fused aromatic	271	cough suppressant, acts on CNS
gitoxigenin	545-26-6	Fused alcohol	390	natural plant glycoside used for cardiac treatment (digoxin family)
2-isopropenyl-3,6-dimethylpyrazine		Hetero-aromatic		pharmaceuticals, perfumes, flavorings
2'-deoxyadenosine	958-09-8	Fused hetero-aromatic	269	naturally occurring adenine is a nucleobase, component of RNA
uracil,5-[(2-trifluoro-1-hydroxy)ethyl]-		Halogenated hetero-aromatic		uracil is a nucleobase
butylated hydroxyanisole (also) 3 tert butyl 4 hydroxyanisole	25013-16-5	ether	180	HVC, food preservative, antioxidant
4-(1,1-dimethylethyl)-2-methyl benzenethiol		thiol	180	base for fragrances
2H-2,4a-methanonaphthalene,1,3,4,5,6,7-hexahydro-1,1,5,5-tetramethyl	1135-66-6	fused aromatic		fragrance, used in cosmetics and PCP
2,4-dioctylphenol	1807-29-0	alkylphenol	318	suspected endocrine disruptor, surfactant

Table B-3 (continued)
Aromatics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
4-methylbenzenesulfonic acid, dodecyl ester	1886-81-3	Acid ester	341	surfactant
nonylphenyl ether	9016-45-9	ether	264	used in industrial and household cleaners, paints, hair color
N,N'-bis(2-chlorophenyl) urea		Halogenated N	170	phenylurea herbicide
atrazine	1912-24-9	triazine	215	triazine pesticide, HVC*, MCL 3 ug/L
bromacil	314-40-9	Hetero-aromatic	261	herbicide, soluble, DW Health advisory 90 ug/l
metolachlor	51218-45-2	Halogenated amine	284	chloroacetanilide type herbicide, slow to degrade in soil and water
chlordane	57-74-9	halogenated aromatic	410	very persistent organochlorine pesticide banned in 1988
N butyl benzenesulfonamide	3622-84-2	amide	213	HVC*, polymer manufacture, plasticizer, neurotoxic
1,1'-biphenyl,2,2'-diethyl				used in food packaging
3 methyl 2,5-(3H,5H) furandione	616-02-4		112	used for resin and polymer production, hydrolyzes and oxidizes
1-isocyanato-2-methylbenzene	614-68-6	isocyanate	134	foam insulation, coatings and sealants, autobody work
1-isocyanato-4-methylbenzene	622-58-2	isocyanate	134	high volume chemical, foam insulation, coatings and sealants, autobody work
2(3H)-benzothiazolone		Aromatic w/ hetero-cyclic	151	rubber component, derivatives used for pharmaceuticals and pesticides
1,1-dimethylnonylbenzene	55191-25-8	alkane	232	partly volatile, found in PVC and vinyl chlorides
nitromethylbenzene	88-72-2 or 99-08-1 or 99-99-0	toluene	138	intermediate in chemical reactions, 3 forms (o,p or m)
1-naphthalenamine	134-32-7	amine	143	used in dyes, rodent poisons, printing

Table B-3 (continued)
Aromatics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
5 chloro 1H-benzotriazole	94-97-3	Hetero-aromatic	154	anticorrosive agent used on metals in chip making, polymer additive
diphenyl ether	101-84-8	ether	170	plasticizers, base for polybrominated diphenyl ethers, flame retardants for plastics
2-dimethylbenzyl-6-t-butylphenol		alkylphenol		used in plastic and rubber manufacture, endocrine disruptor similar to Bisphenol A
2-mercaptobenzothiazole	149-30-4	Hetero-aromatic	172	HVC*, corrosion inhibitor, metal working, plastics and rubber, pesticides
4-chloro-2-methyl-6-nitroaniline	62790-50-5	Halogenated hetero-aromatic	186	synthesis of dyes, antioxidants, pharmaceuticals, gasoline
2H-1-benzopyran-2-one,7-(dimethylamino)-4-methyl	99-41-1	coumarin amide	203	also known as 7 diethylamino? Optical brightener, textile and paper coatings
1-propyloctylbenzene		Alkyl-benzene	232	used as precursor for detergents and insulating oil for buried electrical cables
2-(phenylthio)-quinoline	22190-12-1	heteroaromatic w sulfur	237	base extracted from plants or coal tar, alkaloid solvent, dyes, paints
1,1,4,6,6-penta-methylheptyl benzene	55134-07-1	Alkyl-benzene	246	building materials
1-ethyldecylbenzene	2400-00-2	Alkyl-benzene	246	used as precursor for detergents and insulating oil for buried electrical cables
1-hexylheptyl benzene		Alkyl-benzene	260	used as precursor for detergents and insulating oil for buried electrical cables
1-propyldecyl benzene		Alkyl-benzene	260	used as precursor for detergents and insulating oil for buried electrical cables
1,1':3',1'':3'',1''':3''',1''''-quinquephenyl	3073-05-0	Linked benzenes	382	electronics manufacture

Table B-3 (continued)
Aromatics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
1,3,5-triphenyl-S-triazine-2,4,6(1H,3H,5H)-trione		amine	354	flame retardant residue
2,2',4,4'-tetramethyl diphenylsulphone		Hetero-aromatic	278	byproduct of benzene product manufacture
2,3-dihydro-3-benzofurancarboxylic acid		Acid w/cyclics		from coal oil, used for resins, paints, plastic films
4,7-dimethyl-1,10-phenanthroline		fused aromatic N rings		lab reagent
3 nitro 1,2-benzenedicarboxylic acid (phthalic acid)		phthalate	212	intermediate for polymers
dimethyl phthalate	131-11-3	aromatic ester, phthalate	194	high volume chemical, vapor pressure .00419 mmHg
bis (2-methoxyethyl)phthalate	117-82-8	phthalate	282	
didecyl phthalate	84-77-5		446	HVC*
di-n-octyl phthalate	117-84-0			HVC*1, synthetic resins and adhesives
2 naphthalenamide		PAH [#]		
phenanthrene	85-01-8	PAH [#]	178	incomplete combustion products, coal tar, used in dyes, explosives, pharmaceuticals, Vp 6.8x 10 ⁻⁴ mmHg
2-(1,1-dimethylethyl)1,2,3,4-tetrahydronaphthalene		PAH [#]	188	
phenanthrene, 7-ethenyl-1,2,3,4,4a,4b,5,6,7,8,8a,9-dode		PAH [#]		
1,2,5,6-tetramethylacenaphthylene		PAH [#]	208	somewhat volatile, coal tar, incomplete combustion products

Table B-3 (continued)
Aromatics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
tetradecahydro 4,5 dimethyl phenanthrene	56292-68-3	PAH [#]	220	Incomplete combustion
1,2,3,3a,4,5,6,10b-octahydrofluoranthene		PAH [#]		Incomplete combustion
triindenol[2,3:3',3'',2'',3'''] benzene	548-35-6	PAH [#]		Incomplete combustion
9,10 dihydro 9,9,10 trimethyl acridine		PAH [#]	223	coal tar, an intermediate, used in dyes, analytical
7a,8-dihydro-7a-methyl 7H-dibenzo[b,b]carbazole		PAH [#]		Incomplete combustion
7-hydroxy-7,8,9,10-tetramethyl-7-8-dihydrocyclohepta[d,e] naphthalene		PAH [#]		Incomplete combustion
2H-2,4a-methanonaphthalene		PAH [#]		Incomplete combustion
2 isopropenyl 3,6 dimethyl pyrazine		heteroaromatic w alkyne	146	
1 chloroethyl methylbenzene		halogenated	154	
1,4-dimethyl-2-(2-methylpropyl) benzene		benzene	162	
1,1-dimethylbutyl benzene	1985-57-5	benzene	162	
1,3-dichloro-2-isocyanatobenzene	39920-37-1	Halogenated isocyanate	188	
1,4 dichloro 2 isocyanatobenzene	102-36-3	Halogenated isocyanate	188	
1,2,3-trimethoxy-5-(2-propenyl) benzene	487-11-6	alkene	195	

Table B-3 (continued)
Aromatics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
1-methylnonyl benzene	4537-13-7	alkane	218	
1 methyldecyl benzene	4536-88-3	alkane	232	
1,3,5-tri-tert-butyl benzene	1460-02-2	alkane	246	
1,3,3-trimethylnonyl benzene		alkane	246	
1,1-dimethyldecyl benzene		alkane	246	non volatile, lighter than water, not very soluble
3-(2-cyano-2-phenyletheneyl) toluene		alkene w cyano	258	
1,3,5-trimethyl 2 octadecylbenzene		alkane	372	
1,1'(1,1,2,2-tetramethyl-1,2-ethanediyl)bis		alkane		
4-(2-aminopropyl) phenol		alkylphenol	151	
2-(1,1-dimethylethyl)-4-methylphenol		alkylphenol	164	
4-(2,2,4-trimethylpentyl) phenol		alkylphenol	206	
2,4,6-tris(1,1-dimethylethyl) phenol	732-26-3	alkylpheno	262	
4a,5,6,7,8.8a-hexahydro-7.alpha.-isopropyl-		cyclic	179	
2-methyl 1-indolizinecarboxylic acid ethyl ester		Acid ester	208	
1-(trifluoroacetyl) 2-piperidinecarboxylic acid, butyl ester		Acid ester	276	
4-(octyloxy) benzaldehyde	24038-13-4	ketone	234	
(5,6,7,8-tetrahydro-2-naphthalenyl)-phenyl methanone		ketone	236	
N-(1,1-dimethylethyl)-4-methyl benzamide		amide	191	
2-amino-3,5-dicyano-4,4-dimethyl-6-phenyl(4H)pyran		Coumarin w cyano	281	

Table B-3 (continued)
Aromatics Found in NJ Ground Waters

Compound	CAS#	Class	Mol. Weight	Information
2-(4-hydroxybenzoyl) benzoic acid		acid	242	
2,3-dihydro-4,5,7-trimethyl 1H-indene		Fused aromatic	166	
2,3-dihydro-1-methyl-3-phenyl 1 H indene		Fused aromatic	214	
4-methoxy 9H-xanthen-9-one		Fused aromatic	226	
(5,6,7,8-tetrahydro-2-naphthalenyl)-phenyl methanone		ketone	236	
1 ethyl-4-(2-chloroethyl)-1,2,3,4-tetrahydroquinoxaline		Halogenated fused aromatic	224	
4-(2-cyano-2-phenylethenyl) toluene		Toluene w cyano	224	
N-(4-hydroxyphenyl)-2-methyl benzamide		amide	227	
2,5-dibromo-pyridine		Halogenated	208	
thienol[(3,2-c]pyridine		Hetero-aromatic	140	
o-(4,6-diamino-s-triazin-2-yl) phenol		phenol		
2-phenyl-4,6-di(2-hydroxyphenyl)pyrimidine		Hetero-aromatic	340	

PAH# polynuclear aromatic hydrocarbon

*** High volume chemical**

APPENDIX C

**TREATABILITY OF ORGANIC CHEMICALS
FOUND IN NJ GROUND WATERS**

**Table C-1
Cyclics Found in NJ Ground Waters**

Compound	Treatments			
	Air Stripping	GAC	Oxidation	Biodegradation
Crude and Refined Petroleum Compounds				
1,2,4-trimethylcyclopentane	Yes	Yes	No	
1,1,3,3-tetramethyl cyclopentane	Yes	Yes	No	
Cyclodecane		Yes	No	
1-hexyl-3-methylcyclopentane		Yes?		
1,1'(1,2-dimethyl-1,2-ethanediyl)bis-cyclohexane	Maybe	Yes?	No	
1,7,11 trimethyl-4-(1-methylethyl) cyclotetradecane		Yes?		
Flavor/Fragrances				
(2-thienyl) methanol	Yes	No?		
2 methyl 3 methoxy cyclohex-2-enone	Yes	Yes?		
[1,1'-bicyclopentyl]-1-ol	Yes	Yes?		
4a-methy trans1(2H)-octahydronaphthalenone	Yes	No?	No	
2 (3H) furanone, dihydro 5 octyl (also known as gamma dodecalactone)	Maybe	No?		
1H-cycloprop[e]azulene,decahydro-1,1,7-trimethyl-4-methylene-,[1aR-1a		No?		
5,7a-didehydroindicine petrimethylsilyl ether		No?		
2-propenal,3-(2,2,6-trimethyl-7-oxabicyclo[4.1.0]hept-1-yl)	?	No?		
azulene,1,2,3,4,5,6,7,8-octahydro-1,4-dimethyl-7-(1-methylethylidene)-		No?		Yes
Pharmaceuticals				
Thiazolidine	?	No?	No	
2-cyclohexylpiperidine		Yes?		
5-tert-butyl-4-phenyl,cis-2 oxazolidinone		No?		
Mepivacaine	No	No?	Yes	
3,4-dimethyl-2,5-diphenyl 1,3,2-oxazaborolidine		No?		
Herbicide				
Prometon		Yes?		

Consumer Products				
1,6-dichloro 1,5-cyclooctadiene	Yes	Yes?		
Natural Compounds				
methyl 2,5-di-O-methyl a-D-xylofuranoside		No?		Yes
2,3,4,4a,5,6,7,8-octahydro-1 H-benzocyclohepten-7-ol		Yes?		
Unknown Uses				
a-methyl-a-vinyl 2-furanacetaldehyde		No?		
3-methyl-2(2-oxopropyl)furan	Yes	Yes?		
Cyclodecanol	Maybe	Yes	No	
3-(1,1-dimethylpropyl) dihydro-2,5-furandione	Maybe	No?	No	
6-butylhexan-6-olide	No	No?	No	
1-carboxylic acid, 2,6,6-trimethyl 1,3-cyclohexadiene-, ethyl ester		No?		
1,2-diphenyl cyclopropanecarbonitrile		Yes?		
Cyclododecanemethanol		Yes		
4-(1-phenylethyl)-bicyclo[3.2.1]octa-2,6-diene		Yes?		
1-(phenylthioxomethyl)-2,5-pyrrolidinedione		No?		
2,4-diphenyl 1H-pyrrole		Yes?	?	
5-(4-methylphenyl)-3-phenyl 1,2,4-oxdiazole				
5,9-dimethyl-2-(1-methylethyl)cyclodecane-1,4-dione		No?		
1,3-dioxolane,4-ethyl-5-octyl-2,2-bis(trifluoromethyl)		No?		
tetrahydro-2-(12pentadecynyloxy)-2H-pyran		No?		
2-(12pentadecynyloxy)-2H pyran				
4-ethyl-5-octyl-2,2-bis(trifluoromethyl),trans 1,3 dioxolane		No?		
methyl 2-deoxy-3,4,6-tri-o-methyl-2-(N-methylacetamido) cyclohexyl		No?		

Yes - denotes that removal is probable based on existing information				
Yes? – denotes removal appears to be probable but may not be				
No? – denotes that removal appears not to be probable based on existing information but may be				
No – denotes that removal is not probable based on existing information				
? or Maybe – denotes that removal may or may not be possible based on existing information				
Partial – denotes that removal is probable but only to a limited extent based on existing information				

**Table C-2
Aliphatics Found in NJ Ground Water**

Compound	Treatments			
	Air Stripping	GAC	Oxidation	Biodegradation
Crude and Refined Petroleum Compounds				
2,3-dimethyl-1-hexene	Maybe	Yes	No	
2,3,4,trimethyl hexane	Maybe	Yes	No	
3-methylene undecane	Maybe	Yes	No	
3 methylene tridecane		Yes	No	
2,3-dimethyl 2 pentanol	Maybe	Yes	No	
Flavor/Fragrances				
1-dodecanol	Partial	Yes?	No	Yes
3,5,5-trimethyl hexanoic acid	No	Yes	Partial	
hexanoic acid, heptyl ester (heptyl hexanoate)	No	No?	No	
5-methoxy-4-(phenylthio)pent-4-en-3-one	Maybe	No?		
verticiol		Yes?		
Pharmaceuticals				
1,9-nonanediol		Yes?	No	
thiourea,N ¹ -phenyl-N,N-dipropyl	Not likely	No?		
13-bromotetradecanoic acid	No	Yes	?	
O decylhydroxylamine		No?	No	Yes
Surfactants/Personal Care Products				
1-tridecanol	No	Yes	No	Yes

1-nonadecanol	No	Yes?	No	
1-eicosanol	No	Yes	No	Yes
hexadecanoic acid	No	Yes	No	
octadecanoic acid	No	Yes	No	
2 methoxy, 5 hexadecenoic acid, methyl ester	No	Yes?		
tetradecanoic acid	No	Yes	No	
acetic acid, octadecyl ester	No	No	No	
octadecanoic acid, butyl ester	No	Yes	No	Yes
hexadecanoic acid, octadecyl ester	No	Yes	No	
2 butoxyethanol phosphate(3:1)	No	No?	Yes?	
dodecanamide, N-(2-hydroxyethyl)-	No	No?		
dodecanamide, N,N-bis(2-hydroxyethyl)-	No	No?		
Lubricants/Emulsifiers				
5-octadecene, (E)-	No	Yes	No	Yes
decane, 1,1'-oxybis- OR didecyl ether	No	Yes?	No	
9,12-octadecadienoic acid (Z,Z)-	No	Yes?	No	
9-octadecenamide, (Z)		Yes?		
selenocyanic acid, p-(propylamino)phenyl ester		No?		
9-octadecenamide,N,N-dimethyl		Yes?		
octadecanoic acid, hexadecyl ester	No	Yes	No	Yes
Polymer/Plastic manufacture				
10 undecen-1-ol	Partial	Yes?	No	Yes
nonanoic acid	No	Yes	No	Yes
1,10-decanediol bis(trimethylsilyl) ether	No	Yes?	No	
4 methyl pentadecane		Yes	No	Yes
propanedioic acid, dibutyl ester		Yes?		
3-(4-methoxyphenyl)-2-ethylhexyl ester 2-propenoic acid	No	Yes?	No	
octadecanoic acid, 2-methylpropyl ester	No	Yes	No	
dodecanedioic acid, dimethyl ester	No	Yes	No	Yes?
boric acid (H3BO3), trihexyl ester	No	No?		
Pesticides/Herbicides				
dichlorvos OR 2,2 dichlorovinyl dimethyl phosphate	Yes	No?		Yes

ethanedioic acid, bis(trimethylsilyl) ester	Maybe	Yes?		
1,2-dibromobutane	Partial	No?		Yes?
ethyl pyrophosphate	Partial	No	No	
arsenous acid, tris(trimethylsilyl) ester		No?	some by UV	Yes
Unknown Uses				
2,4-diphenyl-4-methyl-2(Z)-pentene	No	Yes	Yes	
1,2 dibromododecane		Yes?	?	
1 bromo 3 methylpentane	Yes	Yes?		
(Z)6-pentadecen-1-ol	No	Yes?	No	Yes
N-(4-methoxyphenyl) propamide		No?		
7 methyl 7-heptadecanol	Partial	Yes?	No	
dodecyl isopropyl ether	No	Yes?	No	
2,5,8,11,14,17-hexaoxaoctadecane	No	No?	No	
5-methyl-5-phenyl-2 hexanone		Yes	?	
acetic acid, [(trimethylsilyl)oxy]-, trimethylsilyl ester	Maybe	No		Maybe
2,2,13,13-tetramethyl 3,12-dioxo-2,13-disilatetradecane	No	Yes?	No	
hexanoic acid, 3,5,5-trimethyl-1,2,3-propanetriyl ester		Yes?	No	
octadecanoic acid, octadecyl ester	No	Yes	No	
octadecanoic acid, eicosyl ester	No	Yes	No	
butanediyl bis phosphonic acid tetraethyl ester		No?		
3-amino-3-(4-methylphenyl)-1-phenyl-2-propen-1-on		No?	No	Maybe
2,4-dimethyl-2,3-heptadien-5-yne		Yes		
perfluoro-1-heptene	Yes	No?	No	
3,3,7,7-tetramethyl 11-dodec-5-one		Yes?	No	
butyl-2-hydroxybutyl methyl phosphate		No?		
2 undecanone, methyl oxime		No?		
triethyl(S)-2-(carboxymethoxymethyl)oxydiacetate		No?		

Yes - denotes that removal is probable based on existing information				
Yes? – denotes removal appears to be probable but may not be				
No? – denotes that removal appears not to be probable based on existing information but may be				
No – denotes that removal is not probable based on existing information				
? or Maybe – denotes that removal may or may not be possible based on existing information				
Partial – denotes that removal is probable but only to a limited extent based on existing information				

**Table C-3
Aromatics Found in NJ Ground Water**

Compound	Treatments			
	Air Stripping	GAC	Oxidation	Biodegradation
Crude and Refined Petroleum Compounds				
p-xylene (1,4 dimethylbenzene)	Yes	Yes	Yes	
o-xylene (1,2 dimethylbenzene)	Yes	Yes	Yes	
1,2,3-trimethylbenzene	Yes	Yes	Yes	Yes, slow
1,2,4-trimethylbenzene	Yes	Yes	Yes	Yes, slow
1,3,5-trimethylbenzene	Yes	Yes	Yes	Yes, slow
1-ethyl-3-methyl benzene	Yes	Yes	Yes	
2,5-bis (1,1-dimethylethyl) thiophene	Maybe	Yes?		
2,5-bis(1,1-dimethylethyl)-phenol	No	Yes	Yes	
3,5-bis(1,1-dimethylethyl) phenol	No	Yes	Yes	
2,6-bis(1,1-dimethylethyl)-4-ethyl phenol	No	Yes	Yes	
1,2,3,4,5,6,7,8- octahydrotriphenylene		Yes?	Yes	
Flavor/Fragrances				
4-(1,1-dimethylethyl)-2-methyl benzenethiol	Likely	Yes		
2H-2,4a-methanonaphthalene,1,3,4,5,6,7-hexahydro-1,1,5,5-tetramethyl	Partial	Yes?	Yes	
Pharmaceuticals				

isothiazole,4-methyl	?	No	?	
1,2,3,4-tetrahydroisoquinoline	Yes	No?		
benzothiazole		Yes?		
1,2-benzisothiazole		Yes?	Yes	
N-propyl-benzamide	Partial	No	Yes	
1,7-dihydro-1-methyl 6H-purine-6-thione				slow
3-acetamide 1,2-benzisothiazole		Yes?		
(1,1-dimethylethyl)-2-methoxyphenol	Yes	Yes?	Yes	
ampyrone (4-aminoantipyrine)		No?		
4-methyl-2-phenyl pyrrolo[2,3-b]pyridine	No	Yes?		
6,11-dihydrodibenz(b,e)lohexin-11-one		No?	No	
2-hydroxybenzoic acid, phenyl ester		No?		
6-amino-4-oxo-4H-1-benzopyran-2-carboxylic acid, ethyl ester		Yes?		
ergost-14-ene,(5.alpha.)-		Yes?		
2,4-dimethoxy-917.beta.estra-1,3,5(10)-triene-3,17-diol		No?		
trimetazidine		?		
nordextromethorphan	No	Yes?		
gitoxygenin	No	Yes?		Yes
2-isopropenyl-3,6-dimethylpyrazine		Yes?		
Surfactants/Personal Care Products				
2,4-dioctylphenol		Yes?		
4-methyl-benzenesulfonic acid, dodecyl ester	No	No?	?	Slow
nonylphenyl ether		No?		
Polymer/Plastic Manufacture				
N-butylbenzenesulfonamide	No	Yes	Yes	
1,1'-biphenyl,2,2'-diethyl	No	Yes	?	
3-methyl-2,5-(3H,5H)-furan-2-one	No	No?	Yes	yes
1-isocyanato-2-methylbenzene	Yes	Yes?		
1-isocyanato-4-methylbenzene	Yes	Yes?		
2(3H)-benzothiazolone		No?	Yes	
1,1-dimethylnonylbenzene	Yes	Yes	Yes	
2-dimethylbenzyl-6-tert-butylphenol		Yes?		
Pesticides/Herbicides				
N,N'-bis(2-chlorophenyl) urea		No?	No?	
atrazine	No	Yes	Yes	Slow

bromacil		No?	Yes	
metolachlor	No	Maybe	Yes	Slow
chlordane	Partial	Yes	Yes	
Naturally Occuring Compounds				
2'-deoxyadenosine	No	No?		Yes
uracil,5-[(2-trifluoro-1-hydroxy)ethyl]-	No	No?		
Industrial Chemicals				
nitromethylbenzene	Yes	No	Yes	
1-naphthalenamine	Partial	Yes		
5 chloro 1H-benzotriazole	No	No?		
diphenyl ether	Yes	Yes?	No?	
2-mercaptobenzothiazole		No?	Yes	
butylated hydroxyanisole OR 3 tert butyl 4 hydroxyanisole		Yes?	Yes UV	
4-chloro-2-methyl-6-nitroaniline	Maybe	No?	Yes	
2H-1-benzopyran-2-one,7- (dimethylamino)-4-methyl		No?	?	
1-propyloctylbenzene		Yes		Yes
2-(phenylthio)-quinoline		Yes?	Yes	
1,1,4,6,6-pentamethylheptyl benzene	Maybe	Yes		
1-ethyldecylbenzene	Maybe	Yes		Yes
1-hexylheptyl benzene		Yes		Yes
1-propyldecyl benzene		Yes		Yes
1,1':3',1"':3",1""':3""',1""''-quinquephenyl		Yes?		
1,3,5-triphenyl-S-triazine- 2,4,6(1H,3H,5H)-trione		Yes?		
2,2',4,4'-tetramethyl diphenylsulphone		No?		
2,3-dihydro-3-benzofurancarboxylic acid		No?	Yes	
4,7-dimethyl-1,10-phenanthroline	No	Yes?		Maybe
Phthalates				
3 nitro 1,2-benzenedicarboxylic acid (phthalic acid)	No	Yes?	Yes	
dimethyl phthalate	No	Yes	Yes	
Bis (2-methoxyethyl)phthalate	No	Yes?		
didecyl phthalate	No	Yes?	Yes	
di-n-octyl phthalate	No	Yes	Yes	
Polynuclear Aromatic Hydrocarbons				
2 naphthalenamide		Yes?		
Phenanthrene		Yes?	H2O2 with Fe 2+	

2-(1,1-dimethylethyl)1,2,3,4-tetrahydronaphthalene		Yes?	Maybe	
phenanthrene, 7-ethenyl-1,2,3,4,4a,4b,5,6,7,8,8a,9-dode		Yes?	Maybe	
1,2,5,6-tetramethylacenaphthylene		Yes?	H2O2 with Fe 2+	Yes
Tetradecahydro 4,5 dimethyl phenanthrene		Yes?	H2O2 with Fe2+	
1,2,3,3a,4,5,6,10b-octahydrofluoranthene		Yes?	H2O2 with Fe2+	
triindenol[2,3:3',3',2'',3''] benzene		Yes?	H2O2 with Fe 2+	
9,10 dihydro 9,9,10 trimethyl acridine		Yes?		
7a,8-dihydro-7a-methyl 7H-dibenzo[b,b]carbazole		Yes?	H2O2 with Fe 2+	
7-hydroxy-7,8,9,10-tetramethyl-7-8-dihydrocyclohepta[d,e] naphthalene		Yes?	H2O2 with Fe 2+	
2H-2,4a-methanononaphthalene	Partial	Yes?	Maybe	
Unknown Uses				
2 isopropenyl 3,6 dimethyl pyrazine				
1 chloroethyl methylbenzene		Yes?		
1,4-dimethyl-2-(2-methylpropyl) benzene	Yes	Yes		
1,1-dimethylbutyl benzene	Yes	Yes	Yes	
1,3-dichloro-2-isocyanatobenzene	?	Yes?		
1,4 dichloro 2 isocyanatobenzene		Yes?		
1,2,3-trimethoxy-5-(2-propenyl) benzene		No?		
1-methylnonyl benzene	Yes?	Yes	Yes	Yes
1 methyldecyl benzene		Yes	Yes	
1,3,5-tri-tert-butyl benzene	Maybe	Yes	Yes	
1,3,3-trimethylnonyl benzene	Maybe	Yes		
1,1-dimethyldecyl benzene	No	Yes		Yes
3-(2-cyano-2-phenylethenyl) toluene		Yes?		
1,3,5-trimethyl 2 octadecylbenzene	No	Yes?	Yes	

1,1'(1,1,2,2-tetramethyl-1,2-ethanediyl)bis benzene		Yes		
4-(2-aminopropyl) phenol	Yes?	Yes?		
2-(1,1-dimethylethyl)-4-methylphenol	Yes?	Yes?		
4-(2,2,4-trimethylpentyl) phenol	Yes?	Yes?		
2,4,6-tris(1,1-dimethylethyl) phenol		Yes?		
4a,5,6,7,8,8a-hexahydro-7.alpha.-isopropyl-4a.beta.2(1H)naphthalenone		Yes?		
2-methyl 1-indolizinecarboxylic acid ethyl ester		Yes?		
1-(trifluoroacetyl) 2-piperidinecarboxylic acid, butyl ester		Yes?		
4-(octyloxy) benzaldehyde		No?		
(5,6,7,8-tetrahydro-2-naphthalenyl)-phenyl methanone		Yes?	Yes	
N-(1,1-dimethylethyl)-4-methyl benzamide		No?		
2-amino-3,5-dicyano-4,4-dimethyl-6-phenyl(4H)pyran		No?		
2-(4-hydroxybenzoyl) benzoic acid		No?		
2,3-dihydro-4,5,7-trimethyl 1H-indene		Yes?		
2,3-dihydro-1-methyl-3-phenyl 1 H indene		Yes?		
4-methoxy 9H-xanthen-9-one		Yes?		
(5,6,7,8-tetrahydro-2-naphthalenyl)-phenyl methanone		Yes?		
1 ethyl-4-(2-chloroethyl)-1,2,3,4-tetrahydroquinoxaline		No ?		
4-(2-cyano-2-phenylethenyl) toluene		Yes ?		
N-(4-hydroxyphenyl)-2-methyl benzamide		No		
2,5-dibromo-pyridine		Yes?		
thienol[(3,2-c]pyridine		No?		
o-(4,6-diamino-s-triazin-2-yl) phenol	No	Yes		
2-phenyl-4,6-di(2-hydroxyphenyl)pyrimidine				
Yes - denotes that removal is				

probable based on existing information				
Yes? – denotes removal appears to be probable but may not be				
No? – denotes that removal appears not to be probable based on existing information but may be				
No – denotes that removal is not probable based on existing information				
? or Maybe – denotes that removal may or may not be possible based on existing information				
Partial – denotes that removal is probable but only to a limited extent based on existing information				