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Manual

Ground-Water and Leachate Treatment Systems

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Abbreviations

AirS	air stripping
AFF	anaerobic fixed film
ASG	aerobic suspended growth
AS/PC	activated sludge/powdered carbon
ASTM	American Society for Testing and Materials
BDAT	best demonstrable available technology
BEJ	best engineering judgment
BOD	biochemical oxygen demand
BTEX	benzene, toluene, ethylbenzene, and xylenes
CaO	calcium oxide (lime)
ChOx	chemical oxidation; parentheses show oxidation chemical i.e., ChOx(Cl) is chlorine, ChOx(Oz) is ozone, and ChOx(Sur) is surfactant
ChPt	chemical precipitation
COD	chemical oxygen demand
DAF	dissolved air flotation
DCB	dichlorobenzidine
DCE	1,1-dichloroethane
DCM	dichloromethane
DNAPL	dense nonaqueous-phase liquid
DO	dissolved oxygen
DOC	dissolved organic content
EBCT	empty bed contact time
EDTA	ethylene diamine triacetic acid
ENR index	Engineering News Record Construction Cost Index
EPA	U.S. Environmental Protection Agency
EPT/EPDM	ethylene-polypropylene diene-terpolymer
FBR	fluidized bed reactor
$FeCl_2$	ferric chloride
Fil	filtration
F/M	food/microorganism

GAC	granular activated carbon
GC	gas chromatography
H_2O_2	hydrogen peroxide
HPLC	high-performance liquid chromatography
HRT	hydraulic residence time
IE	ion exchange
LNAPL	light nonaqueous-phase liquid
MCC	motor control center
MEK	methyl ethyl ketone
MIK	methyl isoamyl ketone
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
MSDS	material safety data sheet
NH_4-N	amnonium nitrogen
NTU	nephelometric turbidity units
OCA	orthochloroaniline
OLR	organic loading rate
O&M	operation and maintenance
O&G	oil and grease
PAC	powdered activated carbon
PCE	perchloroethylene (tetrachloroethylene)
PLC	programmable logic controller
POTW	publicly owned treatment works
PQL	practical quantitation limit
PVC	polyvinyl chloride
PVDF	polyvinyl idene fluoride
RA	resin adsorption
RAS	return activated sludge
RBC	rotating biological contactor
RCRA	Resource Conservation and Recovery Act
RO	reverse osmosis
SBOD	soluble biochemical oxygen demand
SBR	sequencing batch reactor

Abbreviations (Continued)

SCOD	soluble chemical oxygen demand	TKN	total Kjeldahl nitrogen
SRT	solids retention time	TOC	total organic carbon
SVOC	semivolatile organic compound	TSS	total suspended solids
TBOD	total biochemical oxygen demand	UV	ultraviolet
TCA	trichloroethane	VOA	volatile organic acids
TCE	trichloroethylene	VOC	volatile organic compound
TDS	total dissolved solids	WOx	wet oxidation
ThOD	theoretical oxygen demand	WQBEL	water quality based effluent limits

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Chapter 1
Introduction

1.1 Background

Past disposal of hazardous and solid waste in soils has resulted in ground-water contamination across the United States. At many of these waste sites, remediation of contaminated ground water involves extracting the ground water, then treating it ex situ. In addition, modern land disposal facilities generate leachate that requires collection and treatment.

Although similar compounds and treatment technologies may be involved, the design considerations for ex situ ground-water or leachate treatment systems often differ from those for industrial wastewater treatment systems because of:

- Dilute concentrations of multiple contaminants.
- Variable flow rates from heterogeneous soil formations and stormwater events.
- Process-interfering colloids.
- Contaminant concentrations that vary over time due to landfill age.

In addition, the ground-water remediation schedule (time frame) may be difficult to predict precisely but does affect design issues such as design flow rate (process sizing), materials of construction (longevity), and present worth analysis (evaluation period). Therefore, a flexible design approach may be necessary to address the many technical issues involving ground-water extraction and treatment.

1.2 Purpose of This Manual

This manual was developed for remedial design engineers and regulatory personnel who oversee the ex situ ground-water or leachate treatment efforts of the regulated community. The manual can be used as a treatment technology screening tool in conjunction with other references. More importantly, the manual briefly presents technical considerations (or concepts) for use when evaluating, designing, or reviewing a system design for the treatment of contaminated ground water or leachate from land disposal operations. It is not intended for use as a detailed design manual for specific technologies. For Superfund applications, readers should follow the presumptive guidance for contaminated ground water that EPA's Superfund program has issued.

This manual describes traditional technologies that have evolved from industrial wastewater treatment and that have been implemented at full scale for ground-water or leachate treatment:

- Activated sludge
- Sequencing batch reactor
- Powdered activated carbon
- Rotating biological contactor
- Aerobic fluidized bed biological reactor
- Air stripping
- Activated carbon
- Ion exchange
- Reverse osmosis
- Chemical precipitation of metals
- Chemical oxidation
- Chemically assisted clarification (polymer only)
- Filtration
- Ultraviolet radiation

This manual does not address filtration processes (other than granular media and reverse osmosis) that may be considered to be demonstrated and commercially available for ground-water or leachate treatment; these filtration technologies are microfiltration, nanofiltration, and ultrafiltration.

This manual does not cover emerging and innovative treatment technologies recently evaluated for treating contaminated ground water or leachate, such as:

- Gamma or electron beam radiation
- Surface modified clays
- Pervaporation
- Electrochemical separation
- Wet air oxidation

- Anaerobic fixed-film degradation
- Reinjection of leachate into landfills

Readers are encouraged to keep current with the relevant literature and to be part of the technology evaluation process.

While the manual focuses on ex situ treatment applications, the reader is encouraged also to consider in situ remediation alternatives for ground water, such as surfactant flushing, in situ biodegradation, and oxidation/reduction manipulation. The manual covers dissolved or colloidal contaminants, not nonaqueous phase liquids, and the technical issues associated with aquifer restoration are not addressed.

Users of this manual can consult the U.S. Environmental Protection Agency's (EPA's) Risk Reduction Engineering Laboratory Treatability Database (1) to obtain complete treatability information on many ground-water and leachate contaminants. The database summarizes years of studies on the treatability of compounds regulated under the Clean Water Act, the Safe Drinking Water Act, the Resource Conservation and Recovery Act (RCRA), the Toxic Substances Control Act, and the Superfund Amendments and Reauthorization Act. To date, more than 9,200 aqueous treatment data sets and 6,400 solid waste treatment data sets have been extracted from more than 500 peer-reviewed references. In addition to treatability data, the database contains information on more than 1,200 compounds, including physical and chemical properties, environmental data, and carbon isotherms.

Chapter 2 of this manual is an overview of the characteristics of contaminated ground water and leachate, including sampling and analytical considerations. Chapter 3 presents design considerations for ground-water and leachate treatment systems. Chapter 4 provides guidance for treatment technology screening and includes contaminant removal tables for 20 compounds that occur frequently at hazardous waste sites. Chapter 5 presents case studies describing how treatment technologies were evaluated, selected, designed, and implemented at five sites. Finally, Appendix A is a compendium of information about the most common technologies for treating contaminated ground water and leachate.

1.3 Reference

1. U.S. EPA. 1994. RREL Treatability Database, Version 5.0. Risk Reduction Engineering Laboratory, Cincinnati, OH.

Chapter 2
Characteristics of Contaminated Ground Water and Leachate

2.1 Introduction

This chapter provides a brief overview of the characteristics of contaminated ground water and landfill leachate (Section 2.2 and Tables 2-1 through 2-3). In addition, the chapter presents sampling and analytical considerations for characterizing ground water and leachate before treatment alternatives are evaluated (Section 2.3).

2.2 Ground-Water and Leachate Characteristics

Ground water (often contaminated at the microgram per liter level) and landfill leachate (often contaminated at the milligram per liter level) have different water quality characteristics. From site to site, contaminated ground water may vary in contaminant type, number of contaminants, and concentrations. The wide range of activities that may have occurred at a given site as well as differences in dissolved solids released by various geological formations cause these variations. Some of the most common contaminants occurring at hazardous waste sites are listed in Table 2-1. These contaminants are used in this manual (Section 4.2) for technology performance comparisons.

Selecting design values for landfill leachate is difficult because the actual composition of leachate is site-specific and depends on such variables as types of waste, amount of infiltration water, pH, depth of fills, compaction, and landfill age. In fact, leachate concentrations are frequently reported as ranges, not as discrete values. The ranges are usually quite broad, often spanning several orders of magnitude (see Table 2-2) (1). Because landfill leachates may contain ammonium, readers are referred to the EPA document *Nitrogen Control* (2) for treatment alternatives for ammonium.

The following observations were made from leachate collected from 13 hazardous waste landfills located throughout the United States. The leachates were approximately 99 percent aqueous and 1 percent organic by weight. Only 4 percent of the analytical total organic carbon (TOC) was characterized. Table 2-3 shows that of the characterized TOC (by total mean mole fraction percentage), 39.0 percent was organic acids, 35.8 percent was oxygenated/heteroatomic hydrocarbons, 11.0 percent was halogenated hydrocarbons, 7.2 percent was organic bases, 6.0 percent was aromatic hydrocarbons, and 0.9 percent was aliphatic hydrocarbons (4).

Table 2-1. Contaminants That Occur Frequently at Hazardous Waste Sites

1,1,2-Trichloroethylene
Lead
Chromium
Toluene
Benzene
Perchloroethylene
1,1,1-Trichloroethane
Chloroform
Arsenic
Polychlorinated biphenyls
Cadmium
Zinc
Copper
Xylenes
1,2-trans-Dichloroethylene
Ethylbenzene
Phenol
1,1-Dichloroethane
Methylene chloride
1,1-Dichloroethylene

2.3 Sampling and Analytical Considerations

2.3.1 Sampling Considerations

Ground water or leachate must be characterized before treatment evaluation occurs. Guidance for ground-water sampling methods can be found in references such as *Site Characterization for Subsurface Remediation* (5) and *Subsurface Characterization and Monitoring Techniques* (3).

Table 2-2. Summary of Leachate Characteristics Reported in Literature (1)

Constituent[a]	Range
Biochemical oxygen demand	2-55,000
Chemical oxygen demand	9-90,000
Total suspended solids	5-18,800
Total dissolved solids	130-55,000
pH	3.7-9.0
Total alkalinity as $CaCO_3$	140-20,900
Total hardness as $CaCO_3$	200-25,000
Ammonia-Nitrogen	0-1,110
Total nitrogen	0-2,400
Total phosphorus	0-155
Cadmium	0-17
Calcium	5-7,200
Chloride	2-5,000
Chromium	0-33
Copper	0-10
Iron	2-5,500
Lead	0-12
Magnesium	0-4,000
Manganese	0.05-1,400
Mercury	0-0.2
Nickel	0-9
Potassium	3-3,770
Sodium	0-7,700
Sulfate	1-1,825
Zinc	0-1,000

[a] Concentration of constituents (mg/L) except pH.

2.3.2 Analytical Considerations

Specific analytical methods for various ground-water contaminants include *Standard Methods for the Examination of Water and Wastewater* (6), *Test Methods for Evaluating Solid Waste* (7), and *Methods for Chemical Analysis of Water and Waste* (8). In addition, Volumes 11.01 and 11.02 of the *Annual Book of the American Society for Testing and Materials (ASTM) Standards* (9) also detail analytical methods.

Gas chromatography (GC) or high-performance liquid chromatography (HPLC) can be used to characterize the organic content. If certain peaks are noticed, they can be further pursued for identification.

When ground water and leachate are characterized, it is common to find that the sum of individual organic pollutants does not match the measured TOC and/or chemical oxygen demand (COD) value. In most cases, the sum of the individual organics represents only a certain percentage of the TOC and/or COD value. Because of the complex nature of leachate and contaminated ground water, the compounds cannot always be fully identified, and the unidentified portion of the constituents causes these gaps in mass balance results. This is not necessarily a problem if the treated water does not contain the unidentified compounds.

If compounds are completely identified, the COD value will be lower than the calculated theoretical oxygen demand (ThOD). COD is measured through oxidant consumption using certain chemicals under a specific temperature within a specific period, but this does not ensure 100-percent oxidation. This is particularly true for aromatics and nitrogen-containing aromatic compounds such as pyridine and benzene. (The COD value of benzene, using ASTM Standard Method of Testing for

Table 2-3. Summary of Leachate Organic Chemical Occurrence Data (3)

Chemical Classification	Percent Occurrence	Representative Chemical(s) and Occurrence (Mole Fraction)
Organic acids	39.0%	• Phenol (11.8%) • Substituted phenols (17 compounds at 9.5%) • Benzoic acid and substituted benzoic acids (five compounds total at 5.4%) • Alkanoic acids (13 compounds at 12.3%)
Oxygenated/Heteroatomic hydrocarbons	35.8%	• Acetone (16.5%) • Common ketone solvents, e.g., methyl ethyl ketone, methyl isobutyl ketone, and methyl propyl ketone (9.2%) • Alcohols of all types (16 compounds at 8.1%)
Halogenated hydrocarbons	11.0%	• Methylene chloride (6.8%) • Chlorobenzenes (four compounds at 1.4%) • Multichlorinated alkanes/alkenes (10 compounds at 2.8%)
Organic bases	7.2%	• Aniline and substituted anilines (seven compounds total at 4.3%)
Aromatic hydrocarbons	6.0%	• Toluenes (4.2%) • Benzene and alkyl-substituted benzenes (except toluenes) (1.4%)
Aliphatic hydrocarbons	0.9%	• This group does not have any good representatives in terms of level of occurrence or site distribution

Chemical Oxygen Demand of Waste Water D1252-67, shows only about 70 percent of the ThOD value [10]).

Sample collection and handling can also cause difficulties in achieving mass balance. Leachate and ground water originally are in a reducing environment with low dissolved oxygen (DO). When the samples are taken, sudden oxidation and volatilization occur if the samples are exposed to the atmosphere. Such oxidation and volatilization may continue during subsequent transportation and handling. Therefore, samples should be collected and stored properly and analyzed as soon as possible.

2.4 References

When an NTIS number is cited in a reference, that document is available from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
703-487-4650

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Chapter 3
Design Considerations for Treating Contaminated Ground Water and Leachate

3.1 Introduction

This chapter presents an overview of design considerations for ground-water and leachate treatment systems, many of which are unique to these systems and are not factors in industrial wastewater system design. The chapter addresses the following topics: variable flows and variable concentrations (Section 3.2), unit process design approach (Section 3.3), mass balances (Section 3.4), unit process treatment interferences (Section 3.5), life cycle design (Section 3.6), staging/phased treatment (Section 3.7), residuals management (Section 3.8), availability of package plants (Section 3.9), and materials of construction and materials compatibility (Section 3.10). A thorough discussion of each design consideration is not provided; readers should consult the references for additional information.

3.2 Variable Flows and Variable Concentrations

3.2.1 Fluctuations in Ground-Water Flow Rate and Contaminant Concentrations

The rate of ground-water extraction determines the influent flow to the treatment system and hence is a key design variable. Estimates of flow rate and contaminant loading from extraction wells are subject to uncertainty for several reasons. For instance, the rise and fall of ground-water levels resulting from seasonal changes can alter ground-water recharge and discharge rates. The addition or deletion of capture wells within a given flow net also affects the volume of water that the extraction system can pump. Similarly, agricultural, industrial, and domestic water usage can influence the rate of ground-water extraction. Withdrawal rates also may be varied as part of the overall ground-water remediation or control strategy.

If flow rates are likely to vary during the life of a ground-water remediation project, design provisions should be made for possible low water events as well as for the more typical average and maximum flows. Long-term pumping tests should be used to design the extraction well system, rather than shorter duration, laboratory, or slug tests. If fluctuations are to be expected, other design provisions should be incorporated into the treatment concept to ensure that flow and contaminant loading variations do not affect treatment performance. One such provision is to include flow and/or waste strength equalization (see Section 3.2.3).

Phenomena that can cause ground-water contaminant concentration variability are the mechanisms associated with contaminant transport and release. Concentrations sometimes increase after pumping has stopped for a period because organic contaminants sorbed on the natural organic matter "leach" back into the now relatively slow-moving ground water. The heterogeneity of porous soils can influence the rate of adsorption and desorption of contaminants. Other factors that influence contaminant transport include the contaminants themselves, the fraction and type of natural organic matter, and the type of clay present. The treatment system design thus may need to address changes in pollutant concentration and matrix effects over the life of the project. Technologies that are cost effective at a higher pollutant loading, for example, may require reoptimization or replacement as contaminant loadings decline during a project's life span.

3.2.2 Fluctuations in Leachate Flow and Concentration

Leachate is defined as any contaminated liquid that is generated from water percolating through a solid waste disposal site, accumulating contaminants, and moving into subsurface areas. A second source of leachate arises from the high moisture content of certain disposed wastes. As these wastes are compacted or chemically react, bound water is released as "leachate." In the absence of a confining barrier beneath or surrounding the waste disposal site, this leachate can migrate and contaminate subsurface and surface waters. The volume of leachate generated varies with the amount of precipitation and stormwater run-on and run-off, the volume of ground water entering the waste-containing zone, and the moisture content and absorbent capacity of the waste material. When leachate is collected via perforated pipes, rainfall significantly affects leachate volume and contaminant concentrations. Eckenfelder and Musterman (1) list landfill age, ambient air temperature, precipitation and refuse permeability, depth, temperature, and waste composition as factors that affect leachate quantity and composition. Further, they observe that as landfills age, readily degradable organics undergo anaerobic degradation. Consequently, older landfills are more stabilized and may generate lower concentrations of organics. It should be noted that leachate generation gradually increases for the first 5 to 10 years, then declines upon further aging. The composition and concentrations of leachate may also shift with the age of deposited materials.

It has been reported that leachate composition and strength varies widely from landfill to landfill and even within a given landfill (2). The analytical data presented in Table 3-1 show significant concentrations of several chemicals found in leachate from the Lipari landfill (3). Variability in leachate volume and pollutant concentration is generally less predictable than variability in ground-water flow, hence the design of collection and treatment systems must include provisions for addressing uncertainty. In such instances, flow equalization may be used to offset variable leachate volume and contaminant loading.

Table 3-1. Variability of Leachate Concentrations[a] Within the Lipari Landfill (3)

	Collection Point			
Compound	**1**	**2**	**3**	**4**
Benzene	1,456	2,012	1,620	171
Bis(2-chloroethyl)ether	ND	130,000	210,000	54,000
Cadmium	3	53	9	6
Chromium	40	130	30	50
Copper	110	130	110	95
Ethylbenzene	706	1,100	650	82
Mercury	0.2	0.2	0.2	0.2
Naphthalene	ND	94	49	ND
Phenol	914	2,000	4,400	570
Toluene	14,400	22,400	15,600	1,500

[a] All results in ppb
ND = not detected

3.2.3 Waste Strength and Hydraulic Equalization

One of the principal unit processes to handle flow and waste strength variability is equalization. Hydraulic flow equalization is employed to dampen variations in flow entering the treatment plant. Waste strength equalization is used to reduce waste strength variations over a given period. Both equalization processes yield more uniform or cost-effective treatment performance. Operating with a constant influent source to the treatment train also lowers the costs associated with treatment because, among other reasons, instantaneous treatment capacity demand can be reduced, and the amounts of chemicals required can be optimized for a less erratic set of treatment variables.

Design techniques for waste flow equalization are well established (4, 5). Patterson and Menez (6) have developed a deterministic model to design waste strength and flow rate equalization systems. Integrating a mass balance equation and assuming a completely mixed system give the equation

$$X(t) = X(i) + [X(0) - X(i)] \exp(-t/\tau), \qquad (3\text{-}1)$$

where

$X(t)$ = concentration of contaminant in the equalization basin and effluent
$X(0)$ = concentration of contaminant in the equalization basin at time 0
$X(i)$ = influent concentration of the waste
V = volume of the equalization basin
Q = flow rate of the waste
τ = instantaneous hydraulic detention time = $V/Q(t)$
t = time of operation

The method can also be applied to design for simultaneous flow rate and waste strength equalization.

Batch treatment processes such as the sequencing batch reactor (SBR) process can accommodate major changes in flow and concentration by taking tanks on and off line and/or by using varying fractions of each tank's capacity during a given operating period. This characteristic of SBRs offers an inherent equalization and operational advantage over continuous flow-through treatment units. Advantages also exist for short-term variations. For example, each tank in an SBR system typically receives wastewater for 2 to 12 hours each cycle. As a result, the SBR acts like a stepwise equalization system in which concentration variations are equalized over the period of fill. Thus, for each combination of number of tanks and tank volumes selected, the SBR simultaneously provides for stepwise equalization and the degradation of wastewater constituents in a controlled manner.

In addition to treatment objectives, other considerations for selecting the mode of operation include operation and maintenance requirements, flexibility, and initial toxicity. Batch operation often requires more equipment automation than continuous flow operation does. The extent of automation used for the batch process determines which of the two systems has greater operation and maintenance requirements. Both continuous and batch systems can be easily monitored.

The batch mode provides more flexibility for changing operating parameters than does the continuous mode.

Some adjustments include cycle time and aeration modes to achieve nitrification and/or denitrification. The batch mode provides the most quiescent settling. Furthermore, in a batch system, the treated water can be tested before discharge and treated further if necessary. The SBR exemplifies the advantages of the batch reactor. For smaller systems, the tankage required may be the same or smaller for the batch system. The cost savings exist primarily because both the settling tank and return activated sludge pumps are not built separately.

In biological processes, however, there is some concern that batch treatment exerts more initial toxicity than the complete mixed mode because the system appears not to have the same initial dilution advantage as the continuous mode has. Because the SBR is mathematically represented by (i.e., behaves the same as) a continuous-flow, completely mixed reactor while it is filling, the dilution of toxic substances in the SBR is essentially the same as a conventional continuous flow system. As a result, batch processes are subject to toxic interferences only if they are not designed properly.

3.3 Unit Process Design Approach

Only in rare instances does one technology (unit process) suffice for completely treating or managing ground water or leachate, especially if residuals management techniques are necessary. Several unit treatment processes may be needed to treat a particular ground-water leachate because some processes are limited in their ability to remove inhibiting or interfering chemical constituents or parameters, such as suspended or dissolved solids content, pH, temperature, metals, and organic content. This is especially true if the water contains compounds with different chemical and physical properties or has a high solids content. While not necessarily inhibitory, these parameters may decrease system performance and efficiency.

3.4 Mass Balances

A mass balance is a mathematical equation describing mass flux through a system. Mass balances are essential to describing the fate of a chemical as it moves through a unit process or a treatment system. This information is useful in predicting the performance of the unit process before bench- or pilot-scale treatability studies and before the full-scale use. Mass balances allow the design engineer to quantify the mass used and produced in a system, and to identify and confirm the governing mechanisms involved in that system.

Writing a mass balance involves identifying the specific flow and treatment system process characteristics. Given a chemical to remove and a process to remove it, the general equation describing target chemical mass flow into and out of the system is

$$M_I - M_O +/- M_A \text{ or } M_L = 0, \qquad (3\text{-}2)$$

where

M_I = mass in
M_O = mass out
M_A = mass accumulation
M_L = mass loss

Mass flow through a process is calculated from the volumetric flow at each entry and exit point multiplied by the concentration contained in the respective flows.

The specific equation describing flow depends on the process flow and mixing conditions, such as completely mixed, plug flow, and time-variant flow. A particular flow pattern can be obtained from the process vendor, estimated based on the process design, or theoretically derived. Usually, the assumption of steady-state flow conditions is made, and the average flow is used to complete the equation. The assumptions made to generate the flow equation can be verified by tracer studies during the treatability or pilot phase. Each mass entry and exit point must be considered, as well as the phases in which the chemical could exist. Mass entering at each point in the unit process is summed to provide the "mass in" term, while mass from each point at which the chemical can exit is summed to provided the "mass out" term.

Quantifying the mass flow for the accumulation/loss terms involves several considerations. For example, a chemical entering the activated sludge process in the aqueous phase may undergo several different chemical, physical, or biological transformations, such as:

- Biological degradation, either to complete mineralization or transformation products.
- Volatilization or stripping.
- Sorption to solids, such as microorganisms or other suspended solids.
- Reactions with other chemicals or to pH change.

Each of these terms must be quantified according to the specific reaction taking place and are summed to produce the "mass accumulation or loss" term in the general mass balance equation. Volatilization can then be quantified using the Henry's Law relationship corrected for actual process conditions. Sorption is estimated using an appropriate relationship between the chemical and the solids. Products of chemical reactions are determined by stoichiometry. Finally, the biological transformations are quantified using appropriate biological kinetics.

A mass balance is usually written for the average and maximum conditions under which the unit process will operate. If warranted, minimum conditions can also be assessed, for example, for sensitive biological operations. The resulting conditions provide the probable range of operating parameters and potential products of reaction.

A mass balance written for chemicals that are relatively conservative or subject to fewer potential transformations (e.g., metals or total dissolved solids in the concentrations and processes present in ground water and leachate) provides a fairly accurate assessment of chemical fate. The fate of chemicals that are subject to several, often competing, transformation processes proves more difficult to assess using the mass balance approach. This is usually the case for dilute concentrations of organics. Mass balance equations, however, should still be written to identify the most likely or worst-case fate of the organic chemical. A set of equations describing the mass balance should always be verified with actual operation data.

When properly written, a mass balance can provide the following:

- Guidance for selecting treatability study parameters and ranges.
- Equations to verify and evaluate treatability study and full-scale operation data.
- Predicted operation parameters under average and maximum flow conditions (and minimum conditions, if warranted).
- Quantity and concentration of residuals to be generated from the process.

3.5 Unit Process Treatment Interferences

The chemical matrix of a contaminated wastewater may be of special significance to the design engineer. Often, untargeted species that are present affect the function of a given treatment process. Several types of interferences and the control strategies used to alleviate potential problems are presented in this section.

3.5.1 Air Stripping

Iron and manganese species often exist in ground water. In an air stripping packed tower, iron can be oxidized from the ferrous species to the ferric species. Ferric iron can precipitate, then deposit and foul the tower media, causing unexpected headloss, which in turn results in a decline in system efficiency. The rate of iron oxidation depends on the initial iron concentration, water temperature, and pH, among other factors. For instance, at lower pH, a slower rate of oxidation is observed. Manganese oxidation can cause precipitation of manganese hydroxide at a pH of 9 to 9.5, resulting in excessive tower headloss and plugging. If these metals are present in significant concentrations, iron and manganese pretreatment options must be employed. One such process for iron and manganese removal consists of chemical oxidation followed by precipitation, sedimentation, and/or filtration before the pretreated effluent enters the air stripping tower.

A second common problem experienced with air stripping towers is precipitation and scaling with calcium salts including carbonate. For hard wastewaters or where lime is used for pH adjustment ahead of the stripper, calcium carbonate can cause supersaturation to occur. Air strippers may aggravate this situation due to the uptake of carbonate from the stripper air carbon dioxide at higher wastewater pH values. Scaling control may require the addition of a dispersant, presoftening ahead of the stripper, substitution of caustic for lime, or frequent acid cleaning of the stripper. For the latter measure, management of the spent acid cleaning solution must be addressed.

Biological fouling may also occur in packed bed air stripper wastewaters containing degradable organics. Control may involve biocides or intermittent chlorination. Sloughing of biological slimes associated with intermittent chlorination, however, can aggravate media fouling problems.

3.5.2 Ion Exchange

High concentrations of iron and manganese foul cation exchangers (7, 8). These constituents bind to the resin, reducing its exchange capacity. Consequently, if the water is highly turbid or contains high concentrations of metals, pretreatment using precipitation and either sedimentation or filtration is recommended.

Cation exchange resins are also "blinded" by high concentrations of hardness cations, notably calcium and magnesium. These constituents are often present at orders of magnitude greater than the concentrations of the targeted cations to be removed from a ground water or leachate. One treatment alternative is to use ion-specific resins, available from several resin manufacturers, that can remove heavy metals in the presence of calcium and magnesium. These hardness ions then pass through the column without binding to the resin. Another approach is to soften the water ahead of the ion exchange treatment. Sodium hydrosulfite treatment of the fouled exchange resin can alleviate iron and manganese fouling of cation exchange resins.

Ion exchange may also be used to treat for anions such as chromate, arsenic, or selenium. Interference may result from the presence of competing ions such as sulfate, often at significantly higher concentrations than the targeted anions. Such competition rapidly exhausts the resin's exchange capacity, resulting in early target anion breakthrough and possible generation of excessive regenerant volumes.

Organic fouling is also of concern for ion exchange. Heavier and hydrophobic hydrocarbons, including oil and grease, coat the resin beads and hinder ion exchange. Activated carbon pretreatment may be required to protect the resins. The propensity of ion exchange columns to bind due to excessive influent total suspended solids (TSS) is well established. Most ion exchange systems require prefiltration for TSS control.

3.5.3 *Reverse Osmosis*

Reverse osmosis is a membrane process that has reached the point of practical application in water or wastewater treatment. One of the disadvantages of reverse osmosis is fouling of the membrane by suspended solids, oil and grease, iron, manganese, microbial growth, and precipitation of calcium carbonate and magnesium hydroxide. Hence, extensive pretreatment to prevent membrane deterioration and fouling may be required. Water softening processes, such as lime and soda ash, can be used to remove these interferences before applying a reverse osmosis treatment process. Membranes may also require frequent and specialized cleaning, which produces significant volumes of cleaning and rinse solutions that then require management.

3.5.4 *Metals Precipitation*

Both organic and inorganic ligands interfere with metals precipitation. The chloride ion readily complexes with some metal ions, thereby increasing the metal hydroxide solubility. This is especially the case with copper, cadmium, lead, and zinc, which also form mixed solid salts with chloride, i.e., metal-hydroxide-chloride solid species. Sulfate can also alter the solubility of the metal hydroxide system and hence affect treatment. Copper and lead can, however, form insoluble sulfate salts during the alkaline precipitation process. Carbonate readily complexes with copper, cadmium, lead, and zinc. Like chloride, however, insoluble metal carbonate species can also form during the precipitation process. In fact, carbonate is sometimes added, as soda ash, to directly precipitate metals such as lead, as the carbonate solid phase. When complexes form, the solubility of the ion target increases, resulting in higher residual metals concentrations.

Heavy metals can be chelated by certain organic compounds, such as humic substances commonly present in soils, cyanide, and ethylene diamine triacetic acid (EDTA). These metal chelates are very soluble, hence treatment by precipitation is especially difficult. If precipitation treatment is to be pursued, the interference associated with metals ligands must be overcome. Pretreatment may include oxidative destruction of the chelate, competitive chelation by, for example, addition of large concentrations of substitute cations, or pH shifts to dissociate the metal complex. Activated carbon pretreatment may be effective. For inorganic ligands, two options are available. The first is to reduce the competing anion concentration, for example, by precipitation of carbonate as the calcium salt, by anion exchange, or by another technology. The second option is to apply coprecipitation, which is controlled by factors other than strict metal salt solubility.

3.5.5 *Biological Processes*

Biological processes are susceptible to organic and inorganic toxicity. The result is inhibition of biological activity. Heavy metals retard cellular metabolism by disrupting protein functions in enzyme systems (9). Acclimation of biological sludges to metals, however, can increase the toxic threshold of the microbial population, enhancing biological treatment performance. Precipitation pretreatment may effectively offset heavy metals toxicity.

Some organic compounds can also exhibit toxicity. Phenol, for example, can be toxic at high concentrations but is biodegradable at low concentrations (10). Brusseau (11) reported biodegradation occurring at alcohol concentrations of less than 1 percent and concentrations greater than 10 percent causing toxicity to microorganisms. Using a fixed film process, Faghani-Shoya et al. (12) observed localized phenol inhibition in a rotating tube reactor at phenol concentrations near 150 mg/L. Activated carbon ahead of or in conjunction with biological treatment may control toxicity effects.

High concentrations of oxidizing agents such as chlorine, ozone, and hydrogen peroxide attack protein and destroy cellular integrity, resulting in decreased biological activity. Thus, it is important to study the effect of employing oxidation pretreatment before a biological process. Strong oxidants can be effectively reduced by chemical additives.

3.6 Life Cycle Design

Many important engineering design factors need to be considered when planning a leachate or ground-water treatment system. For example, leachate flows and characteristics are a function of the landfill's contents and age, as well as the site's prevailing weather conditions and geology. Flows may increase during wet weather months. Organic acid production usually increases in the early years, then decreases as the landfill contents age. The leachate will require treatment during the active years of the landfill and for many additional years, possibly decades, after the facility is closed. Leachate treatment designs can vary dramatically in size, ranging from a few gallons per minute to several hundreds of gallons per minute.

Ground water frequently presents design challenges that are similar to those observed for leachate. The design hydraulic flow rate for a ground-water treatment system may remain relatively constant over the life of the project or be quite variable, depending on the aquifer characteristics. Daily volumes treated are typically much smaller than conventional wastewater treatment systems. Also, pollutant concentrations will most likely decrease significantly over time. Relatively large volumes of water may have to be treated to remove only trace amounts of contaminants.

The lifespan of some ground-water treatment systems may be of shorter duration than conventional treatment systems designed to last for many years for an active industry. Therefore, capital and operating costs are evaluated much differently, and cost tradeoffs not normally considered in conventional systems may play a significant role in the ground-water project's success. Lower quality materials or fabrications without special coatings may be used to minimize capital expenditures. Similarly, an engineer may opt for manual controls to reduce capital costs. Conversely, long-duration ground-water treatment design should stress minimization of operating costs. High-quality products and protective coatings extend equipment life and reduce maintenance costs. For long-term projects, the engineer should design equipment to be highly automated, thereby reducing operating expenses.

To successfully engineer a properly functioning leachate or ground-water treatment system, the designer should take into account these types of considerations, termed "life cycle design." For purposes of discussion, the key considerations of life cycle design have been grouped into the following three areas:

- Technical considerations
- Time effect of cost on treatment parameters
- Capital and operating cost considerations

Each of these areas should be thoroughly evaluated before proceeding with a ground-water or leachate system life cycle design. Further discussion of these key factors is presented in the following sections.

3.6.1 *Technical Considerations of Life Cycle Design*

As the life cycle of a project develops, physical or chemical changes may occur that offset the original design parameters. For example, the contaminant concentration may increase or decrease or the flow rate may change with seasonal variations or depletion of the aquifer. Other developments, such as urban sprawl, may present changing conditions and a demand for the property to be remediated more quickly than originally planned. The design engineer should incorporate flexibility into the design so that options remain available over the life of the project. For example, modular package plants offer the required flexibility of life cycle design. Some additional examples of design flexibility are described below.

Anaerobic treatment is a biological process often used to treat very high concentrations of organics (typically more than 10,000 mg/L). Aerobic biological treatment is commonly used to treat moderate organic concentrations (200 to 1,000 mg/L). At lower organic concentrations (less than 200 mg/L), the aerobic fluidized bed has shown promise. In between these ranges, either aerobic or anaerobic treatment is considered depending on the desired target effluent quality and the overall economics. For ground water or leachate with an initially high concentration of organics, anaerobic treatment may well be the technology of choice. If anaerobic treatment is selected, some form of heating equipment will be required. The methane produced from anaerobic conversion of 1,000 to 3,000 mg/L of COD produces sufficient heat to increase the normal ground-water temperature from approximately 13°C to 20-25°C for optimum operation. A source of heat (whether from methane or other sources) should be considered in the design and selection of anaerobic treatment systems.

As contaminant concentrations decrease over time, system flexibility should allow for replacement of the anaerobic system with an aerobic unit, such as a sequencing batch reactor. Removable baffles may be incorporated into the design to allow for additional system flexibility. Similarly, a continued decrease in concentration would allow the more economical anaerobic fluidized bed to be substituted for the aerobic process. Life cycle design allows the designer to select the most appropriate technology to complete the required treatment in the shortest possible time and at the lowest cost. For short-duration projects, the design engineer should consider use of package plants, rental or leased equipment, or equipment that could be easily converted from the anaerobic to the aerobic configuration. Long-duration projects may justify the purchase of more permanent types of facilities.

Knowing beforehand that flow rates could very likely be variable over the life of the project, the experienced designer would evaluate the use of multiple units for a particular technology. As the flow rate declines or increases, modular units can be shut down or added. The reduced number of active units at a site in turn reduces power and chemical requirements, and requires less operator attention. The surplus units can be sold, used at other sites, or returned to the lessor. In some circumstances, flow from the aquifer or landfill can be interrupted at regular intervals to allow diffusion to increase the concentration of contaminant as an alternative treatment method in later years. Using this approach where possible would result in lower power and chemical costs over the life of the project.

Another strategy that should be considered is the use of treatment trains to meet project objectives. Various processes can be installed at a site in series to take advantage of the strengths of each process. Treatment trains are effective where multiple contaminants are present that a single technology cannot remove efficiently. As concentrations or stream characteristics change, technologies that have been preselected can be easily and economically added or removed from the train.

3.6.2 *Time Effect of Cost on Treatment Parameters*

Some ground-water treatment projects may last only 6 months to 5 years; leachate may have to be treated for decades. The traditional cost-estimating method used to compare treatment alternatives consists of amortizing capital costs into an annual cost and adding it to other operating costs (e.g., power, chemicals, labor, residuals disposal,. and maintenance costs). The option that meets the treatment objective and has the lowest estimated annual operating cost is usually selected as most cost effective.

By definition, in life cycle design, the conditions and changes that occur during the life expectancy of the project must be taken into consideration. For example, as ground-water remediation progresses, concentrations of contaminants normally decrease. Some treatment processes, such as biological treatment, may actually lose efficiency as concentrations begin to decline; thus, at some point, biological treatment may fail to operate. The designer must plan for changes that may be necessary during the life cycle of the project.

The following case history is presented to provide an example of a project that used life cycle design to optimize equipment selection for remediation of contaminated ground water.

3.6.2.1 Life Cycle Case History

A project that used life cycle design analysis involved the removal of 1,1,1-trichloroethane (TCA) and 1,1-dichloroethene (DCE) from a facility's foundation ground-water drainage sumps. The ground water from the sump flowed at 4 gal/min (15 L/min) and contained average concentrations of 1.3 mg/L TCA and 0.2 mg/L DCE. EPA's RREL Treatability Database was reviewed, and three candidate treatment technologies were selected for consideration:

- Granular activated carbon, liquid phase.
- Air stripping with vapor-phase granular activated carbon.
- Ultraviolet (UV) light with hydrogen peroxide (H_2O_2) oxidation.

From a technical standpoint, all three technologies were capable of meeting the project's effluent quality objectives. Based on information obtained from modeling of the aquifer, concentration of contaminants were predicted to decrease by a factor of one-half for each year of equipment operation.

Capital and operating costs for the three candidate technologies were estimated and are shown in Table 3-2. The operating costs shown are for the first year of operation.

Table 3-2. Estimated Capital and First-Year Operating Costs for Selected Technologies

	Capital	Operating
Carbon Adsorption	$38,500	$92,000
Air Stripping	$61,000	$26,500
UV/H_2O_2 Oxidation	$188,500	$27,500

The capital cost (cost of equipment) was estimated from manufacturers' quotes. Capital costs included the following:

- Equipment.
- Building (wood construction).
- Concrete foundations.
- Installation labor (piping, electrical, and mechanical) and materials.
- Heating and ventilation.
- Factors for contingency, engineering, profit and overhead, and labor index.

Operating costs were estimated using treatment modeling programs, vendor information, and previous related experience. Operating costs included the following:

- Electrical power.
- Operator labor.
- Chemicals (granular activated carbon [GAC], UV/H_2O_2).
- Regeneration and disposal (GAC).
- Routine maintenance (acid wash, etc.).
- Equipment rentals.
- Transportation.

Because capital costs are an initial investment and operating costs are annual expenses, the two costs must be converted to the same basis to obtain an unbiased view of overall project expenditures. The present worth analysis has been selected as the method of comparison, with interest assumed at 8 percent. The cost for the life of the project is shown in Table 3-3 and is estimated for intervals of 7, 10, and 20 years using the data provided in Table 3-2 as the cost basis. Based strictly on present worth analysis, the Table 3-3 cost data appear to indicate that carbon adsorption would be the least cost-effective choice for all three time increments selected.

Table 3-3. Present Worth Analysis Results

	Years of Operation		
	5	10	20
Carbon Adsorption	$406,500	$656,500	$943,000
Air Stripping	$166,000	$237,500	$319,000
UV/H_2O_2 Oxidation	$298,000	$372,500	$457,500

In Figure 3-1, the impact that life cycle design can have on equipment selection is illustrated. In this figure, the capital cost (neglecting inflation) for each of the three equipment options was placed on the ordinate at time zero. Annual operation costs were then added to the capital cost for each year. Time is plotted on the abscissa. In this example, however, the impact of decreasing contaminant concentration (estimated previously to be about 50 percent per year) has been taken into consideration. This decreasing concentration has a significant impact on the amount of carbon used annually. Thus, as the project progresses, the use of carbon continues to decrease as the ground water's contaminant concentration is reduced. The following assumptions were used to assist in the calculations:

- All of the technologies consistently meet the desired effluent concentration for the life of the project.
- The cost of vapor-phase carbon for treating the air stripper off-gas will decrease with time; however, canister rental will remain relatively constant throughout the project.
- The liquid phase granular activated carbon usage rate decreases proportionally to the decrease in contaminant concentration.
- The air-to-water ratio is fixed; therefore, the power requirements (and corresponding operating costs) will remain constant.

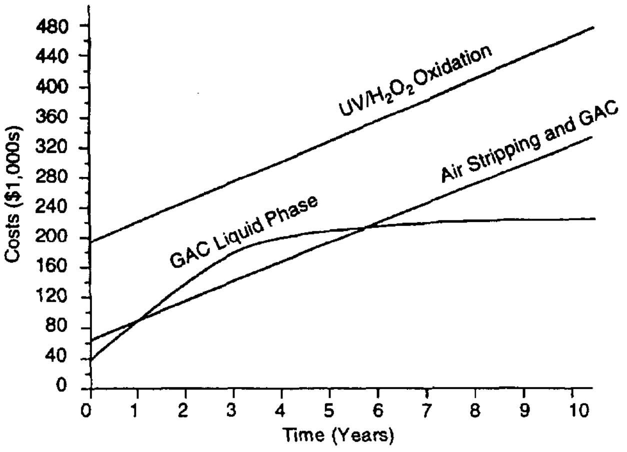

Figure 3-1. Operating costs as a function of time for the three treatment processes.

Using life cycle analysis to compare the costs of the three technologies reveals that activated carbon would be the most cost-effective alternative if the project is expected to last 6 years or longer. The other two technologies (air stripping and UV/H_2O_2) are not significantly affected by changes in contaminant concentration; therefore, their operating costs remain relatively constant over the life cycle of the project. If the designer only relied on the present worth analysis, he or she may not have selected the most cost-effective choice.

3.6.3 Capital and Operating Cost Considerations

3.6.3.1 Capital Cost Considerations

Another important factor to consider when designing leachate and ground-water treatment systems is the cost of money. The annual cost of short-term projects is greater than the cost of long-term projects, such as wastewater treatment systems. Annual costs of financing a project are calculated from the following formula:

$$a = \frac{\text{capital}}{[1-(1+i)^{-N}]/i}, \qquad (3\text{-}3)$$

where

a = annual cost

i = interest (assumed at 8 percent)

capital = an assumed investment

N = life of the loan

Calculating the annual costs of projects of varying lengths (up to 10 years) illustrates the effect of time. Figure 3-2 shows the impact of the annual cost of money for a project with a capital cost of $50,000 and an interest rate of 8 percent. For a 1-year project, the annual cost would be $54,000; for a 5-year project, the annual cost reduces to $12,500; and for a 10-year project, the annual cost further reduces to $7,500.

The effect of this phenomenon is two-fold. First, purchasing costly equipment that might complete a finite project in a shorter time may be more expensive than purchasing inexpensive equipment and using it longer. Secondly, renting equipment may be more cost effective than purchasing equipment with a long service life.

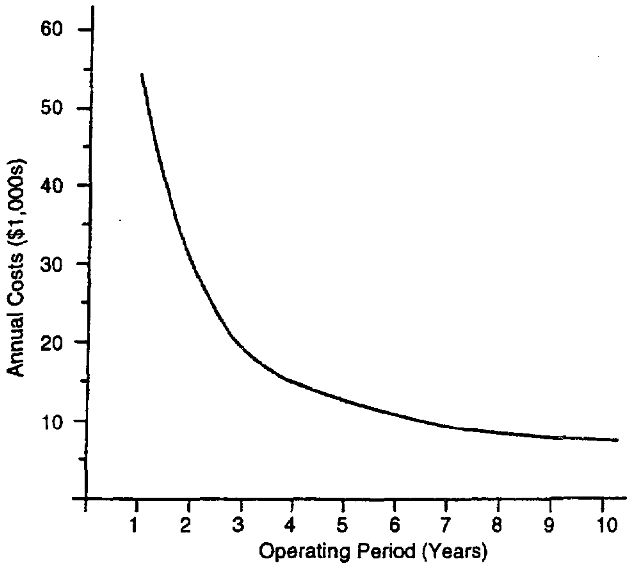

Figure 3-2. Annual costs versus time for an initial investment of $50,000.

Another option that may make the purchase of equipment cost effective is reuse at another site. The equipment owner may have multiple sites that can be remediated with the same equipment. The option to remediate other sites at a later date may be a cost-effective approach based solely on equipment expenditures. Other factors, however, such as regulatory deadlines, may make this option infeasible. In addition, equipment planned for use at multiple sites must be easily transportable.

3.6.3.2 Operational Cost Considerations

Operating labor can have a major impact on the overall annual cost of a ground-water and leachate treatment system. If an operator is hired at $10 per hour to operate the treatment system for 8 hours per day, 5 days per week, the annual cost would be $10/hr x 40 hrs/week x 52 weeks = $20,800/yr. The cost of operating labor can easily approach the cost for other operating expenses, even without any allowance for employee benefits. For smaller treatment systems, labor expenses can increase the operating costs to a high percentage of the capital cost.

If labor costs are expected to be excessive, the engineer of the treatment system should evaluate alternatives for reducing operating costs by automating the equipment. Some operator attention is always required; however, the potential for savings by automating should be considered in the life cycle design.

3.6.4 Summary

Ground-water and leachate treatment system design should be flexible and consider the possibility of changing field conditions in the design and cost analysis of technically and economically attractive alternatives. Very few projects will fall into the "rapid cleanup" category; therefore, long project life will most likely be required. Due to the time value of money, rapid cleanups for finite problems may not be cost effective if expensive equipment is used for a short period unless operating costs are significantly less. Also, operator attention may be costly, so reducing this annual expense in favor of automation may prove economically attractive.

3.7 Staging/Phased Treatment

For both ground-water and leachate treatment, loading is anticipated to decrease with time, unless slug concentrations are expected. A consideration should be given to designing the treatment system with sufficient turndown capability.

3.8 Residuals Management

One of the most significant issues encountered in designing treatment systems is the management and disposal of waste residues generated from treatment processes. Types of wastes include:

- Suspended solids sludges resulting from wastewater sedimentation or filtration processes.
- Concentrated brine solutions generated from reverse osmosis separation processes.
- Metal sludges produced by chemical precipitation reactions.
- Spent carbon from activated carbon adsorbers.
- Concentrated ion exchange regenerant solutions.
- Waste biological solids.

This section addresses the types of solid and liquid waste residues associated with treating contaminated ground water and leachate. Several types of solid waste generated from treatment processes and the methods of handling them are described below. In addition, Section 8.3 discusses control of air emissions from ground-water and leachate treatment processes.

3.8.1 Solids

3.8.1.1 Suspended Solids Sludge

The removal of particulate and colloidal organic and inorganic contaminants, as well as biological sludges, is a primary goal for pretreatment or treatment of contaminated ground water and leachate. Suspended solids removal is often enhanced by the addition of a polyelectrolyte, which causes the electrostatic surface charge on the particles to be destabilized and results in particle agglomeration (smaller particles join together to form larger particles, which are more easily settled and/or filtered from suspensions). This sludge can then be further dewatered prior to disposal. Disposal is typically to a landfill but can be by incineration, if appropriate.

3.8.1.2 Biological Sludge

Biological sludge is a slurry high in suspended solids (0.5 to 2 percent) that is produced from a biological treatment process such as the activated sludge or its modifications. Parameters used to define acceptable sludge stability include odor, pathogens, toxins, and dewaterability (13). A range of sludge stabilization options exists for the thickened sludge; these include digestion, lime treatment, irradiation, drying, and incineration. None of these, however, provides complete stabilization.

Sludge dewatering typically occurs after the stabilization step and before disposal, which could be by landfilling, landspreading, or incineration.

3.8.1.3 Heavy Metal Sludges

As described in previous sections, the most common method used to treat dissolved heavy metals is chemical precipitation. This is a unit operation in which soluble metal ions are converted to insoluble salts. These salts are removed from solution by sedimentation or direct filtration. The result is a clarified supernatant or filtrate and concentrated, metal-containing sludge.

The extent of the metal precipitation reaction can be approximated by considering the equilibrium constants of the reacting species but is better estimated through treatability studies. System kinetics are also important because, in some instances, insufficient time is available for equilibrium to be achieved. Predicting criteria for optimal metal removal versus the volume of sludge generated is a complex process. Kinetic and equilibrium features can most accurately be assessed through treatability studies. The amount of sludge produced, the mass of metal (total) within the sludge, the mass fraction of individual metals, and the physical settling characteristics must be examined for each treatability option. These will determine appropriate procedures for sludge handling, including the extent of dewatering necessary and mode of ultimate management.

As an example, the effect of pH on sludge volume in the precipitation treatment of a wastewater containing copper, cadmium, lead, and zinc is shown in Figure 3-3. In this case, optimal effluent treatment conditions, representing discharge limits obtained with lowest sludge volume, occurred at pH 8.5. The volume of sludge at pH 8.5 was approximately 33 percent lower than at pH 9.5. Operating at the lower pH not only reduced the amount (and costs) of chemical additions but lowered the disposal cost by generating less sludge. Additionally, final effluent pH adjustment was unnecessary because the discharge pH limit was 6.5 to 9.0.

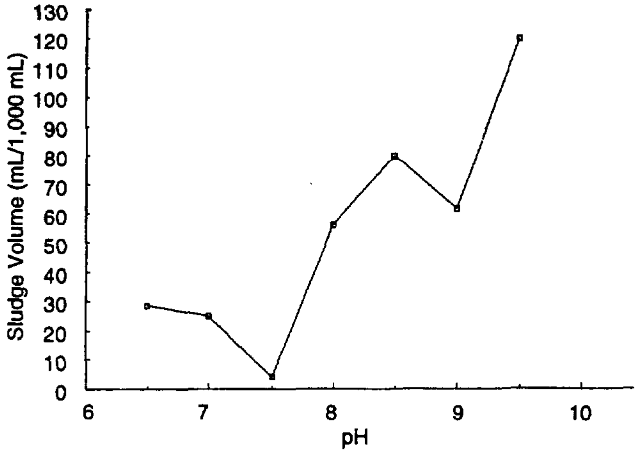

Figure 3-3. Sludge volume produced as a function of treatment pH (14).

3.8.1.4 Solids Handling

To minimize the potential liability and costs associated with disposal, the volume of sludge generated should be minimized and/or the residual should be classified as nonhazardous. The volume of sludge produced can be reduced by optimizing the precipitation process, such as by obtaining an effluent quality that meets permit limits yet avoids excessive chemical addition. A second way to minimize the volume of sludge to be disposed of is to remove as much water as possible. Several types of dewatering unit operations are described below.

3.8.1.5 Sludge Thickening

Gravity or flotation thickeners can double the sludge solids concentration by inducing the sludge to release water and thicken. For example, gravity thickening of lime sludges has been reported to increase the solids content to 30 percent when thickener loadings of 12.5 lb/day ft^2 (61 kg/day m^2) have been used. Gravity thickening of alum sludges has increased the solids content from 1 to 2 percent at loadings of 4.0 lb/day ft^2 (19.5 kg/day m^2) (15). The supernatant from a sludge thickener is generally returned to the head of the treatment process.

Conditioning can further enhance sludge dewatering characteristics. It has been reported that hard-to-dewater sludges, such as those produced during the hydroxide precipitation of metals, can be conditioned by heating. Schroeder (16) reported that vacuum filtration of a heat conditioned sludge increased the solids content by nearly 21 percent. Thermal conditioning, however, may not be practical because of the high capital and maintenance costs associated with the process.

Chemical sludge conditioners can also be added to enhance settling and dewatering. Typically, long-chain charged organic compounds, such as polyelectrolytes, are added to cause the sludge particles to further agglomerate and settle. Inorganic conditioners such as ferric chloride ($FeCl_3$) and lime (CaO) can also enhance sludge dewatering.

3.8.1.6 Final Dewatering

Several unit processes are available for final dewatering. These include vacuum filters, centrifuges, and belt or plate and frame filter presses. Vacuum filtration of a thickened lime sludge has been shown to increase the solids content from nearly 30 percent to about 65 percent (15). The filter may be precoated (e.g., with diatomaceous earth) to enhance dewatering and sludge release.

Centrifuges also increase the solids content of a thickened sludge. A centrifuge is a mechanical device that uses centrifugal force to separate solids from liquids. Rates of solids capture by centrifuges of 70 to 95 percent have been reported (15). One problem with centrifugation is the potentially high operation and maintenance (O&M) costs associated with this unit process. To reduce O&M costs, filter presses can be used. Filter pressing a lime sludge can achieve a solids content of 60 to 65 percent (15). Tradeoffs between solids content (percent volume reduced) as a function of a given dewatering process and disposal and O&M costs must be considered.

During final dewatering, it may be advantageous to add a stabilization chemical, such as trisodium phosphate, lime or cement kiln dust, or Portland cement. These stabilization chemicals bind heavy metal contaminants that could otherwise cause the sludge to be classified as a hazardous waste.

Another "dewatering" method is incineration, which includes control of gaseous particulate and vapor emissions. This process may be useful if the sludge has a high content of organic compounds; however, incineration can have a high O&M cost. In addition, because many industrial sludges are primarily inorganic and less than 75 percent combustible, a substantial amount of ash—typically hazardous—may need disposal.

3.8.2 *Liquid Wastes*

3.8.2.1 Ion Exchange

Typically, an ion exchange process, like a fixed bed carbon column, is operated continuously in a bed or packed column. Contaminated water is passed through the column until the contaminant concentration in the column effluent exceeds a required level, i.e., breakthrough.

At breakthrough, the column resin is "spent" and must be regenerated. Regenerating the resin involves reversing the exchange reaction using a concentrated solution of ions to exchange with the resin-bound contaminant ions. First, the exchange column is backwashed to remove accumulated solids. The resin is then regenerated by passing the concentrated regenerant solution through the column until the original exchange resin ions have displaced the resin-bound contaminant(s). The resultant regenerant brine and rinsewater must be managed.

A list of potential alternatives available for the management of the spent brine include disposal on land, disposal to sanitary sewers, and deep well injection. Depending on the brine characteristics, pretreatment may be required. For disposal to land, typical options available are landspreading, lagooning, and landfilling. If the brine is discharged to a sanitary sewer, it eventually discharges with the treated sewage effluent. Disposal of spent brine to saline aquifers simply returns the brine to an aquifer of similar characteristics. In general, the degree of pretreatment and choice of ultimate disposal alternative is largely governed by cost and regulatory considerations.

3.8.2.2 Reverse Osmosis

Proper design considerations for reverse osmosis eliminate many of the concerns about excessive power requirements, fouling due to inadequate pretreatment, and poorly designed clean-in-place procedures. The primary disadvantage is the disposal of concentrated "brine" solutions resulting from the concentrating of dissolved solids. Disposal methods have included deep well injection and evaporation ponds.

3.8.3 *Air Emissions*

3.8.3.1 Air Stripping

Air stripping involves the transfer of volatile organic compounds from the liquid to the air stream. A liquid-gas contactor (e.g., packed tower) is typically employed. The organic compounds transferred from the water contaminate the stripper off-gas. Air emissions of this type are regulated by the Clean Air Act, and, depending on the applicable requirements, further treatment may be needed. Common air emission controls are carbon adsorption, thermal incineration, catalytic oxidation, and flaring. Flares are basically open pipes that vent a combustible gas at a safe height directly to the atmosphere. The end of the pipe contains a flame device and a continuous pilot(s) to ignite the waste gas.

Many ground waters naturally contain dissolved radon in addition to the contamination from site activities. The incidental removal of radon (Rn-222) from ground-water treatment systems using activated carbon or air stripping may cause radiological exposure to the public or system operators. Rn-222 has a half-life of 3.82 days. Four radioactive elements immediately follow Rn-222 in the decay chain: polonium-218, lead-214, bismuth-214, and polonium-214. These elements have very short half-lives. Air modeling can be used to estimate releases from air stripping units. Vessel shielding can be used for reducing exposure from radionuclides adsorbed onto carbon, which eventually decay.

3.8.3.2 Biological/Equalization Tanks

Three mechanisms of volatile organic compound (VOC) removal in wastewater treatment have been identified: volatilization to the atmosphere, sorption, and biodegradation (17). Several models are available that predict the VOC fate in various unit processes.

Tramp or fugitive emissions of VOCs may be regulated by the Clean Air Act. Collection of fugitive emissions is a difficult task; however, emissions may be reduced by covering untreated and partially treated ground-water unit processes, such as the equalization tank shown in Figure A-17. If the emissions can be collected, they can be treated by GAC adsorption, thermal incineration, or catalytic oxidation.

3.9 Availability of Package Plants

Package plants can be purchased as complete aqueous-phase treatment systems that are mounted on skids or in trailers. Many of the traditional technologies used for wastewater treatment (e.g., sedimentation, biological oxidation, filtration) can be directly applied or modified for treatment of ground water and leachate. In addition, other applicable treatment technologies (e.g., air stripping, granular activated carbon) are easily adaptable to a package plant configuration. Many of the innovative technologies not discussed in this manual, such as wet air oxidation and anaerobic fixed film, are also available in package plants from vendors. Because package plants are limited in size by transport requirements, they are usually of low capacity (more than 100 gal/min or more than 380 L/min). Their small size and capacity make package plants ideal for many ground-water and leachate treatment applications.

Many market-niche companies specialize in the design and manufacturing of specific types of package plants. Complete, ready-to-operate package plants are offered at lower prices than field-constructed systems because shop assembly and fabrication costs less than field erection. Because package plant size is restricted, parts are similar and design engineering costs are significantly reduced, typically consisting only of system upgrades and special modifications. Similarly, construction costs for package plants are lower because piping, wiring, and assembly are completed by factory workers under ideal shop conditions. Startup costs are also reduced because experienced factory field technicians require less time to get equipment on line. The availability of spare parts makes field repair simply a matter of parts exchange, as opposed to the special fabrication/construction required with permanent systems. Package plants are excellent for temporary ground-water and leachate treatment installations where the technology has been well documented based on previous experience for similar applications.

3.9.1 Description

Skid-mounted or trailer-mounted package plants are available for all treatment processes normally used to remove contaminants from ground water and leachate. Table 3-4 contains a list of the most common vendor-supplied biological and physical-chemical package plants that are available for treatment of ground water and/or leachate. Basic information about each process is also provided.

Package plants are usually installed on a structural steel skid. The skids are fitted with fork truck slots and/or lift eyes to facilitate easy loading and unloading. Some process equipment, such as tanks, have the lift eyes/fork truck slots attached directly to the tanks. Hold-down connections may be installed to prevent overturning in high winds or earthquakes. Many skid designs are provided with secondary containment systems to collect spills and leakage.

Piping and wiring on package plants are usually installed at the factory. Connections for pipes should be provided at the perimeter of the skid for convenient field hookup. Electrical wiring is enclosed in conduit between the control panel and electrical devices, motors, and instruments. Electrical connections usually are provided in terminal boxes for remote devices such as motors, controls, and signals. Power connections are normally made directly to the terminals inside of the control panel, on the skid.

Process equipment may consist of fabricated items such as mixing tanks, settling tanks, reactors, packed columns, filters, pressure vessels, and machines such as belt presses and centrifuges. These items are bolted or welded to the skids along with secondary process equipment such as pumps, blowers, air compressors, and vacuum pumps. Miscellaneous equipment such as valves, instruments, and controls should be installed in the piping and connected to the control panel at the package plant factory.

3.9.2 Field Installation

Foundations must be provided at the site for package plants. At a minimum, the ground should be leveled and compacted. A few inches of gravel or crushed stone should be placed over clay or topsoil to provide drainage and support. Timber can also be used to support package plants. Most soils can support approximately 2,000 lb/ft^2 (9,765 kg/m^2); therefore, sufficient timbers should

Table 3-4. Available Package Plants

		Physical Information			
Type of Plant	Description	Flow Rate (gal/min)	Typical Size[a] LxWxH (ft)	Max. Hp	Common Chemical Requirements
Activated sludge	Package plants include cylindrical or rectangular aeration tanks and clarifiers, positive displacement blower, air diffusers, sludge recycle pump, sludge waste pump, chemical feed pumps, and control panel. Liquid flow meters for influent and recycle flows are typical instrumentation. Air flow meters and pH monitors are useful but not mandatory.	1-10 10-50 50-100 100-200	23x12x12 45x24x12 45x50x12 45x100x12	5 15 25 47	Ammonium chloride, phosphoric acid
Sequencing batch reactor (SBR)	Package plants include one or two rectangular SBR tanks, blowers, air diffusers, influent pumps, waste sludge pump, effluent pump, and chemical pumps. The control panel may contain a logic controller to operate the equipment in a batch sequence mode. Some systems use a floating mixer instead of the sludge pump for mixing sludge with the accumulated wastewater before the aeration step, and others use the sludge pump. A floating decanter removes clear water from the reactor water surface at the end of a treatment cycle. Some SBR systems offer a sludge digester (extended aeration) chamber with separate blowers to reduce the volume of sludge solids.	1-10 10-50 50-100	20x10x12 30x15x14 40x20x14	7 40 80	Ammonium chloride, phosphoric acid
Biological fluidized bed	Package plants include an enclosed vertical cylindrical vessel, influent pump, air compressor or blower, air diffuser, effluent recycle pump, and media/biomass separation tank. Flow meters for influent and effluent recycle are essential. Some systems use an ozone generator to enhance the biomass growth if contaminant concentration is great. A clarifier may be needed to remove fine biomass particles from the effluent. Nutrient feed pumps and chemical storage tanks may be required, depending on the feedwater characteristics.	1-10 10-50 50-100 100-400	13x7x15 18x10x15 18x12x15 18x16x15	7 10 12 40	Ammonium chloride, phosphoric acid
Rotating biological contactor (RBC)	A package plant RBC has a skid-mounted vat, rotating disc pack, chain drive, and variable speed motor. The discs may be covered for odor and emission control, or for weather protection. The cover must be vented to permit air to circulate past the upper, exposed surface of the discs. Controls include a switch for the speed reducer and a disc speed controller. If a clarifier is not included with the RBC, a separate clarifier will be required, because biological solids exit the RBC with the effluent. Sludge is not recycled to the RBC. A sludge pump is required to remove sludge from the clarifier. An influent pump may be supplied with the RBC, and an influent flow meter is required. Nutrient stock tanks and chemical feed pumps may be required.	1-10 10-50 50-100 100-200	8x6x6 10x11x12 20x11x12 16x16x18	1 5 10 20	Ammonium chloride, phosphoric acid
Fixed film reactor	A package plant includes a rectangular tank that contains the media cell and a clarifier cell. An influent pump may be included. Other equipment includes a blower for air, effluent recycle pump, effluent discharge pump, and sludge pump. Large fixed film reactors may require a separate clarifier. Flow meters for influent, recycle, and effluent are required. An air flow meter is optional. Chemical pumps are optional depending on nutrient requirements.	1-10 10-50 50-100	9x9x9 24x12x12 24x24x12	6 17 34	Ammonium chloride, phosphoric acid
Wet air oxidation	Package plants have a high-pressure feed pump, influent/effluent heat exchanger, oxidation reactor tower, air compressor, steam boiler, gas separation effluent tank, and control panel. Instrumentation includes pressure and temperature gauges, temperature controls, and pressure controls. An influent or effluent flow meter is required. The control panel has starters and switches for the equipment motors. A recorder for the process variables is a helpful option.	1-10 10-50 50-100	8x7x15 16x12x15 18x12x22	15 40 75	None

Table 3-4. Available Package Plants (Continued)

		Physical Information			
Type of Plant	Description	Flow Rate (gal/min)	Typical Size[a] LxWxH (ft)	Max. Hp	Common Chemical Requirements
Activated carbon	Package systems include one to three pressure vessels on a skid, interconnecting piping, a feed pump, optionally a backwash pump, pressure gauges, differential pressure gauges, influent flow meter, backwash flow meter, and control panel. Valves may be manual or powered, with automatic controls. A separate backwash tank may be required for storage of clean water, and storage for spent carbon should be provided. Disposable coated carbon steel or plastic pressure vessel adsorbers are available. Permanent pumps, pipes, and connection hoses are required. Spent adsorbers are disconnected and sent to regeneration centers or disposal landfills. Powdered activated carbon (PAC) package plants are also available. PAC is typically added to an activated sludge package plant by mixing with water and metering into wastewater as a slurry. Mixers, mix tank, eductors, and metering pumps are included in PAC package plants.	1-10	12x8x8	2	Activated carbon
		10-50	14x8x8	7	
		50-100	20x10x8	10	
		100-200	20x20x8	20	
Air stripping	Package plants consist of a tall packed tower or compact tray tower, feed pump, air blower, and effluent pump. Flow meters for influent and air flow are required. An influent throttle valve and blower damper are required to adjust the air/water ratio. A chemical tank and chemical pump may be included to backwash the tower packing with an acid solution. Alternatively, the influent pump may be used to recirculate the acid wash solution over the packing. Low and high level switches in the reservoir at the base of the packed tower may be included to protect the effluent pump from running dry and to signal an alarm if the reservoir overflows. Air discharged from the air stripper may need treatment with vapor-phase carbon.	1-10	4x4x20	2	Acid or chlorine for packing wash
		10-50	6x8x25	5	
		50-100	7x10x30	8	
		100-400	8x12x40	20	
Metal reduction and precipitation	Package plants have a rapid-mix tank, flocculation chamber, and settling tank. The tankage can be rectangular or circular. Inclined plate gravity separation or circular clarifiers are used for settling. Typical equipment includes a rapid mixer, flocculator and drive, feed pump, sludge pump, acid and caustic soda pumps for pH control, and a polymer pump. Chemical storage tanks or shipping containers may be used to hold acid and caustic soda. If polymer addition is required, a mixer and solution tank are needed. The control panel encloses motor starters, switches, and a pH controller. An influent flow meter is required to permit monitoring of chemical feed rates. Some form of filter may be required downstream to remove fine particulates from the effluent. If sludge treatment is necessary, a vacuum filter, belt filter, or filter press may be required. A sludge thickener hopper is available for some gravity plate separators. Otherwise, a separate sludge holding tank or thickener may be required.	1-10	8x4x9	3	Acid, caustic soda, polymer, lime, alum, ferric chloride, calcium chloride
		10-50	10x4x13	5	
		50-100	11x6x14	7	

Table 3-4. Available Package Plants (Continued)

Type of Plant	Description	Physical Information Flow Rate (gal/min)	Typical Size[a] LxWxH (ft)	Max. Hp	Common Chemical Requirements
Reverse osmosis	Granular activated carbon adsorption and pH adjustment pretreatment may be required and are available as package plant options. An acid metering pump is part of the pH control system. Reverse osmosis package plants require 5- or 10-µm cartridge prefilters, a high-pressure feed pump, reverse osmosis modules, pressure vessels, and a backpressure valve. Pressure and temperature gauges are required at the inlets and outlets of prefilters and pressure vessels. A temperature gauge and high-pressure stop switch are installed in the feed pump discharge piping. A low-pressure switch in the feed pump suction piping stops the pump if suction pressure goes negative to prevent disastrous cavitation. The control panel contains motor starters, control switches, and a pH controller if required. Flow meters on influent, effluent (product), and reject (brine) are required to balance the flows. The concentrated brine may require disposal by evaporation. Piping is usually stainless steel and requires careful assembly to prevent leaks. An optional wash tank and pump are available to clean the modules.	1-10 10-50 50-100	8x3x6 12x6x6 14x12x8	13 35 85	Carbon, sulfuric acid, detergent, citric acid
Ultrafiltration/ Microfiltration	Package plants have a prefilter or screen, high pressure feed pump, membrane or ceramic media modules, pressure vessels, and backpressure valve. High- and low-pressure switches protect the system and pump, respectively. Temperature controls and a heat exchanger may be provided, because some concentrate may be recycled. Pressure gauges and temperature gauges are installed at inlets and outlets of all pressure vessels and prefilters. Flow meters are provided for influent, permeate, and concentrate. A source of cooling water may be required. Concentrate disposal may require additional equipment such as an evaporator. Cleaning solution recirculation systems are optional.	1-10 10-50 50-100	8x4x6 20x8x8 40x12x8	10 45 80	Cleaning detergent for washing the modules, caustic soda or acid for pH adjustment
Ion exchange	Package plants include resin-filled pressure vessels, regeneration chemical tanks, and waste brine storage tanks. Acid and caustic soda solution pumps are provided to regenerate the resin. Controls include conductivity meters and pH meters for regeneration. Piping may include manual valves or powered valves that are controlled by programmable logic controllers (PLCs). A feed pump is required if line pressure is insufficient. Flow meters are required on the influent and regeneration lines to the pressure vessels. A totalizer in the effluent pipe is useful to predict the remaining life of the resin before regeneration is required. Spent acid and caustic soda brines may be combined and neutralized. Some metals are recoverable; however, the disposal of spent brines needs consideration. Resins can be selected that are ion-specific; they will remove selected metals only.	1-10 10-50 50-100	8x3x6 14x5x8 17x6x10	3 10 12	Acid, caustic, sodium chloride

Table 3-4. Available Package Plants (Continued)

		Physical Information			
Type of Plant	**Description**	**Flow Rate (gal/min)**	**Typical Size[a] LxWxH (ft)**	**Max. Hp**	**Common Chemical Requirements**
Filtration: Down-flow pressure filters	Package filters consist of one or more pressure vessels on a skid. A feed pump, backwash pump, interconnecting piping, and manual and/or powered valves complete the system. Flow meters for influent and backwash are required. Compressed air may be used for air scour during backwashing, and a compressor may be provided with an air flow meter. Differential pressure gauges measure headloss across each filter. Sophisticated filter systems automatically backwash each filter on a timed cycle or when differential pressure switches trigger the backwash cycle. Control panels enclose starters and switches. Logic for backwashing is programmed into a PLC or mechanical cycle timers. A backwash storage tank is required if not provided on the skid. Multiple filter systems may have sufficient capacity to backwash one off-line filter with on-line filter effluent. Spent backwash is normally recycled to the plant influent equalization tank. Effluent is pressurized sufficiently for discharge at some distance from the filter.	1-10 10-50 50-100 100-250	10x4x8 14x6x8 18x8x8 24x10x8	2 3 5 15	None
Filtration: Upflow filters	Upflow package filters consist of a cylindrical open top tank and an air compressor for the air lift sand recycle system. Usually, upflow filters are fed by gravity flow from an upstream process, such as a parallel plate gravity separator. If a feed pump is required, a static leg influent pipe is required to prevent drainage of the filter through the pump. Controls and instruments include an influent and effluent flow meter and a flow meter and pressure regulator for the air lift system. Backwash continually flows to the influent end of the treatment system. Effluent pressure is limited to the height of the filter tank.	1-10 10-50 50-100 100-300	4x4x10 5x5x12 6x6x13 8x8x18	0.5 1 3 7.5	None
Polymer addition	A manual package polymer system consists of a mix tank, propeller mixer, chemical feed pump, and eductor. Starters and switches for the motors are enclosed in a control panel. Automatic systems are available that meter the liquid or dry polymer into a mix tank, fill the tank with water, mix the solution, and transfer the solution to a stock tank. The mixing process is repeated automatically when the stock tank is almost empty. The automatic system may require a polymer solution metering pump. These polymer systems need power and a water supply to operate.	1-10 10-50 50-100	6x3x5 15x6x6 20x8x7	1 1.5 2	Water under pressure, polymer (powder or liquid)
Anaerobic treatment	Package plants include an anaerobic contact tank, a degassifier, and a solids settling tank. Variations of the process have a two-stage anaerobic contact system consisting of an acid-phase tank and the methane former phase tank. The contact tanks may have fixed media or may be of the fluidized bed type that uses sand or granular activated carbon media. Gas fired heaters may be provided. Accessories include a methane gas vacuum pump, solids recycle pump, solid waste pump, influent pump, and mechanical or gas recycle sparger mixing system. Instrumentation includes an influent flow meter, recycle flow meter, gas production totalizer, and pH meter. Chemical pumps may be required for phosphorus, nitrogen, and pH control. A control panel encloses all motor controls. Because of the relatively long hydraulic retention time for anaerobic water treatment, large contact tanks are required, and multiple units are necessary for larger flow rates.	1-10 10-50 50-100	40x10x9 40x20x9 80x20x9	7 15 30	Ammonium chloride, phosphoric acid, lime

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[a] Dimensions are for overall envelope of the erected package plant, as obtained from manufacturer's literature.

be provided under the equipment to result in a soil pressure that does not exceed 2,000 lb/ft^2 (9,765 kg/m^2).

Concrete pads also serve well to support package plants. A 6-in. (15-cm) thick reinforced concrete pad usually suffices, because the concrete is sandwiched between soil and the package plant skid. If the loads are concentrated on legs, concrete may have to be thicker. In special cases, a structural engineer may be needed to design the concrete pad.

Crushed stone or gravel and timber foundations are suitable for projects that last less than 1 year. Longer projects may require concrete foundations. In cold climates, a low-cost metal or wood building may be required to prevent pipe freezing and provide security. Fencing may be sufficient for security in warm climates or where the project will not last through a winter.

Loading and unloading package plants may require special equipment. Large, bulky systems and tanks probably need to be unloaded with cranes. Spreader bars should be used to keep lift cables and chains away from vulnerable pipes and instruments. Large fork trucks are recommended for unloading skid-mounted equipment. The fork truck needs sufficient capacity to unload the equipment yet must be able to clear overhead power lines for safe unloading operations.

Power for skid-mounted package plants is usually 460 volts, three-phase, 60 cycle. Poles and a power line may have to be installed by the local electric utility company, with a transformer, kilowatt-hour meter, and power disconnect switch. The package plant can be connected to the power supply with Type S0 cable, direct burial cable, or overhead lines. Type S0 cable can be laid on the ground for temporary installation; however, buried or suspended lines are recommended for projects that extend beyond 6 months. Check local and national codes for exact requirements.

3.10 Materials of Construction and Materials Compatibility

The selection of proper materials of construction has a significant impact on the successful design of groundwater and leachate treatment systems. The safety of operating personnel and surrounding equipment can be jeopardized if chemical attack occurs in pipes and vessels of incompatible materials. Sudden failure or leakage of deteriorating pipes can cause corrosion, violent reactions, fires, and explosions that might lead to injury and property damage. The importance of material selection on the successful outcome of a project cannot be overemphasized.

The three primary classes of equipment that require careful selection of materials of construction include:

- Fabrications
- Pipe and fittings
- Elastomers

Brief descriptions of each of these primary equipment classes are discussed further below. Also, guidelines to assist in the selection of proper materials of construction are provided in Table 3-5.

3.10.1 Fabrications

Equipment that is not normally mass produced can be built to specifications and drawings in fabrication shops. Examples of specialized treatment system fabrications include tanks, pressure vessels, mounting platforms, support structures, access stairs, and unique machinery. Fabrications can be manufactured from various metals or plastics, and shops usually specialize in one or the other material of construction.

Carbon steel fabrications are suitable for many normal applications at low cost. Bare steel may be suitable for use on short projects or for noncorrosive service. Additional steel thickness is usually provided for corrosion allowance. Enamel paints protect steel fabrications for about 2 to 5 years. For projects of longer life expectancy, epoxy paints give better protection (up to 20 years). Fabrication interiors are usually sandblasted and coated with epoxy or phenolic resins where corrosion will be encountered. Steel fabrications have monetary value at the completion of a project and are usually recycled as scrap metal.

Fiberglass is used for many applications in corrosive environments. Stair treads, handrails, and grating provide maintenance-free service and are aesthetically pleasing in appearance. Fiberglass tanks offer flexible design and long life (10 to 20 years) for containing corrosive fluids at reasonable cost.

Some caution should be exercised when selecting fiberglass for a particular application. For example, after the fiberglass resin cures, major modifications to the fabrication are difficult and require specialized, skilled labor. Bolted adapters are available, however, for assisting in making field modifications to fiberglass tanks. Fiberglass can be used for only limited pressure and temperature applications, and only if designed properly. Incompatible solvents also tend to dissolve the fiberglass resin.

Fiberglass fabrications are usually very specific and have little salvage value after a project is completed. Disposal of fiberglass fabrications may also be a cost consideration. Fiberglass construction is usually cost-effective for smaller tanks; however, stainless steel may offer cost savings and similar corrosion resistance for larger tanks.

Stainless steel provides excellent service for applications where solvents would be expected to attack coat-

Table 3-5. Guidelines for Selecting Proper Materials of Construction

Application	Suitable Material of Construction Carbon Steel	 Stainless Steel	 Fiberglass	 Plastics[a]	 Elastomers[a]	 Coatings
Skids	X					X
Panels	X	X	X			
Pressure vessels	X	X	X			X
Small tanks		X	X	X		
Large tanks	X					X
Gaskets					X	
Hoses				X	X	
Acid service		X	X	X	X	
Base service	X		X	X	X	
Solvents	X	X			X	
Structures	X		X			X
Covers			X			
Biogas storage	X			X	X	
Pumps	X	X	X	X	X	
Mixers		X				X

[a] Refer to Tables 3-6 and 3-7 for specific material.

ings and plastics. Types 302 and 304 stainless steels offer good corrosion resistance for most applications at low cost. Some fatty acids, organic compounds containing chromium and arsenic, and chlorides (such as hydrochloric acid) may cause stainless steels to develop stress cracking and pitting corrosion. Calcium chloride (an inorganic coagulant) and ammonium chloride (a source of nitrogen) are chemicals that are commonly used for wastewater treatment. Other chlorides such as zinc chloride, mercuric chloride, and sodium chloride may be present in the water being treated. If these compounds are present at high concentrations, other materials or grades of stainless steel should be considered.

By adding 2 to 3 percent of molybdenum to stainless steel, the stress cracking and pitting corrosion tendencies can be reduced. Type 316 stainless steel has improved corrosion resistance to many compounds as a result of increased molybdenum content. Type 316 stainless steel can handle all concentrations of phosphoric acid, as well as sulfuric acid concentrations below 20 percent and above 85 percent. The treatment system designer should consult the corrosion resistance guides for stainless steel for a comprehensive listing of compounds that do not affect stainless steel. Because stainless steel is expensive, only wetted surfaces of tanks are fabricated from the metal.

Structural members of painted carbon steel are typically welded to stainless steel tanks to provide support at reduced cost. Stainless steel structural shapes are available in a limited number of sizes for specific applications. Stainless steel fabrications are usually not selected over other materials of construction unless there is a special consideration because of its relatively high cost. Obsolete stainless steel fabrications have salvage value as scrap metal.

Aluminum has limited use in ground-water and leachate treatment systems. It is usually found only where the fabrication weight is of critical importance, for example, floating covers for tanks and pontoons. Aluminum handrails are structures that provide decorative appearance without maintenance. Fabrication of aluminum items requires special welding techniques and skilled labor. Scrap aluminum has a relatively high salvage value.

3.10.2 Pipes and Fittings

Fluids from ground-water and leachate treatment projects are typically transferred to and from tanks, supply sources, and discharge points. The selection of proper materials for pipes and fittings depends on temperature, pH, corrosiveness, pressure, and abrasiveness. The life of a project is also a consideration. Stainless steel pipes and fittings have excellent corrosion resistance to many chemicals found in contaminated ground water and leachate. Many types of plastic pipes and fittings also offer excellent corrosion resistance for compatible materials—at a much lower cost than stainless steel. Plastic pipes may be adequate for short projects where service life will not be reduced by UV light or gradual deterioration by the contaminants. Extensive replacement of failed plastic pipes, however, may ultimately be more expensive than initially selecting the more expensive stainless steel.

For some projects, selection of pipe materials is dependent on other factors. Safety should have the highest priority. Pipes for low concentrations of sulfuric acid can be made of polyvinyl chloride (PVC) and will last for years at ambient temperatures. Breakage of PVC acid pipes, however, can cause spills that risk safety. Concentrated sulfuric acid attacks the glue in PVC pipe joints, causing leaks. At high sulfuric acid concentrations, lined steel pipes offer the highest margin of safety. When safety is a consideration, request advice from the material supplier and select the most appropriate pipe material for the application.

Many types of plastic pipe are suitable for the service encountered in treatment of contaminated ground water and leachate. Chemicals present in the water are usually in dilute form unless a treatment method concentrates the contaminant(s). Any damage to plastic pipes by dilute chemicals will be gradual and may result in pipe swelling and loss of strength over time. Corrosion resistance charts usually show the suitability of a material for various chemical concentrations and temperatures. Some chemicals become more aggressive at increased temperatures and attack some materials. Also, at elevated temperatures, the plastics may soften and lose strength, which reduces the safe pressure rating. The interaction of temperature and concentration is an important factor in material selection. Plastic pipe may be suitable for low-concentration sulfuric acid at low temperatures, but not at high concentrations (95+ percent) or temperatures over 75°F. As an alternate material, Type 316 stainless steel can handle concentrated sulfuric acid but not medium concentrations (20 to 85 percent). Final selection of piping materials should be on the basis of comprehensive corrosion guides and information from supplier experts.

3.10.3 Elastomers

Parts that flex are made of elastomers. Examples of elastomer parts are seals, gaskets, pump diaphragms, expansion joints, hose, and valve parts. Many of the synthetic and natural elastomers (e.g., rubber compounds) are attacked by chlorinated solvents. Damage appears as gumminess, swelling, cracking, and loss of strength.

Many of the elastomer part suppliers provide chemical resistance charts in their catalogs. Elastomers should be selected that have a good rating for exposure to contaminants that are likely to be present in the ground water or leachate being treated. If chemical resistance data are not available, the supplier should be contacted for recommendations. Specialized elastomer compounds such as Viton and Teflon are suitable for almost all chemical service except tetrachloroethylene (perchloroethylene), which is absorbed by Teflon. These compounds may be used with little risk where no data support the use of other elastomers. When transferring water with low concentrations of contaminants, lower grade elastomers will most likely be adequate for the life of a project. If the contaminant is pure or high in concentration or concentrated chemicals will need to be added to the treatment scheme, then specialized elastomers should be considered if safety is a requirement.

3.10.4 Chemical Resistance Tables

Table 3-6 summarizes chemical resistance information for the most commonly used materials of construction for treatment of contaminants most likely to be present in ground water and leachates from Superfund sites. Table 3-7 presents chemical resistance information for additional contaminants and chemicals that would most likely be used for the treatment of the contaminants listed in Tables 3-6 and 3-7. The materials, contaminants, and chemicals listed in Tables 3-6 and 3-7 were cross-referenced from catalogs of pipes, elastomers, and fiberglass products. Vendor catalogs usually contain detailed information on the suitability of proposed materials for chemical resistance and are excellent resources that can be easily accessed.

In Tables 3-6 and 3-7, materials of construction are noted according to suitability. An "A" rating means that the material can be used without risk at all concentrations up to 100 percent strength with the contaminant of interest. Rating a material "B" means that it is suitable for a particular contaminant under most conditions at lower concentrations and temperature. The product catalogs or vendors should be consulted to determine the exact concentrations and temperature at which use of the product becomes a risk. Products having a "C" rating for a given contaminant may be suitable only under certain temperatures and concentrations; some compounds for a given element may not be compatible for the selected material of construction. In the case of a "C" rating, the designer should definitely consult the supplier or catalog resistance charts. The "NR," or "not recommended," rating applies to products that should not be used with a given contaminant. In remote cases, certain compounds of selected elements may not attack the material under consideration, and further assessment of suppliers' chemical resistance tables might be justified if no other choice is available. In Tables 3-6 and 3-7, a numerical rating (200, etc.) has been given to the maximum temperature (°F) at which the material can be safely used for the contaminants listed. At higher temperatures, strength or chemical resistance is reduced.

3.10.5 Coatings

Tables 3-6 and 3-7 also list coatings that can be applied to steel and/or concrete that greatly improve the corrosion resistance of those materials. Preparation of the surface is usually required. Sandblasting and chemical etching with acid are typical. Some coatings may be

Table 3-6. Materials of Construction and Coatings Compatibility for Ground-Water/Leachate Treatment Systems (18-24)

	Materials of Construction								Elastomers							Coatings	
Contaminant	Carbon Steel	SS	PVC	HDPE	PP	PVDF	PTFE	Fiberglass	Rubber	Neoprene	Buna-N	Hypalon	EPT/ EPDM	Viton	Teflon	Phenolic Epoxy	Polyamide Polyester
Arsenic	NR	C	C	E	200	275	450	E	NR	E	C	NR	NR	NR	E	C	NDF
Benzene	E	E	NR	C	NR	150	450	NR	NR	NR	C	NR	NR	E	E	C	C
Cadmium	NDF	NDF	G	NDF	NDF	NDF	NDF	E	NR	E	NR	E	NR	NR	E	NDF	NDF
Chloroform	NR	E	NR	C	NR	125	450	NR	NR	NR	NR	NR	NR	E	E	NR	NR
Chromium and compounds	NR	C	C	E	125	175	450	C	C	C	C	C	C	E	E	NDF	NDF
Copper and compounds	NR	E	E	E	175	225	450	E	E	E	E	E	E	E	E	E	NDF
1,1-Dichloroethane (1,1-DCA)	NDF	NDF	NDF	C	75	125	450	NR	NR	NR	NR	NR	NR	E	E	NDF	NR
1,1-Dichloroethylene (1,1-DCE)	NDF	C	NR	NR	125	225	450	NR	NR	NR	NR	NR	NR	E	E	NDF	NDF
1,2,-trans-Dichloroethylene (1,2-trans-DCE)	NDF	C	NDF	NR	125	225	450	NDF	NR	NR	NR	NR	NR	E	E	NDF	NDF
Ethylbenzene	C	E	NR	C	NR	125	450	NR	NR	NR	NR	NR	NR	E	E	NDF	NDF
Lead	C	C	C	E	NDF	NDF	NDF	NDF	C	C	G	C	C	E	E	NDF	NDF
Methylene chloride	NR	E	NR	C	NR	125	450	NR	NR	NR	NR	NR	C	G	E	NR	NR
Polychlorinated biphenyls (PCBs)	NDF	NDF	NDF	NDF	NDF	NDF	NDF	NDF	NR	NR	NR	NR	NR	E	E	NDF	NDF
Perchloroethylene (PCE)	C	E	NDF	C	NR	275	450	G	NR	NR	NR	NR	NR	E	E	E	C
Phenol	NR	E	NR	SS	150	125	450	NR	E	G	NR	G	NR	G	E	C	NR
Toluene	E	E	NR	C	NR	175	450	C	NR	NR	C	NR	NR	E	E	G	C
1,1,1-Trichloroethane (1,1,1-TCA)	NDF	NDF	NDF	C	NR	150	450	C	NR	NR	NR	NR	NR	E	E	C	NR
1,1,2-Trichloroethylene (1,1,2-TCE)	C	E	NR	C	NR	275	450	NDF	NR	NR	NR	NR	NR	E	E	NR	NR
Xylenes	E	E	NR	C	NR	200	450	NDF	NR	NR	C	NR	NR	E	E	E	E
Zinc and compounds	NR	C	E	E	175	200	450	NDF	G	C	C	C	E	E	E	C	C

Key	C	Conditional; consult supplier	HDPE	High density polyethylene	PVC	Polyvinyl chloride
	E	Excellent, all concentrations	NDF	No data found	PVDF	Polyvinyl idene fluoride (Kynar)
	EPT/EPDM	Ethylene-polypropylene Diene-terpolymer	NR	Not recommended	SS	Stainless steel
			PP	Polypropylene	200, etc.	Suitable to temperature shown, °F
	G	Good, low concentrations preferred	PTFE	Polytetrafluoroethylene (Teflon)		

applied over rust on steel, but service life will not be long. Application instructions accompany each product. The designer should ask the coating suppliers for recommendations of suitable products. Proper selection of coatings can extend the life of carbon steel fabrications to 20 years or more. Without good surface coatings, steel fabrications may have a service life of between 2 and 5 years.

3.10.6 Material Compatibility

When dissimilar metals contact each other in the presence of moisture, galvanic corrosion may result. The wet metals behave like a battery and produce an electrical current. The surfaces of one or both metals become pitted and corrode as the exchange of electrons takes place. Galvanic corrosion can seriously weaken metal parts, which eventually will fail. Structures could collapse and piping could break or develop leaks if materials are incompatible.

The most common dissimilar metal combinations are carbon steel/aluminum and carbon steel/copper. When these metals are likely to be in contact, they should be coated with nonconductive material such as epoxy or phenolic paint. Elastomer membranes or gaskets can

Table 3-7. Materials of Construction and Coatings Compatibility for Selected Chemicals/Compounds (18-24)

	Materials of Construction								Elastomers							Coatings	
Chemical/ Compound	Carbon Steel	SS	PVC	HDPE	PP	PVDF	PTFE	Fiberglass	Rubber	Neoprene	Buna-N	Hypalon	EPT/ EPDM	Viton	PTFE	Phenolic Epoxy	Polyamide Polyester
Alcohol	C	E	C	E	75	75	450	C	E	E	E	E	G	G	E	C	NDF
Aluminum sulfate	NR	NDF	E	E	225	275	450	E	E	E	E	E	E	E	E	G	E
Ammonium phosphate	NR	E	E	E	225	275	450	E	E	E	E	E	E	E	E	E	NDF
Calcium chloride	NR	E	E	E	225	275	450	E	E	E	E	E	E	E	E	E	NDF
Caustic soda	C	E	E	E	200	C	450	C	G	G	C	G	E	G	E	N	RC
Chlorides	C	C	C	C	C	225	450	G	C	C	C	C	C	E	E	NDF	NDF
Chlorinated solvents	C	C	NR	C	NR	NR	450	NDF	NR	NR	NR	NR	NR	E	E	NDF	NDF
Diesel fuel, fuel oil	E	E	C	C	75	275	450	G	NR	G	E	C	NR	E	E	E	E
Ferric chloride	NR	NR	E	E	200	275	450	E	E	E	E	E	E	E	E	NDF	E
Gasoline	E	E	NR	C	75	275	450	G	NR	C	E	NR	NR	E	E	E	C
Hydrochloric acid	NR	C	G	E	200	275	450	C	C	C	C	G	C	G	E	NRC	
Hydrogen peroxide	C	E	E	E	125	75	450	C	C	NR	C	C	C	E	E	NR	NR
Lime	G	E	E	E	225	200	450	E	E	E	E	E	E	E	E	E	NDF
Oil and grease	E	E	E	C	175	250	450	NDF	NR	G	E	C	NR	E	E	NDF	NDF
Phosphoric acid	NR	E	E	E	225	225	450	E	C	G	NR	G	G	E	E	NR	C
Polymer	C	E	E	E	NDF	NDF	NDF	NDF	NDF	NDF	NDF	NDF	NDF	NDF	NDF	NDF	NDF
Potassium compounds	C	E	C	E	125	C	450	NDF	C	G	C	G	E	G	E	C	C
Sodium hypochlorite	NR	E	E	E	150	125	450	G	NR	NR	NR	E	C	E	E	NDF	E
Sulfides	C	C	C	C	150	125	450	NDF	G	G	G	G	G	G	E	NDF	NDF
Sulfuric acid	NR	C	C	C	C	200	450	C	NR	NR	NR	C	NR	G	E	NDF	C

Key C	Conditional; consult supplier	HDPE	High density polyethylene	PVC	Polyvinyl chloride
E	Excellent, all concentrations	NDF	No data found	PVDF	Polyvinyl idene fluoride (Kynar)
EPT/EPDM	Ethylene-polypropylene	NR	Not recommended	SS	Stainless steel
	Diene-terpolymer	PP	Polypropylene	75, etc.	Suitable to temperature shown, °F
G	Good, low concentrations preferred	PTFE	Polytetrafluoroethylene (Teflon)		

also be used to separate the two metals. Isolation unions are available for copper/steel pipe joints. Flanges with elastomer gaskets can be used to join large pipes of dissimilar metals. Bolts and washers should be stainless steel; the more noble metals such as stainless steel are more resistant to galvanic corrosion.

Connecting plastic to metal or different types of plastics together does not create galvanic corrosion. Different rates of thermal expansion and strength should be considered when joining plastic and metal. Plastic pipes should be threaded into metal parts. If the outer part is plastic, the inner metal part of a joint may crack the plastic outer part when tightened. When joining plastic to metal pipe, flanged joints with gaskets are recommended. Plastic has a much greater thermal expansion rate than metal. Therefore, adequate expansion joints need to be provided. If plastic and metal pipes are parallel, such as in double containment pipe applications, allowance needs to be made for the differential expansion rates. Plastic pipe installation manuals contain installation instructions and calculations for computing thermal stress for confined plastic pipe and should be consulted before installation.

Wet activated carbon in contact with bare steel causes corrosion of the steel. Tanks and pressure vessels that will contain activated carbon should be coated to resist corrosion. Suppliers of activated carbon line their pressure vessels and tanks with various elastomers or epoxy coatings. Liners and coatings must be thick and hard enough to resist scratching. Surface abrasion by the carbon may also cause corrosion.

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Chapter 4
Treatment Technology Screening Guidance

4.1 Introduction

An engineer or scientist can use several approaches in the planning stage to narrow the technology or treatment train options for a particular contaminated ground water or leachate:

- Literature information, including regulatory agency guidance.
- Best engineering judgment (BEJ) using contaminant characteristics.
- Treatability studies.

This chapter presents guidance for screening treatment technologies using each of these approaches. Section 4.2 discusses the use of information available from the literature, Section 4.3 discusses BEJ using contaminant characteristics, and Section 4.4 explains the use of treatability studies.

4.2 Literature

Available literature from industry, consultants, academia, and government sources contains ground-water and leachate treatment data. While these data may be useful for technology screening purposes, they must be used with some degree of caution if the chemical constituents or waste parameters of the ground water or leachate to be treated are different from those in the literature. The literature also includes several bench-scale studies; systems may perform differently under bench-scale conditions than under full-scale conditions. Section 4.4.4 discusses the limitations of using treatability studies for designing full-scale systems.

EPA has established best demonstrated available technologies (BDATs) for multisource leachate from land disposal operations for RCRA hazardous waste. Biological treatment systems or wet air oxidation followed by a combination of biological and activated carbon treatment systems were used to set the BDAT performance standards for multisource leachate compounds shown in Table 4-1.

Data on the removal efficiency of 11 technologies used to treat the 20 contaminants that frequently occur at Superfund sites appear in Tables 4-2 through 4-22; these data come from EPA's RREL Treatability Database (2). In Table 4-2, the technologies that demonstrated at least 90 percent removal efficiency for selected organics are shown. Tables 4-3 through 4-22 provide specific treatability data for each of the 20 contaminants.

These tables are designed to assist readers in determining whether a proposed treatment method is appropriate for the specific compound present in the ground water or leachate to be treated. Regulatory agency personnel who review water treatment plans and proposals, practicing environmental engineers who design ground-water and leachate treatment systems, and public or private research personnel should find these data summaries to be extremely useful. Although the tables are not intended to provide sufficient information to design treatment systems, their purpose is to summarize data available from many published, peer-reviewed studies on treatment of the most commonly found chemical compounds at Superfund sites. The reader is cautioned that the percent removal may include removal by incidental mechanisms, such as air stripping from a biological treatment or chemical treatment unit process. The reader is also cautioned not to judge a technology solely on the basis of a limited number of data points associated with a given concentration range.

4.3 Best Engineering Judgment Using Contaminant Characteristics

The selection of a technology can be based on the physical or chemical characteristics of the contaminant(s) (e.g., vapor pressure, Henry's Law constant, solubility, partitioning coefficient) or less defined parameters, such as biodegradability. Table 4-23 provides values for selected parameters used in technology evaluation for various compounds. The use of such data for technology screening purposes is acceptable for less complicated ground-water problems involving one contaminant or a group of similar contaminants, such as volatile contaminants.

Many tables have been published to provide guidance for technology selection based on the physical and chemical characteristics of a contaminant. Table 4-24 groups various organic compounds based on a high,

Table 4-1. BDAT Treatment Standards for Multisource Leachate (1)

Regulated Organic and Inorganic Constituents	Maximum for Any 24-Hr Composite, Total Composition (mg/L)
Organics	
Acenaphthalene	0.059
Acenaphthene	0.059
Acetone	0.28
Acetonitrile	0.17
Acetophenone	0.010
2-Acetylaminofluorene	0.059
Acrylonitrile	0.24
Aldrin	0.021
4-Aminobiphenyl	0.13
Aniline	0.81
Anthracene	0.059
Aroclor 1016	0.013
Aroclor 1221	0.014
Aroclor 1232	0.013
Aroclor 1242	0.017
Aroclor 1248	0.013
Aroclor 1254	0.014
Aroclor 1260	0.014
Benz(a)anthracene	0.059
Benzene	0.14
alpha-Benzene hexachloride (alpha-BHC)	0.00014
beta-Benzene hexachloride (beta-BHC)	0.00014
delta-Benzene hexachloride (delta-BHC)	0.023
gamma-Benzene hexachloride (gamma-BHC)	0.0017
Benzo(b)fluoranthene	0.055
Benzo(k)fluoranthene	0.059
Benzo(g,h,i)perylene	0.0055
Benzo(a)pyrene	0.061
Bis(2-chloroethoxy)methane	0.036
Bis(2-chloroethyl)ether	0.033
Bis(2-chloroisopropyl)ether	0.055
Bis(2-ethylhexyl)phthalate	0.28
Bromodichloromethane	0.35
Bromomethane	0.11
4-Bromophenyl phenyl ether	0.055
n-Butyl alcohol	5.6
Butylbenzyl phthalate	0.017
2-sec-Butyl-4,6-dinitrophenol	0.066
Carbon disulfide	0.14
Carbon tetrachloride	0.057
Chlordane	0.0033
p-Chloroaniline	0.46
Chlorobenzene	0.057
Chlorobenzilate	0.10
p-Chloro-m-cresol	0.018
Chlorodibromomethane	0.057
Chloroethane	0.27
2-Chloroethyl vinyl ether	0.057
Chloroform	0.046
Chloromethane (Methyl chloride)	0.19
2-Chloronaphthalene	0.055
2-Chlorophenol	0.044
3-Chloropropene	0.036
Chrysene	0.059
m-Cresol	0.77
o-Cresol	0.11
p-Cresol	0.77
Cyclohexanone	0.36
Dibenzo(a,h)anthracene	0.055
1,2-Dibromo-3-chloropropane	0.11
1,2-Dibromoethane	0.028
Dibromomethane	0.11
Di-n-butyl phthalate	0.057
m-Dichlorobenzene	0.036
o-Dichlorobenzene	0.088
p-Dichlorobenzene	0.090
Dichlorodifluoromethane	0.23
o,p'-Dichlorodiphenyldichloroethane	0.023
p,p'-Dichlorodiphenyldichloroethane	0.023
o,p'-Dichlorodiphenyldichloroethylene	0.031
p,p'-Dichlorodiphenyldichloroethylene	0.031
o,p'-Dichlorodiphenyltrichloroethane	0.0039
p,p'-Dichlorodiphenyltrichloroethane	0.0039
1,1-Dichloroethane	0.059
1,2-Dichloroethane	0.21
trans-1,2-Dichloroethene	0.054
1,1-Dichloroethylene	0.025
2,4-Dichlorophenol	0.044
2,6-Dichlorophenol	0.044
2,4-Dichlorophenoxyacetic acid	0.72
1,2-Dichloropropane	0.85
cis-1,3-Dichloropropene	0.036
trans-1,3-Dichloropropene	0.036
Dieldrin	0.017
Diethyl phthalate	0.20
p-Dimethylaminoazobenzene	0.13
2,4-Dimethyl phenol	0.036
Dimethyl phthalate	0.047
1,4-Dinitrobenzene	0.32
4,6-Dinitrocresol	0.28
2,4-Dinitrophenol	0.12
2,4-Dinitrotoluene	0.32
2,6-Dinitrotoluene	0.55
Di-n-octyl phthalate	0.017

Table 4-1. BDAT Treatment Standards for Multisource Leachate (1) (Continued)

Regulated Organic and Inorganic Constituents	Maximum for Any 24-Hr Composite, Total Composition (mg/L)	Regulated Organic and Inorganic Constituents	Maximum for Any 24-Hr Composite, Total Composition (mg/L)
1,4-Dioxane	0.12	Nitrobenzene	0.068
1,2-Diphenylhydrazine	0.087	4-Nitrophenol	0.12
Di-n-propylnitrosoamine	0.40	N-Nitroso-di-n-butylamine	0.40
Disulfoton	0.017	N-Nitrosodiethylamine	0.40
Endosulfan I	0.023	N-Nitrosomethylethylamine	0.40
Endosulfan II	0.029	N-Nitrosomorpholine	0.40
Endosulfan sulfate	0.029	N-Nitrosopiperidine	0.013
Endrin	0.0028	N-Nitrosopyrrolidine	0.013
Endrin aldehyde	0.025	5-Nitro-o-toluidine	0.32
Ethyl acetate	0.34	Parathion	0.017
Ethyl benzene	0.057	Pentachlorobenzene	0.055
Ethyl cyanide	0.24	Pentachlorodibenzo-p-dioxins	0.000063
Ethylene oxide	0.12	Pentachlorodibenzo-furans	0.000035
Ethyl ether	0.12	Pentachloronitrobenzene	0.055
Ethyl methacrylate	0.14	Pentachlorophenol	0.089
Famphur	0.017	Phenacetin	0.081
Fluoranthene	0.068	Phenanthrene	0.059
Fluorene	0.059	Phenol	0.039
Heptachlor	0.0012	Phorate	0.021
Heptachlor epoxide	0.016	Pronamide	0.093
Hexachlorobenzene	0.055	Pyrene	0.067
Hexachlorobutadiene	0.055	Pyridine	0.014
Hexachlorocyclopentadiene	0.057	Safrole	0.081
Hexachlorodibenzo-p-dioxins	0.000063	Silvex (2,4,5-TP)	0.72
Hexachlorodibenzo-furans	0.000063	1,2,4,5-Tetrachlorobenzene	0.055
Hexachloroethane	0.055	Tetrachlorodibenzo-p-dioxins	0.000063
Hexachloropropene	0.035	2,3,7,8-Tetrachlorodibenzo-p-dioxin	0.000063
Indeno(1,2,3,-c,d)pyrene	0.0055	Tetrachlorodibenzo-furans	0.000063
Iodomethane	0.19	1,1,1,2-Tetrachloroethane	0.057
Isobutyl alcohol	5.6	1,1,2,2-Tetrachloroethane	0.057
Isodrin	0.021	Tetrachlorethene	0.056
Isosafrole	0.081	2,3,4,6-Tetrachlorophenol	0.030
Kepone	0.0011	Toluene	0.080
Methacrylonitrile	0.24	Toxaphene	0.0095
Methapyrilene	0.081	Tribromomethane (Bromoform)	0.63
Methoxychlor	0.25	1,2,4-Trichlorobenzene	0.055
3-Methylchloanthrene	0.0055	1,1,1-Trichloroethane	0.054
4,4-Methylene-bis(2-chloroaniline)	0.50	1,1,2-Trichloroethane	0.054
Methylene chloride	0.089	Trichloroethene	0.054
Methyl ethyl ketone	0.28	Trichloromonofluoromethane	0.020
Methyl isobutyl ketone	0.14	2,4,5-Trichlorophenol	0.18
Methyl methacrylate	0.14	2,4,6-Trichlorophenol	0.035
Methyl methansulfonate	0.018	2,4,5-Trichlorophenoxyacetic acid (2,4,5-T)	0.72
Methyl parathion	0.014	1,2,3-Trichloropropane	0.85
Naphthalene	0.059	1,1,2-Trichloro-1,2,2-trifluoroethane	0.057
2-Naphthylamine	0.52	Vinyl chloride	0.27
p-Nitroaniline	0.028	Xylene(s)	0.32

Table 4-1. BDAT Treatment Standards for Multisource Leachate (1) (Continued)

Regulated Organic and Inorganic Constituents	Maximum for Any 24-Hr Composite, Total Composition (mg/L)	Regulated Organic and Inorganic Constituents	Maximum for Any 24-Hr Composite, Total Composition (mg/L)
Inorganics		Lead	0.28
Antimony	1.9	Mercury	0.15
Arsenic	5.0	Nickel	0.55
Barium	1.2	Selenium	0.82
Beryllium	0.82	Silver	0.29
Cadmium	0.20	Sulfide	14
Chromium (total)	0.37	Vanadium	0.042
Copper	1.3	Zinc	1.0
Fluoride	35		

Table 4-2. Demonstrated Treatment Technologies for Selected Organics[a]

Pollutant	AirS	GAC	RO	ChO_x	UV	Aerob. Biol.	AS/PC	AFF
Benzene	•	•	•			•		•
Chloroform	•	•	•			•		•
1,1-dichloroethane	•		•					
1,1-dichloroethylene	•		•			•		
1,2-trans-dichloroethylene	•	•				•		•
Ethylbenzene	•	•	•			•		•
Methylene chloride						•		
Perchloroethylene	•	•		•		•	•	•
PCBs			•					
Phenol		•	•	•		•	•	•
Toluene	•	•	•			•	•	•
1,1,1-Trichloroethane	•	•	•	•	•	•		•
Trichloroethylene	•	•		•		•	•	•
Xylenes	•	•	•			•		

[a] Demonstrated 90 percent efficient at full scale (includes incidental removal)

AirS	air stripping	UV	ultraviolet radiation
GAC	granular activated carbon	Aerob. Biol.	aerobic biological
RO	reverse osmosis	AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)	AFF	aerobic fixed film

medium, or low Henry's Law constant. Table 4-25 presents the classes of organic compounds that are adsorbed on carbon. Table 4-26 provides carbon adsorption capacities for adsorbable compounds and identifies less adsorbable compounds based on specific testing conditions. The limitation of using an approach based on classifying compounds as strippable or adsorbable is that a technology may be able to adsorb or strip many compounds in a contaminated medium but only be economical for a portion of these compounds. A contaminated medium with several contaminants of various contaminant classes may require treatability studies.

Preliminary performance and cost modeling programs are available to compare technologies, such as packed tower aeration with granular activated carbon, for treating specific contaminants in ground water. Performance and cost are based on compound characteristics, level of removal, and residuals management requirements (6).

Table 4-3. Treatability Data for Arsenic

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS	GAC	IE		RO		ChPt		ChO$_x$		Fil		UV
>100–1,000 mg/L	NA	NA				F		F	NA	F		F	NA
						P		P		P		P	
						B		B		B		B	
>10–100 mg/L						F		F		F		F	
						P		P		P		P	
						B		B		B		B	
>1–10 mg/L						F		F		F		F	
					99+	P 1	95	P 1		P		P	
						B	65 - 95	B 4		B		B	
>100–1,000 µg/L						F	75 - 95+	F 2		F 1	0	F 1	
			>75 - >80	P 2		P		P		P		P	
						B	75	B 1		B		B	
0–100 µg/L					85	F 1	40	F 1		F	15	F 1	
					85	P 1	30 - >90	P 2		P		P	
						B	0	B 1		B		B	

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG	AS/PC	AFF
>100–1,000 mg/L	NA	NA	NA
10–100 mg/L			
>1–10 mg/L			
>100–1,000 µg/L			
0–100 µg/L			

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO$_x$	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-4. Treatability Data for Benzene

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO_x		Fil	UV	
>100–1,000 mg/L		F		F	NA		F	NA			NA		F
		P		P			P						P
		B		B			B						B
>10–100 mg/L		F		F			F						F
	45	P 1		P			P						P
	90	B 1	65	B 1			B						B
>1–10 mg/L	95	F 1	95 - 99+	F 2		90	F 1						F
		P		P			P						P
		B		B			B		8 - 10	B 2			B
>100–1,000 µg/L	>90 - 99+	F 2	>90	F 1		90	F 1						F
	>90 - 99+	P 3		P		75	P 1						P
		B		B			B						B
0–100 µg/L	30	F 1	0 - >75	F 6		95	F 1		>65 - 90	F 2			F
		P		P		15	P 1					>80	P 1
		B		B			B					50	B 1

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L	99+	F 1		F		F
		P		P		P
				B		B
>10–100 mg/L	99+	F 1		F		F
		P		P		P
		B		B		B
>1–10 mg/L	99+	F 4		F		F
	99+	P 1		P		P
	95	B 1		B		B
>100–1,000 µg/L	70 - 99+	F 15		F		F
	99+	P 1	>95	P 1		P
	99+	B 2	99+	B 2		B
0–100 µg/L	>20 - >95	F 9		F	95	F 1
	40 - 99+	P 3	>75	P 1		P
	95	B 1	>80	B 1		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:

F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-5. Treatability Data for Cadmium

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS	GAC	IE	RO	ChPt	ChO$_x$	Fil	UV
>100–1,000 mg/L	NA	NA	:F	:F	:F	NA	:F	NA
			:P	99+ :P 1	:P		:P	
			:B	:B	:B		:B	
>10–100 mg/L			:F	:F	85 :F 1		:F	
			:P	:P	90 :P 1		:P	
			:B	:B	95 - 99+ :B 6		:B	
>1–10 mg/L			:F	:F	90 - 99+ :F 3		:F	
			95 :P 1	80 - 85 :P 3	99+ :P 1		:P	
			:B	:B	65 - 90 :B 2		:B	
>100–1,000 µg/L			:F	:F	:F		:F	
			99+ :P 1	99+ :P 1	70 - 95 :P 4		:P	
			:B	:B	45 - 85 :B 4		:B	
0–100 µg/L			:F	:F	55 - 90 :F 4		0 - 45 :F 5	
			0 :P 1	75 - >90 :P 2	:P		0 - 40 :P 2	
			:B	:B	40 - 95 :B 16		:B	

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG	AS/PC	AFF
>100–1,000 mg/L	NA	NA	NA
>10–100 mg/L			
>1–10 mg/L			
>100–1,000 µg/L			
0–100 µg/L			

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO$_x$	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:

F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-6. Treatability Data for Chloroform

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO_x		FIL	UV	
>100–1,000 mg/L		F		F	NA		F	NA		F	NA		F
		P		P			P			P			P
	90	B 1		B			B			B			B
>10–100 mg/L		F		F			F			F			F
		P		P			P			P			P
	80	B 1		B			B			B			B
>1–10 mg/L		F		F		95	F 1			F			F
	95	P 1		P			P			P			P
	90	B 1		B			B		5 - 15	B 2			B
>100–1,000 µg/L	>90	F 1	30 - >95	F 9		85 - 95	F 2		0	F 1			F
	99+	P 2		P			P			P			P
	80 - 95	B 3		B			B		95	B 1		95	B 1
0–100 µg/L	75 - 80	F 2	25 - >95	F 4			F			F			F
	75 - 99+	P 4	>95	P 1		0 - 70	P 2		35	P 2		25 - 50	P 2
	85 - 95	B 2		B			B			B			B

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
		P		P		P
		B		B		B
>10–100 mg/L		F		F		F
		P		P		P
	99+	B 1		B		B
>1–10 mg/L	85 - 99+	F 8		F		F
	90	P 1		P		P
		B		B		B
>100–1,000 µg/L	50 - >95	F 10		F		F
	60 - 95	P 5		P	20	P 1
		B	99+	B 1		B
0–100 µg/L	45 - 95	F 30	70	F 1	85 - 95	F 2
	>75 - >95	P 3	>85 - >95	P 2	85	P 1
		B	>45	B 1		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-7. Treatability Data for Chromium

Physical/Chemical Treatability Data: Reported Removal Efficiency (%) Influent Conc. Range	AirS	GAC	IE	RO	ChPt	ChO$_x$	Fil	UV
>100–1,000 mg/L	NA	NA	:F	:F	:F	NA	:F	NA
			:P	:P	:P		:P	
			:B	:B	95 - 99+ :B 4		:B	
>10–100 mg/L			:F	:F	99 - 99+ :F 4		:F	
			:P	:P	99+ :P 1		:P	
			:B	:B	80 - 99+ :B 4		:B	
>1–10 mg/L			:F	:F	85 - 90 :F 2		:F	
			:P	99+ :P 2	90 :P 1		:P	
			:B	:B	85 - 99+ :B 8		:B	
>100–1,000 μg/L			:F	:F	60 - 75 :F 3		:F	
			:P	95 - 99+ :P 2	>60 - 85 :P 4		90 :P 1	
			:B	:B	0 - 85 :B 8		:B	
0–100 μg/L			:F	:F	>50 - 85 :F 2		15 - 75 :F 7	
			0 - 80 :P 2	70 - 95 :P 2	0 - 65 :P 2		:P	
			:B	:B	0 - 95 :B 7		:B	

Biological Treatability Data: Reported Removal Efficiency (%) Influent Conc. Range	ASG	AS/PC	AFF
>100–1,000 mg/L	NA	NA	NA
>10–100 mg/L			
>1–10 mg/L			
>100–1,000 μg/L			
0–100 μg/L			

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO$_x$	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-8. Treatability Data for Copper

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS	GAC	IE		RO		ChPt		ChO_x	Fil		UV
>100–1,000 mg/L	NA	NA		F		F		F	NA		F	NA
				P		P	99+	P 2			P	
				B		B	20 - 95	B 3			B	
>10–100 mg/L				F		F	95 - 99+	F 2			F	
				P	99+	P 1	90	P 1			P	
				B		B	55 - 99+	B 7			B	
>1–10 mg/L				F		F	95 - 99+	F 4			F	
			85	P 1	90 - 99+	P 3	15 - 99+	P 2			P	
				B		B	15 - 99+	B 18			B	
>100–1,000 μg/L				F		F	25 - 85	F 4		5 - 25	F 3	
			10 - 95	P 3	90	P 1	70 - 90	P 3			P	
				B		B	90 - 95	B 4			B	
0–100 μg/L				F		F	65	F 1		10 - >75	F 4	
				P	70 - 90	P 2	80	P 1		20	P 1	
				B		B	25 - 99+	B 12			B	

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG	AS/PC	AFF
>100–1,000 mg/L	NA	NA	NA
>10–100 mg/L			
>1–10 mg/L			
>100–1,000 μg/L			
0–100 μg/L			

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-9. Treatability Data for 1,1-Dichloroethane

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO$_x$		FIL	UV	
>100–1,000 mg/L		F		F	NA		F	NA			NA		F
		P		P			P						P
		B		B			B						B
>10–100 mg/L		F		F			F						F
		P	99 +	P 1			P						P
		B		B			B						B
>1–10 mg/L		F		F		90	F 1						F
	75	P 1		P			P						P
		B	99 +	B 1			B		10	B 2			B
>100–1,000 μg/L	>90	F 1		F		85	F 1						F
	>95	P 1		P			P						P
		B		B			B		0	B 1		85	B 1
0–100 μg/L		F	>80	F 1		95	F 1		55	F 1			F
	50 - >95	P 2		P			P		0	P 1		40 - >95	P 3
		B		B			B					>95	B 2

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
		P		P		P
		B		B		B
>10–100 mg/L		F		F		F
		P		P		P
		B		B		B
>1–10 mg/L		F		F		F
		P		P		P
		B		B		B
>100–1,000 μg/L		F		F		F
	65 - 90	P 3		P	35	P 1
	>95	B 1	99 +	B 1		B
0–100 μg/L	>75 - >85	F 2		F		F
	55 - >95	P 2		P	90	P 1
		B		B		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO$_x$	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-10. Treatability Data for 1,1-Dichloroethylene

Physical/Chemical Treatability Data:
Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO_x		Fil	UV	
>100–1,000 mg/L		F		F	NA		F	NA		F	NA		F
		P		P			P			P			P
		B		B			B			B			B
>10–100 mg/L		F		F			F			F			F
		P		P			P			P			P
		B		B			B			B			B
>1–10 mg/L	99+	F 1		F		75	F 1			F			F
	99+	P 1		P			P			P			P
		B		B			B		15	B 1			B
>100–1,000 µg/L		F		F			F			F			F
	90	P 1		P			P			P		99+	P 2
		B		B			B			B			B
0–100 µg/L		F	>50 - >70	F 3		70 - 95	F 2			F			F
	>90 - >95	P 4	>95	P 1			P			P		>95	P 1
		B		B			B		0	B 1		>70 - 99+	B 4

Biological Treatability Data:
Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
		P		P		P
		B		B		B
>10–100 mg/L		F		F		F
		P		P		P
		B		B		B
>1–10 mg/L		F		F		F
		P		P		P
		B		B		B
>100–1,000 µg/L	>90 - >95	F 3		F		F
	60 - 90	P 3		P	60	P 1
		B		B		B
0–100 µg/L	>85 - >95	F 3		F		F
	>95 - 99+	P 2		P	>95	P 1
	>90	B 1		B		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-11. Treatability Data for 1,2-Trans-Dichloroethylene

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	OX		FIL	UV	
>100–1,000 mg/L		F		F	NA		F	NA		F	NA		F
		P		P			P			P			P
	80	B 1		B			B			B			B
>10–100 mg/L		F		F		60	F 1			F			F
		P		P			P			P			P
		B		B			B			B			B
>1–10 mg/L	>95	F 1		F			F			F			F
	99+	P 1		P			P			P			P
	80	B 1		B			B		10 - 99+	B 2			B
>100–1,000 µg/L		F	0 - >90	F 2			F			F			F
	>95	P 2		P			P			P			P
		B		B			B			B			B
0–100 µg/L	65	F 1	>30	F 1			F			F			F
	95	P 1		P			P		90	P 1		>60	P 1
		B		B			B			B			B

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
		P		P		P
		B		B		B
>10–100 mg/L		F		F		F
		P		P		P
		B		B		B
>1–10 mg/L		F		F		F
		P		P		P
		B		B		B
>100–1,000 µg/L	>10 - >95	F 2		F		F
		P		P		P
		B		B		B
0–100 µg/L	70 - 90	F 3		F	95	F 1
		P		P		P
		B		B		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
OX	Oxidation (chlorine, ozone, peroxide)
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-12. Treatability Data for Ethylbenzene

Physical/Chemical Treatability Data:
Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO_x		FIL	UV	
>100–1,000 mg/L		F		F	NA		F	NA		F	NA		F
		P		P			P			P			P
		B		B			B			B			B
>10–100 mg/L		F		F			F			F			F
	99+	P 1		P			P			P			P
		B		B			B			B			B
>1–10 mg/L		F		F		95	F 1			F			F
	95	P 1		P			P			P			P
		B	85	B 1			B		5 - 10	B 2			B
>100–1,000 µg/L	>95	F 1	>90 - >95	F 2			F			F			F
		P		P			P			P			P
		B		B			B			B			B
0–100 µg/L	35 - >90	F 3	35 - >55	F 4			F			F			F
	>90	P 1	>50	P 1		70 - 90	P 2			P			P
		B		B			B		0	B 1		>10 - >45	B 2

Biological Treatability Data:
Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
		P		P		P
		B		B		B
>10–100 mg/L	99+	F 1		F		F
		P		P		P
	99+	B 1		B		B
>1–10 mg/L	>95 - 99+	F 5		F		F
		P		P		P
		B		B		B
>100–1,000 µg/L	80 - 99+	F 12		F	90	F 1
	75 - >95	P 6		P	70	P 1
	99+	B 2	99+	B 1		B
0–100 µg/L	>40 - 99+	F 21		F	90	F 1
	>95 - 99+	P 2	>75	P 1	>95	P 1
	99+	B 1	>75 - 99+	B 2		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-13. Treatability Data for Lead

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS	GAC	IE	RO	ChPt	ChO$_x$	FIL	UV
>100–1,000 mg/L	NA	NA	F	F	F	NA	F	NA
			P	P	P		P	
			B	B	B		B	
>10–100 mg/L			F	F	F		F	
			P	P	95 P 1		P	
			B	B	99+ B 2		B	
>1–10 mg/L			F	F	>80 F 1		F	
			P	95 - 99+ P 2	90 - 99+ P 2		65 P 1	
			B	B	95 - 99+ B 5		B	
>100–1,000 µg/L			F	F	>75 - 80 F 2		F	
			95 P 1	95 P 1	75 P 1		60 P 1	
			B	B	0 - 99+ B 8		B	
0–100 µg/L			F	F	45 - 80 F 3		20 - 50 F 2	
			P	>70 - 85 P 2	95 P 1		P	
			B	B	25 - >85 B 13		B	

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG	AS/PC	AFF
>100–1,000 mg/L	NA	NA	NA
>10–100 mg/L			
>1–10 mg/L			
>100–1,000 µg/L			
0–100 µg/L			

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO$_x$	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-14. Treatability Data for Methylene Chloride

Physical/Chemical Treatability Data:
Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO_x		Fil	UV
>100–1,000 mg/L		F		F	NA		F	NA		F	NA	NDF
		P		P			P			P		
		B		B			B			B		
>10–100 mg/L		F		F		40	F 1			F		
		P		P			P			P		
		B		B			B			B		
>1–10 mg/L		F		F			F			F		
		P		P			P			P		
		B		B			B		0 - 15	B 2		
>100–1,000 µg/L	>90	F 1	0 - 99+	F 5		65	F 1			F		
	99+	P 2		P			P			P		
		B		B			B			B		
0–100 µg/L		F	>40 - >70	F 3			F		35	F 1		
		P		P			P			P		
		B		B			B			B		

Biological Treatability Data:
Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
		P		P		P
	99+	B 1		B		B
>10–100 mg/L	10 - 99+	F 3		F		F
		P	99+	P 1		P
		B	99+	B 1		B
>1–10 mg/L	5 - 99+	F 7		F		F
		P		P		P
		B		B		B
>100–1,000 µg/L	30 - 99+	F 8		F	55 - 85	F 4
	75 - >95	P 2		P		P
	99+	B 1		B		B
0–100 µg/L	0 - >90	F 29		F	5 - 75	F 5
	25 - 95	P 3		P		P
		B	>75	B 1		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-15. Treatability Data for PCBs

Physical/Chemical Treatability Data:
Reported Removal Efficiency (%)

Influent Conc. Range	AirS	GAC	IE	RO		ChPt	ChO_x	Fil	UV	
>100–1,000 mg/L	NDF	NDF	NA		F	NDF	NDF	NDF		F
					P					P
					B					B
>10–100 mg/L					F					F
					P					P
					B					B
>1–10 mg/L					F					F
					P					P
					B					B
>100–1,000 µg/L					F					F
					P					P
					B					B
0–100 µg/L				99+	F 1					F
					P				99+	P 1
					B					B

Biological Treatability Data:
Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC	AFF
>100–1,000 mg/L		F	NDF	NDF
		P		
		B		
>10–100 mg/L		F		
		P		
		B		
>1–10 mg/L		F		
		P		
		B		
>100–1,000 µg/L		F		
		P		
		B		
0–100 µg/L	40 - 90	F12		
		P		
		B		

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-11. Treatability Data for 1,2-Trans-Dichloroethylene

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	OX		FIL	UV	
>100–1,000 mg/L		F		F	NA		F	NA		F	NA		F
		P		P			P			P			P
	80	B 1		B			B			B			B
>10–100 mg/L		F		F		60	F 1			F			F
		P		P			P			P			P
		B		B			B			B			B
>1–10 mg/L	>95	F 1		F			F			F			F
	99+	P 1		P			P			P			P
	80	B 1		B			B		10 - 99+	B 2			B
>100–1,000 µg/L		F	0 - >90	F 2			F			F			F
	>95	P 2		P			P			P			P
		B		B			B			B			B
0–100 µg/L	65	F 1	>30	F 1			F			F			F
	95	P 1		P			P		90	P 1		>60	P 1
		B		B			B			B			B

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
		P		P		P
		B		B		B
>10–100 mg/L		F		F		F
		P		P		P
		B		B		B
>1–10 mg/L		F		F		F
		P		P		P
		B		B		B
>100–1,000 µg/L	>10 - >95	F 2		F		F
		P		P		P
		B		B		B
0–100 µg/L	70 - 90	F 3		F	95	F 1
		P		P		P
		B		B		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
OX	Oxidation (chlorine, ozone, peroxide)
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-12. Treatability Data for Ethylbenzene

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO_x		Fil	UV	
>100–1,000 mg/L		F		F	NA		F	NA		F	NA		F
		P		P			P			P			P
		B		B			B			B			B
>10–100 mg/L		F		F			F			F			F
	99+	P 1		P			P			P			P
		B		B			B			B			B
>1–10 mg/L		F		F		95	F 1			F			F
	95	P 1		P			P			P			P
		B	85	B 1			B		5 - 10	B 2			B
>100–1,000 µg/L	>95	F 1	>90 - >95	F 2			F			F			F
		P		P			P			P			P
		B		B			B			B			B
0–100 µg/L	35 - >90	F 3	35 - >55	F 4			F			F			F
	>90	P 1	>50	P 1		70 - 90	P 2			P			P
		B		B			B		0	B 1		>10 - >45	B 2

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
		P		P		P
		B		B		B
>10–100 mg/L	99+	F 1		F		F
		P		P		P
	99+	B 1		B		B
>1–10 mg/L	>95 - 99+	F 5		F		F
		P		P		P
		B		B		B
>100–1,000 µg/L	80 - 99+	F 12		F	90	F 1
	75 - >95	P 6		P	70	P 1
	99+	B 2	99+	B 1		B
0–100 µg/L	>40 - 99+	F 21		F	90	F 1
	>95 - 99+	P 2	>75	P 1	>95	P 1
	99+	B 1	>75 - 99+	B 2		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-13. Treatability Data for Lead

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS	GAC	IE		RO		ChPt		ChO$_x$	FIL		UV
>100–1,000 mg/L	NA	NA		F		F		F	NA		F	NA
				P		P		P			P	
				B		B		B			B	
>10–100 mg/L				F		F		F			F	
				P		P	95	P 1			P	
				B		B	99 +	B 2			B	
>1–10 mg/L				F		F	>80	F 1			F	
				P	95 - 99 +	P 2	90 - 99 +	P 2		65	P 1	
				B		B	95 - 99 +	B 5			B	
>100–1,000 μg/L				F		F	>75 - 80	F 2			F	
			95	P 1	95	P 1	75	P 1		60	P 1	
				B		B	0 - 99 +	B 8			B	
0–100 μg/L				F		F	45 - 80	F 3		20 - 50	F 2	
				P	>70 - 85	P 2	95	P 1			P	
				B		B	25 - >85	B 13			B	

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG	AS/PC	AFF
>100–1,000 mg/L	NA	NA	NA
>10–100 mg/L			
>1–10 mg/L			
>100–1,000 μg/L			
0–100 μg/L			

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO$_x$	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-14. Treatability Data for Methylene Chloride

Physical/Chemical Treatability Data:
Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO_x		Fil	UV
>100–1,000 mg/L		F		F	NA		F	NA		F	NA	NDF
		P		P			P			P		
		B		B			B			B		
>10–100 mg/L		F		F		40	F 1			F		
		P		P			P			P		
		B		B			B			B		
>1–10 mg/L		F		F			F			F		
		P		P			P			P		
		B		B			B		0 - 15	B 2		
>100–1,000 µg/L	>90	F 1	0 - 99+	F 5		65	F 1			F		
	99+	P 2		P			P			P		
		B		B			B			B		
0–100 µg/L		F	>40 - >70	F 3			F		35	F 1		
		P		P			P			P		
		B		B			B			B		

Biological Treatability Data:
Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
		P		P		P
	99+	B 1		B		B
>10–100 mg/L	10 - 99+	F 3		F		F
		P	99+	P 1		P
		B	99+	B 1		B
>1–10 mg/L	5 - 99+	F 7		F		F
		P		P		P
		B		B		B
>100–1,000 µg/L	30 - 99+	F 8		F	55 - 85	F 4
	75 - >95	P 2		P		P
	99+	B 1		B		B
0–100 µg/L	0 - >90	F 29		F	5 - 75	F 6
	25 - 95	P 3		P		P
		B	>75	B 1		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:

F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-15. Treatability Data for PCBs

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS	GAC	IE	RO		ChPt	ChO_x	Fil	UV	
>100–1,000 mg/L	NDF	NDF	NA		F	NDF	NDF	NDF		F
					P					P
					B					B
>10–100 mg/L					F					F
					P					P
					B					B
>1–10 mg/L					F					F
					P					P
					B					B
>100–1,000 µg/L					F					F
					P					P
					B					B
0–100 µg/L				99+	F 1					F
					P				99+	P 1
					B					B

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC	AFF
>100–1,000 mg/L		F	NDF	NDF
		P		
		B		
>10–100 mg/L		F		
		P		
		B		
>1–10 mg/L		F		
		P		
		B		
>100–1,000 µg/L		F		
		P		
		B		
0–100 µg/L	40 - 90	F12		
		P		
		B		

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-16. Treatability Data for Perchloroethylene

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO_x		FIL	UV	
>100–1,000 mg/L		F		F	NA		F	NA		F	NA		F
		P		P			P			P			P
		B		B			B			B			B
>10–100 mg/L		F		F			F			F			F
		P		P			P			P			P
		B		B			B			B			B
>1–10 mg/L		F	99+	F 1			F		99+	F 1			F
	99+	P 1		P			P			P			P
		B		B			B		5	B 2			B
>100–1,000 µg/L	>85 - 99+	F 4	80 - 99+	F 4			F			F			F
	95 - 99+	P 3	99+	P 1			P			P			P
		B		B			B			B			B
0–100 µg/L	50 - >95	F 5	>80 - 99+	F 4			F 0			F			F
	90 - 99+	P 8		P 0		65 - 80	P 2		80 - 85	P 2		>90 - >95	P 3
		B	99+	B 1			B		0	B 1		>60 - 85	B 2

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
		P		P		P
		B		B		B
>10–100 mg/L		F		F		F
		P		P		P
		B		B		B
>1–10 mg/L	85 - 99+	F 2	90	F 1		F
		P		P		P
		B		B		B
>100–1,000 µg/L	45 - >95	F 8		F	80	F 1
	95	P 1		P		P
		B	>90 - 99+	B 2		B
0–100 µg/L	45 - >95	F 27	80	F 1	50 - >95	F 5
	90	P 1	>75	P 1		P
		B		B		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-17. Treatability Data for Phenol

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO_x		Fil	UV
>100–1,000 mg/L		F		F	NA		F	NA		F	NA	NDF
		P		P			P			P		
		B		B			B		99+	B 2		
>10–100 mg/L		F	95	F 1			F			F		
		P		P			P			P		
		B		B			B			B		
>1–10 mg/L		F	99+	F 2		90	F 1		99+	F 1		
		P		P			P			P		
		B		B			B		99+	B 1		
>100–1,000 µg/L		F	0 ->95	F 4			F		50 - >60	F 2		
		P		P			P			P		
		B	99	B 1			B		90 - >95	B 2		
0–100 µg/L	35 - >35	F 2	>5 - >85	F 4			F			F		
		P		P			P			P		
		B		B			B			B		

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L	99+	F 2		F	99+	F 1
	99+	P 4		P		P
	99+	B 3		B		B
>10–100 mg/L	95 - 99+	F 3		F		F
	95 - 99+	P 2		P	45	P 1
	95	B 1	99+	B 1		B
>1–10 mg/L	85 - 99+	F 9	>95	F 1		F
		P 0		P	99+	P 1
		B	99+	B 3		B
>100–1,000 µg/L	45 - 99+	F 19	>85	F 1	>80 - >95	F 2
	30 - >95	P 7		P	>45	P 1
		B		B		B
0–100 µg/L	>60 - >95	F 12	90	F 1	90 - 95	F 2
	>90 - 95	P 4	>20 - >95	P 2	90	P1
		B		B		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-18. Treatability Data for Toluene

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO$_x$		FIL	UV	
>100–1,000 mg/L		F	0 - 95	F 2	NA			NA			NA		F
		P		P			P						P
		B		B			B						B
>10–100 mg/L	99+	F 1	99+	F 1			F						F
	90 - 99+	P 2	99+	P 1			P						P
	90	B 1		B			B						B
>1–10 mg/L	95 - 99+	F 2		F		95	F 1						F
		P		P			P						P
		B	80	B 1			B		5 - 15	B 2			B
>100–1,000 µg/L	99+	F 1	40 - >95	F 3		90	F 1						F
		P		P			P						P
		B		B			B		0	B 1		>95	B 1
0–100 µg/L	30 - >95	F 3	>30 - >95	F 4			F						F
	95 - >95	P 2		P		85	P 1						P
		B		B			B					>70	B 1

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
	99+	P 1		P		P
		B		B		B
>10–100 mg/L	99+	F 2		F		F
		P		P		P
	99+	B 1		B		B
>1–10 mg/L	85 - 99+	F 16		F		F
	99+	P		P		P
	95	B 1	99+	B 1		B
>100–1,000 µg/L	0 - 99+	F 22	99+	F 1	>95	F 2
	60 - 99+	P 6	>90	P 1		P
	>95 - 99+	B 2	99+	B 1		B
0–100 µg/L	>50 - 99+	F 22		F	85 - >95	F 4
	>25	P 1	>95	P 1		P
		B	>90	B 1		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO$_x$	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:

F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-19. Treatability Data for 1,1,1-Trichloroethane

Treatability Data: Physical/Chemical
Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO$_x$		Fil	UV	
>100–1,000 mg/L		F		F	NA		F	NA		F	NA		F
	95	P 1		P			P			P			P
		B		B			B			B			B
>10–100 mg/L		F		F			F			F			F
		P	99+	P 1			P			P			P
		B	99+	B 1			B			B			B
>1–10 mg/L	99+	F 1		F			F			F			F
	95 - 99+	P 3		P			P			P			P
		B		B			B		5	B 2			B
>100–1,000 µg/L	>90	F 1	75 - 99+	F 3		90 - 95	F 2		>95	F 1			F
	85 - 99+	P 5	99+	P 1			P			P			P
		B		B			B			B			B
0–100 µg/L	>50 - 90	F 3	>90 - 99+	F 2			F		80	F 1			F 0
	85 - >95	P 6	>95	P 1		95	P 2			P		20 - >95	P 3
		B		B			B			B		40 - >95	B 2

Treatability Data: Biological
Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
		P		P		P
	95	B 1		B		B
>10–100 mg/L		F		F		F
		P		P		P
		B		B		B
>1–10 mg/L	85 - 99+	F 2		F		F
		P		P		P
		B	99+	B 1	95	B 1
>100–1,000 µg/L	70 - 99+	F 10		F	90 - 95	F 2
	>95 - 99+	P 3		P		P
	>95	B 1	90	B 1		B
0–100 µg/L	35 - >95	F 29	60	F 1	>50 - 90	F 3
	>80	P 1	>95	P 1		P
		B		B		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO$_x$	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	activated carbon (granular)
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-20. Treatability Data for Trichlorethylene

Treatability Data: Physical/Chemical Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO$_x$		FIL	UV	
>100–1,000 mg/L		F		F	NA		F	NA		F	NA		F
	40	P 1		P			P			P			P
		B		B			B			B			B
>10–100 mg/L		F		F			F			F			F
		P		P			P			P			P
		B		B			B			B			B
>1–10 mg/L	99+	F 1	99+	F 2			F			F			F
	80 - 99+	P 4		P			P			P			P
		B		B			B		5	B 2			B
>100–1,000 μg/L	40 - 99+	F 5	95 - 99+	F 4		75	F 1			F			F
	80 - 99+	P 12		P			P		95	P 1		99+	P 3
		B		B			B		0	B 1		>95 - 99+	B 4
0–100 μg/L	>50 - 99+	F 7	80 - 99+	F 4		75	F 1		95	F 1			F
	85 - 99+	P 13	>40	P 1		30	P 1		70 - 95	P 2			P
		B		B			B			B		55	B 1

Treatability Data: Biological Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF	
>100–1,000 mg/L		F		F		F
		P		P		P
		B		B		B
>10–100 mg/L		F		F		F
		P		P		P
	99+	B 1	99+	B 1		B
>1–10 mg/L	99+	F 1		F		F
		P		P		P
		B		B		B
>100–1,000 μg/L	70 - 99+	F 8	95	F 1	99+	F 1
	95 - 99+	P 2		P		P
	95	B 1	99+	B 1		B
0–100 μg/L	>55 - >95	F 19	75	F 1	90 - >95	F 4
	10	P 1	>95	P 1		P
		B	>85	B 1		B

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AirS	air stripping
ChO$_x$	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	activated carbon (granular)
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
AS/PC	activated sludge/powdered carbon
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:

F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-21. Treatability Data for Xylenes

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO		ChPt	ChO_x	Fil	UV	
>100–1,000 mg/L		F		F	NA		F	NA	NDF	NA		F
		P		P			P					P
		B		B			B					B
>10–100 mg/L		F		F			F					F
		P		P			P					P
		B		B			B					B
>1–10 mg/L		F		F			F					F
	95	P 1		P		95	P 1					P
		B	85	B 1			B					B
>100–1,000 µg/L		F		F			F					F
		P		P			P					P
		B		B			B				>80	B 1
0–100 µg/L	95	F 1		F			F					F
		P		P			P					P
		B		B			B					B

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC	AFF
>100–1,000 mg/L		F	NDF	NDF
		P		
		B		
>10–100 mg/L		F		
	99+	P 1		
		B		
>1–10 mg/L	99+	F 1		
		P		
		B		
>100–1,000 µg/L		F		
	>95 - 99+	P 3		
		B		
0–100 µg/L		F		
		P		
		B		

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	Air Stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-21a. Treatability Data for m-Xylene

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO	ChPt	ChO_x		Fil	UV
>100–1,000 mg/L		F		F	NA	NDF	NA		F	NA	NDF
		P		P					P		
		B		B					B		
>10–100 mg/L		F		F					F		
		P		P					P		
		B		B					B		
>1–10 mg/L		F		F					F		
		P		P					P		
		B		B				10 - 45	B 2		
>100–1,000 µg/L		F	>95	F 1					F		
		P		P					P		
		B		B					B		
0–100 µg/L	15 - 25	F 2	20 - >90	F 3					F		
	>70	P 1		P					P		
		B		B					B		

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF
>100–1,000 mg/L		F		F	NDF
		P		P	
		B		B	
>10–100 mg/L		F		F	
		P		P	
		B		B	
>1–10 mg/L	99+	F 3		F	
		P		P	
		B		B	
>100–1,000 µg/L		F		F	
		P		P	
		B		B	
0–100 µg/L	>5 - >95	F 3		F	
		P		P	
		B	>70	B 1	

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-21b. Treatability Data for o-Xylene

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC	IE	RO		ChPt	ChO$_x$	Fil	UV
>100–1,000 mg/L		F	NDF	NA		F	NA	NDF	NA	NDF
		P				P				
		B				B				
>10–100 mg/L		F			95	F 1				
		P				P				
		B				B				
>1–10 mg/L		F				F				
		P				P				
		B				B				
>100–1,000 µg/L		F				F				
		P				P				
		B				B				
0–100 µg/L		F				F				
	>90	P 1				P				
		B				B				

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC		AFF
>100–1,000 mg/L		F		F	NDF
		P		P	
		B		B	
>10–100 mg/L		F		F	
		P		P	
		B		B	
>1–10 mg/L		F		F	
		P		P	
		B		B	
>100–1,000 µg/L		F		F	
		P		P	
	99+	B 1		B	
0–100 µg/L	90 - >95	F 4		F	
		P		P	
		B	>90	B 1	

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO$_x$	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-21c. Treatability Data for p-Xylene

Physical/Chemical Treatability Data:
Reported Removal Efficiency (%)

Influent Conc. Range	AirS		GAC		IE	RO	ChPt	ChO_x	Fil	UV
>100–1,000 mg/L		F		F	NA	NDF	NA	NDF	NA	NDF
		P		P						
		B		B						
>10–100 mg/L		F		F						
		P		P						
		B		B						
>1–10 mg/L		F		F						
		P		P						
		B		B						
>100–1,000 µg/L		F		F						
		P		P						
		B		B						
0–100 µg/L		F	35	F 1						
	>90	P 1		P						
		B		B						

Biological Treatability Data:
Reported Removal Efficiency (%)

Influent Conc. Range	ASG		AS/PC	AFF
>100–1,000 mg/L		F	NDF	NDF
		P		
		B		
>10–100 mg/L		F		
		P		
		B		
>1–10 mg/L		F		
		P		
		B		
>100–1,000 µg/L		F		
		P		
		B		
0–100 µg/L		F		
	95	P 1		
		B		

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO_x	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-22. Treatability Data for Zinc

Physical/Chemical Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	AirS	GAC	IE		RO		ChPt		ChO$_x$	FIL		UV
>100–1,000 mg/L	NA	NA		F		F		F 0	NA		F	NA
				P		P		P			P	
				B		B	80 - 99+	B 16			B	
>10–100 mg/L				F		F	95 - 99+	F 6			F	
				P	99+	P 1	90 - 95	P 2			P	
				B		B	80 - 99+	B 10			B	
>1–10 mg/L				F		F	90 - 95	F 2			F	
				P	80 - 99+	P 4	90 - 95	P 4		65	P 1	
				B		B	90 - 99+	B 3			B	
>100–1,000 µg/L				F		F	60 - 75	F 2		35 - 80	F 3	
			0 - 95	P 3	90	P 1	65 - 95	P 3			P	
				B		B	10 - 95	B 8			B	
0–100 µg/L				F		F	>10	F 1		0 - 60	F 4	
			0	P 1	75	P 1		P			P	
				B		B	80 - 85	B 2			B	

Biological Treatability Data: Reported Removal Efficiency (%)

Influent Conc. Range	ASG	AS/PC	AFF
>100–1,000 mg/L	NA	NA	NA
>10–100 mg/L			
>1–10 mg/L			
>100–1,000 µg/L			
0–100 µg/L			

KEY:

AFF	aerobic fixed film (including trickling filters and/or rotating biological contactors)
AirS	air stripping
ASG	aerobic suspended growth (including activated sludge, aerated lagoons, and/or sequencing batch reactors)
AS/PC	activated sludge/powdered carbon
ChO$_x$	oxidation (chlorine, ozone, peroxide)
ChPt	chemical precipitation
Fil	filtration
GAC	granular activated carbon
IE	ion exchange
NA	not applicable (or incidental removal only)
NDF	no data found
RO	reverse osmosis
UV	ultraviolet radiation (including ozone, peroxide, or both)

Number of studies from which data were extracted:
F = full-scale
P = pilot-scale
B = bench-scale

Note: All data in this table are from EPA/RREL Treatability Database and are rounded to the lowest multiple of five.

Table 4-23. Water Solubility, Vapor Pressure, Henry's Law Constant, K_{oc}, and K_{ow} Data for Selected Chemicals (3)

Chemical Name	CAS #	EPA	Water Solubility (mg/L)	Vapor Pressure (mm Hg)	Henry's Law Constant (atm-m^3/mol)	K_{oc} (mL/g)	K_{ow}
Pesticides							
Acrolein (2-Propenal)	107-02-8	PP	2.08E+05	2.69E+02	9.54E-05		8.13E-01
Aldicarb (Temik)	116-06-3		7.80E+03				5.00E+00
Aldrin	309-00-2	HPP	1.80E-01	6.00E-06	1.60E-05	9.60E+04	2.00E+05
Captan	133-06-2		5.00E-01	6.00E-05	4.75E-05	6.40E+03	2.24E+02
Carbaryl (Sevin)	63-25-2		4.00E+01	5.00E-03	3.31E-05	2.30E+02	2.29E+02
Carbofuran	1563-66-2		4.15E+02	2.00E-05	1.40E-08	2.94E+01	2.07E+02
Carbophenothion (Trithion)	786-19-6					4.66E+04	
Chlordane	57-74-9	HPP	5.60E-01	1.00E-05	9.63E-06	1.40E+05	2.09E+03
p-Chloroaniline (4-Chlorobenzenamine)	106-47-8	HSL	5.30E+03	2.00E-02	6.40E-07	5.61E+02	6.76E+01
Chlorobenzilate	510-15-6		2.19E+01	1.20E-06	2.34E-08	8.00E+02	3.24E+04
Chlorpyrifos (Dursban)	2921-88-2		3.00E-01	1.87E-05	2.87E-05	1.36E+04	6.60E+04
Crotoxyphos (Ciodrin)	7700-17-6		1.00E+03	1.40E-05	5.79E-09	7.48E+01	
Cyclophosphamide	50-18-0		1.31E+09			4.20E-02	6.03E-04
Diazonin (Spectracide)	333-41-5		4.00E+01	1.40E-04	1.40E-06	8.50E+01	1.05E+03
1,2-Dibromo-3-chloropropane (DBCP)	96-12-8		1.00E+03	1.00E+00	3.11E-04	9.80E+01	1.95E+02
Dichlorodiphenyldichloroethane (DDD)	72-54-8	HPP	1.00E-01	1.89E-06	7.96E-06	7.70E+05	1.58E+06
Dichlorodiphenyldichloroethylene (DDE)	72-55-9	HPP	4.00E-02	6.50E-06	6.80E-05	4.40E+06	1.00E+07
Dichlorodiphenyltrichloroethane (DDT)	50-29-3	HPP	5.00E-03	5.50E-06	5.13E-04	2.43E+05	1.55E+06
1,2-Dichloropropane	78-87-5	HPP	2.70E+03	4.20E+01	2.31E-03	5.10E+01	1.00E+02
1,3-Dichloropropene (Telone)	542-75-6	HPP	2.80E+03	2.50E+01	1.30E-01	4.80E+01	1.00E+02
Dichlorvos	62-73-7		1.00E+04	1.20E-02	3.50E-07		2.50E+01
Dieldrin	60-57-1	HPP	1.95E-01	1.78E-07	4.58E-07	1.70E+03	3.16E+03
Dimethoate	60-51-5		2.50E+04	2.50E-02	3.00E-07		5.10E-01
Dinoseb	88-85-7		5.00E+01	5.00E-05	3.16E-07	1.24E+02	1.98E+02
N,N-Diphenylamine	122-39-4		5.76E+01	3.80E-05	1.47E-07	4.70E+02	3.98E+03
Disulfoton	298-04-4		2.50E+01	1.80E-04	2.60E-06	1.60E+03	
alpha-Endosulfan	115-29-7	HPP	1.60E-01	1.00E-05	3.35E-05		3.55E+03
beta-Endosulfan	115-29-7	HPP	7.00E-02	1.00E-05	7.65E-05		4.17E+03
Endosulfan sulfate	1031-07-8	HPP	1.60E-01				4.57E+03
Endrin	72-20-8	HPP	2.40E-02	2.00E-07	4.17E-06		2.18E+05
Endrin aldehyde	7421-93-4	PP					
Endrin ketone		HSL					
Ethion	563-12-2		2.00E+00	1.50E-06	3.79E-07	1.54E+04	
Ethylene oxide	75-21-8		1.00E+06	1.31E+03	7.56E-05	2.20E+00	6.03E-01
Fenitrothion	122-14-5		3.00E+01	6.00E-06	7.30E-08		2.40E+03
Heptachlor	76-44-8	HPP	1.80E-01	3.00E-04	8.19E-04	1.20E-04	2.51E+04
Heptachlor epoxide	1024-57-3	HPP	3.50E-01	3.00E-04	4.39E-04	2.20E+02	5.01E+02
alpha-Hexachlorocyclohexane	319-84-6	HPP	1.63E+00	2.50E-05	5.87E-06	3.80E+03	7.94E+03
beta-Hexachlorocyclohexane	319-85-7	HPP	2.40E-01	2.80E-07	4.47E-07	3.80E+03	7.94E+03
delta-Hexachlorocyclohexane	319-86-8	HPP	3.14E+01	1.70E-05	2.07E-07	6.60E+03	1.26E+04
gamma-Hexachlorocyclohexane (Lindane)	58-89-9	HPP	7.80E+00	1.60E-04	7.85E-06	1.08E+03	7.94E+03
Isophorone	78-59-1	HPP	1.20E+04	3.80E-01	5.75E-06		5.01E+01
Kepone	143-50-0		9.90E-03			5.50E+04	1.00E+02
Leptophos	21609-90-5		2.40E+00			9.30E+03	2.02E+06
Malathion	121-75-7		1.45E+02	4.00E-05	1.20E-07	1.80E+03	7.76E+02
Methoxychlor	72-43-5	HSL	3.00E-03			8.00E+04	4.75E+04
Methyl parathion	298-00-0		6.00E+01	9.70E-06	5.59E-08	5.10E+03	8.13E+01
Mirex (Dechlorane)	2385-85-5		6.00E-01	3.00E-01	3.59E-01	2.40E+07	7.80E+06
Nitralin	4726-14-1		6.00E-01	9.30E-09	7.04E-09	9.60E+02	
Parathion	56-38-2		2.40E+01	3.78E-05	6.04E-07	1.07E+04	6.45E+03
Phenylurea (Phenylcarbamide)	64-10-8					7.63E+01	6.61E+00
Phorate (Thimet)	298-02-2		5.00E+01	8.40E-04	8.49E-11	3.26E+03	

Table 4-23. Water Solubility, Vapor Pressure, Henry's Law Constant, K_{oc}, and K_{ow} Data for Selected Chemicals (3) (Continued)

Chemical Name	CAS #	EPA	Water Solubility (mg/L)	Vapor Pressure (mm Hg)	Henry's Law Constant (atm-m^3/mol)	K_{oc} (mL/g)	K_{ow}
Phosmet	732-11-6		2.50E+01	E-03			6.77E+02
Ronnel (Fenchlorphos)	299-84-3		6.00E+00	8.00E-04	5.64E-05		4.64E+04
Strychnine	57-24-9		1.56E+02				8.51E+01
2,3,7,8-Tetrachlorodibenzo-p-dioxin	1746-01-6		2.00E-04	1.70E-06	3.60E-03	3.30E+06	5.25E+06
Toxaphene	8001-35-2	HPP	5.00E-01	4.00E-01	4.36E-01	9.64E+02	2.00E+03
Trichlorfon (Chlorofos)	52-68-6		1.54E+05	7.80E-06	1.71E-11	6.10E+00	1.95E+02
Herbicides							
Alachlor	15972-60-8		2.42E+02			1.90E+02	4.34E+02
Ametryn	834-12-8		1.85E+02			3.88E+02	
Amitrole (Aminotriazole)	61-82-5		2.80E+05			4.40E+00	8.32E-03
Atrazine	1912-24-9		3.30E+01	1.40E-06	2.59E-13	1.63E+02	2.12E+02
Benfluralin (Benefin)	1861-40-1		E+00	3.89E-04		1.07E+04	
Bromocil	314-40-9		8.20E+02			7.20E+01	1.04E+02
Cacodylic acid	75-60-5		8.30E+05			2.40E+00	1.00E+00
Chloramben	133-90-4		7.00E+02	E-03		2.10E+01	1.30E+01
Chlorpropham	101-21-3		8.80E+01			8.16E+02	1.16E+03
Dalapon (2,2-Dichloropropanoic acid)	75-99-0		5.02E+05				5.70E+00
Diallate	2303-16-4		1.40E+01	6.40E-03	1.65E-04	1.90E+03	5.37E+00
Dicamba	1918-00-9		4.50E+03	2.00E-05	1.30E-09	2.20E+00	3.00E+00
Dichlobenil (2,6-Dichlorobenzonitrile)	1194-65-6		1.80E+01	3.00E-06	3.77E-08	2.24E+02	7.87E+02
2,4-Dichlorophenoxyacetic acid (2,4-D)	94-75-7		6.20E+02	4.00E-01	1.88E-04	1.96E+01	6.46E+02
Dipropetryne	47-51-7		1.60E+01	7.50E-07	1.53E-08	1.18E+03	
Diuron	330-54-1		4.20E+01	E-06		3.82E+02	6.50E+02
Fenuron	101-42-8		3.85E+03	E-04		4.22E+01	1.00E+01
Fluometuron	2164-17-2		9.00E+01			1.75E+02	2.20E+01
Linuron	330-55-2		7.50E+01	1.50E-05	6.56E-08	8.63E+02	1.54E+02
Methazole (Oxydiazol)	20354-26-1		1.50E+00			2.62E+03	
Metobromuron	3060-89-7		3.30E+02	3.00E-06	3.10E-09	2.71E+02	
Monuron	150-68-5		2.30E+02	5.00E-07	5.68E-10	1.83E+02	1.33E+02
Neburon	555-37-3		4.80E+00			3.11E+03	
Oxadiazon	19666-30-9		7.00E-01	E-06		3.24E+03	
Paraquat	4685-14-7		1.00E+06			1.55E+04	1.00E+00
Phenylmercuric acetate (PMA)	62-38-4		1.67E+03				
Picloram	1918-02-1		4.30E+02	E-07		2.55E+01	2.00E+00
Prometryne	7287-19-6		4.80E+01	1.00E-06	6.62E-09	6.14E+02	
Propachlor	1918-16-7		5.80E+02			2.65E+02	5.60E+02
Propazine	139-40-2		8.60E+00	1.60E-07	5.63E-09	1.53E+02	7.85E+02
Silvex (Fenoprop)	93-72-1		1.40E+02			2.60E+03	
Simazine	122-34-9		3.50E+00	3.60E-08	2.73E-09	1.38E+02	8.80E+01
Terbacil	5902-51-2		7.10E+02			4.12E+01	7.80E+01
2,4,5-Trichlorophenoxyacetic acid	93-76-5		2.38E+02			8.01E+01	4.00E+00
Triclopyr	55335-06-3		4.30E+02	1.26E-06	9.89E-10	2.70E+01	3.00E+00
Trifluralin	1582-09-8		6.00E-01	2.00E-04	1.47E-04	1.37E+04	2.20E+05
Aliphatic Compounds							
Acetonitrile (Methyl cyanide)	75-05-8		Infinite	7.40E+01	4.00E-06	2.20E+00	4.57E-01
Acrylonitrile (2-Propenenitrile)	107-13-1	PP	7.94E+04	1.00E+02	8.84E-05	8.50E-01	1.78E+00
Bis(2-chloroethoxy)methane	111-91-1	HPP	8.10E+04	E-01			1.82E+01
Bromodichloromethane (Dichlorobromomethane)	75-27-4	HPP	4.40E+03	5.00E+01	2.40E-03	6.10E+01	7.59E+01
Bromomethane (Methyl bromide)	74-83-9	HPP	1.30E+04	1.40E+03	1.30E-02		1.26E+01
1,3-Butadiene	106-99-0		7.35E+02	1.84E-03	1.78E-01	1.20E+02	9.77E+01
Chloroethane (Ethyl chloride)	75-00-3	HPP	5.74E+03	1.00E+03	6.15E-04	1.70E+01	3.50E+01
Chloroethene (Vinyl chloride)	75-01-4	HPP	2.67E+03	2.66E+03	8.19E-02	5.70E+01	2.40E+01

Table 4-23. Water Solubility, Vapor Pressure, Henry's Law Constant, K_{oc}, and K_{ow} Data for Selected Chemicals (3) (Continued)

Chemical Name	CAS #	EPA	Water Solubility (mg/L)	Vapor Pressure (mm Hg)	Henry's Law Constant (atm-m^3/mol)	K_{oc} (mL/g)	K_{ow}
Chloromethane (Methyl chloride)	74-87-3	HPP	6.50E+03	4.31E+03	4.40E-02	3.50E+01	9.50E-01
Cyanogen (Ethanedinitrile)	460-19-5		2.50E+05				
Dibromochloromethane	124-48-1	HPP	4.00E+03	1.50E+01	9.90E-04	8.40E+01	1.23E+0
Dichlorodifluoromethane (Freon 12)	75-71-8		2.80E+02	4.87E+03	2.97E+00	5.80E+01	1.45E+0
1,1-Dichloroethane (Ethylidine chloride)	75-34-3	HPP	5.50E+03	1.82E+02	4.31E-03	3.00E+01	6.17E+0
1,2-Dichloroethane (Ethylene dichloride)	107-06-2	HPP	8.52E+03	6.40E+01	9.78E-04	1.40E+01	3.02E+0
1,1-Dichloroethene (Vinylidine chloride)	75-35-4	HPP	2.25E+03	6.00E+02	3.40E-02	6.50E+01	6.92E+0
cis-1,2-Dichloroethene	540-59-0		3.50E+03	2.08E+02	7.58E-03	4.90E+01	5.01E+0
trans-1,2-Dichloroethene	540-59-0	HPP	6.30E+03	3.24E+02	6.56E-03	5.90E+01	3.02E+0
Dichloromethane (Methylene chloride)	75-09-2	HPP	2.00E+04	3.62E+02	2.03E-03	8.80E+00	2.00E+01
Ethylene dibromide (EDB)	106-93-4		4.30E+03	1.17E+01	6.73E-04	4.40E+01	5.75E+01
Hexachlorobutadiene	87-68-3	HPP	1.50E-01	2.00E+00	4.57E+00	2.90E+04	6.02E+04
Hexachlorocyclopentadiene	77-47-4	HPP	2.10E+00	8.00E-02	1.37E-02	4.80E+03	1.10E+05
Hexachloroethane (Perchloroethane)	67-72-1	HPP	5.00E+01	4.00E-01	2.49E-03	2.00E+04	3.98E+04
Iodomethane (Methyl iodide)	77-88-4		1.40E+04	4.00E+02	5.34E-03	2.30E+01	4.90E+01
Isoprene	78-79-5			4.00E+02			
Pentachloroethane (Pentalin)	76-01-7		3.70E+01	3.40E+00	2.44E-02	1.90E+03	7.76E+02
1,1,1,2-Tetrachloroethane	630-20-6		2.90E+03	5.00E+00	3.81E-04	5.40E+01	
1,1,2,2-Tetrachloroethane	79-34-5	HPP	2.90E+03	5.00E+00	3.81E-04	1.18E+02	2.45E+02
Tetrachloroethene (PERC)	127-18-4	HPP	1.50E+02	1.78E+01	2.59E-02	3.64E+02	3.98E+02
Tetrachloromethane (Carbon tetrachloride)	56-23-5	HPP	7.57E+02	9.00E+01	2.41E-02	4.39E+02	4.37E+02
Tribromomethane (Bromoform)	75-25-2	HPP	3.01E+03	5.00E+00	5.52E-04	1.16E+02	2.51E+02
1,1,1-Trichloroethane (Methylchloroform)	71-55-6	HPP	1.50E+03	1.23E+02	1.44E-02	1.52E+02	3.16E+02
1,1,2-Trichloroethane (Vinyl trichloride)	79-00-5	HPP	4.50E+03	3.00E+01	1.17E-03	5.60E+01	2.95E+02
Trichloroethene (TCE)	79-01-6	HPP	1.10E+03	5.79E+01	9.10E-03	1.26E+02	2.40E+02
Trichlorofluoromethane (Freon 11)	75-69-4	PP	1.10E+03	6.67E+02	1.10E-01	1.59E+02	3.39E+02
Trichloromethane (Chloroform)	67-66-3	HPP	8.20E+03	1.51E+02	2.87E-03	4.70E+01	9.33E+01
1,1,2-Trichloro-1,2,2-trifluoroethane	76-13-1		1.00E+01	2.70E+02			1.00E+02
Aromatic Compounds							
Benzene	71-43-2	HPP	1.75E+03	9.52E+01	5.59E-03	8.30E+01	1.32E+02
1,1-Biphenyl (Diphenyl)	92-52-4		7.50E+00	6.00E-02	1.50E-03		7.54E+03
Bromobenzene (Phenyl bromide)	108-86-1		4.46E+02	4.14E+00	1.92E-03	1.50E+02	9.00E+02
Chlorobenzene	108-90-7	HPP	4.66E+02	1.17E+01	3.72E-03	3.30E+02	6.92E+02
4-Chloro-m-cresol (Chlorocresol)	59-50-7	HPP	3.85E+03	5.00E-02	2.44E-06	4.90E+02	9.80E+02
2-Chlorophenol (o-Chlorophenol)	95-57-8	HPP	2.90E+04	1.80E+00	1.05E-05	4.00E+02	1.45E+02
Chlorotoluene (Benzyl chloride)	100-44-7		3.30E+03	1.00E+00	5.06E-05	5.00E+01	4.27E+02
m-Chlorotoluene	108-41-8		4.80E+01	4.60E+00	1.60E-02	1.20E+03	1.90E+03
o-Chlorotoluene	95-49-8		7.20E+01	2.70E+00	6.25E-03	1.60E+03	2.60E+03
p-Chlorotoluene	106-43-4		4.40E+01	4.50E+00	1.70E-02	1.20E+03	2.00E+03
Cresol (Technical) (Methylphenol)	1319-77-3		3.10E+04	2.40E-01	1.10E-06	5.00E+02	9.33E+01
o-Cresol (2-Methylphenol)	95-48-7	HSL	2.50E+04	2.43E-01	1.50E-06		8.91E+01
p-Cresol (4-Methylphenol)	106-44-5	HSL		1.14E-01			8.51E+01
Dibenzofuran		HSL					1.32E+04
1,2-Dichlorobenzene (o-Dichlorobenzene)	95-50-1	HPP	1.00E+02	1.00E+00	1.93E-03	1.70E+03	3.98E+03
1,3-Dichlorobenzene (m-Dichlorobenzene)	541-73-1	HPP	1.23E+02	2.28E+00	3.59E-03	1.70E+03	3.98E+03
1,4-Dichlorobenzene (p-Dichlorobenzene)	106-46-7	HPP	7.90E+01	1.18E+00	2.89E-03	1.70E+03	3.98E+03
2,4-Dichlorophenol	120-83-2	HPP	4.60E+03	5.90E-02	2.75E-06	3.80E+02	7.94E+02
Dichlorotoluene (Benzal chloride)	98-87-3		2.50E+00	3.00E-01	2.54E-02	9.90E+03	1.60E+04
Diethylstilbestrol (DES)	56-53-1		9.60E-03			2.80E+01	2.88E+05
2,4-Dimethylphenol (m-Xylenol)	1300-71-6	HPP	4.20E+03	6.21E-02	2.38E-06	2.22E+02	2.63E+02

Table 4-23. Water Solubility, Vapor Pressure, Henry's Law Constant, K_{oc}, and K_{ow} Data for Selected Chemicals (3) (Continued)

Chemical Name	CAS #	EPA	Water Solubility (mg/L)	Vapor Pressure (mm Hg)	Henry's Law Constant (atm-m^3/mol)	K_{oc} (mL/g)	K_{ow}
1,3-Dinitrobenzene	99-65-0		4.70E+02			1.50E+02	4.17E+01
4,6-Dinitro-o-cresol	534-52-1	HPP	2.90E+02	5.00E-02	4.49E-05	2.40E+02	5.01E+02
2,4-Dinitrophenol	51-28-5	HPP	5.60E+03	1.49E-05	6.45E-10	1.66E+01	3.16E+01
2,3-Dinitrotoluene	602-01-7		3.10E+03			5.30E+01	1.95E+02
2,4-Dinitrotoluene	121-14-2	HPP	2.40E+02	5.10E-03	5.09E-06	4.50E+01	1.00E+02
2,5-Dinitrotoluene	619-15-8		1.32E+03			8.40E+01	1.90E+02
2,6-Dinitrotoluene	606-20-2	HPP	1.32E+03	1.80E-02	3.27E-06	9.20E+01	1.00E+02
3,4-Dinitrotoluene	610-39-9		1.08E+03			9.40E+01	1.95E+02
Ethylbenzene (Phenylethane)	100-41-4	HPP	1.52E+02	7.00E+00	6.43E-03	1.10E+03	1.41E+03
Hexachlorobenzene (Perchlorobenzene)	118-74-1	HPP	6.00E-03	1.09E-05	6.81E-04	3.90E+03	1.70E+05
Hexachlorophene (Dermadex)	70-30-4		4.00E-03			9.10E+04	3.47E+07
Nitrobenzene	98-95-3	HPP	1.90E+03	1.50E-01	2.20E-05	3.60E+01	7.08E+01
2-Nitrophenol (o-Nitrophenol)	88-75-5	HPP	2.10E+03				5.75E+01
4-Nitrophenol (p-Nitrophenol)	100-07-7	HPP	1.60E+04				8.13E+01
m-Nitrotoluene (Methylnitrobenzene)	99-08-1		4.98E+02				2.92E+02
Pentachlorobenzene	608-93-5		1.35E-01	6.00E-03		1.30E+04	1.55E+05
Pentachloronitrobenzene (Quintozene)	82-68-8		7.11E-02	1.13E-04	6.18E-04	1.90E+04	2.82E+05
Pentachlorophenol	87-86-5	HPP	1.40E+01	1.10E-04	2.75E-06	5.30E+04	1.00E+05
Phenol	108-95-2	HPP	9.30E+04	3.41E-01	4.54E-07	1.42E+01	2.88E+01
Pyridine	110-86-1		1.00E+06	2.00E+01			4.57E+00
Styrene (Ethenylbenzene)	100-42-5	HSL	3.00E+02	4.50E+00	2.05E-03		
1,2,3,4-Tetrachlorobenzene	634-66-2		3.50E+00	4.00E-02		1.80E+04	2.88E+04
1,2,3,5-Tetrachlorobenzene			2.40E+00	7.00E-02		1.78E+04	2.88E+04
1,2,4,5-Tetrachlorobenzene	95-94-3		6.00E+00	5.40E-03		1.60E+03	4.68E+04
2,3,4,6-Tetrachlorophenol	58-90-2		7.00E+00	4.60E-03		9.80E+01	1.26E+04
Toluene (Methylbenzene)	108-88-3	HPP	5.35E+02	2.81E+01	6.37E-03	3.00E+02	5.37E+02
1,2,3-Trichlorobenzene	87-61-6		1.20E+01	2.10E-01	4.23E-03	7.40E+03	1.29E+04
1,2,4-Trichlorobenzene	120-82-1	HPP	3.00E+01	2.90E-01	2.31E-03	9.20E+03	2.00E+04
1,3,5-Trichlorobenzene	108-70-3		5.80E+00	5.80E-01	2.39E-02	6.20E+03	1.41E+04
2,4,5-Trichlorophenol	95-95-4	HSL	1.19E+03	1.00E+00	2.18E-04	8.90E+01	5.25E+03
2,4,6-Trichlorophenol	88-06-2	HPP	8.00E+02	1.20E-02	3.90E-06	2.00E+03	7.41E+03
1,2,4-Trimethylbenzene (Pseudocumene)	95-63-6		5.76E+01	2.03E+00	5.57E-03		
Xyelene (mixed)	1330-20-7	HSL	1.98E+02	1.00E+01	7.04E-03	2.40E+02	1.83E+03
m-Xylene (1,3-Dimethylbenzene)	108-38-3		1.30E+02	1.00E+01	1.07E-02	9.82E+02	1.82E+03
o-Xylene (1,2-Dimethylbenzene)	95-47-6		1.75E+02	6.60E+00	5.10E-03	8.30E+02	8.91E+02
p-Xylene (1,4-Dimethylbenzene)	106-42-3		1.98E+02	1.00E+01	7.05E-03	8.70E+02	1.41E+03
Polyaromatic Hydrocarbons							
Acenapthene	83-32-9	HPP	3.42E+00	1.55E-03	9.20E-05	4.60E+03	1.00E+04
Acenaphthylene	208-96-8	HPP	3.93E+00	2.90E-02	1.48E-03	2.50E+03	5.01E+03
Anthracene	120-12-7	HPP	4.50E-02	1.95E-04	1.02E-03	1.40E+04	2.82E+04
Benz(c)acridine	225-51-4		1.40E+01			1.00E+03	3.63E+04
Benzo(a)anthracene	56-55-3	HPP	5.70E-03	2.20E-08	1.16E-06	1.38E+06	3.98E+05
Benzo(b)fluoranthene	205-99-2	HPP	1.40E-02	5.00E-07	1.19E-05	5.50E+05	1.15E+06
Benzo(k)fluoranthene	207-08-9	HPP	4.30E-03	5.10E-07	3.94E-05	5.50E+05	1.15E+06
Benzo(g,h,i)perylene	191-24-2	HPP	7.00E-04	1.03E-10	5.34E-08	1.60E+06	3.24E+06
Benzo(a)pyrene	50-32-8	HPP	1.20E-03	5.60E-09	1.55E-06	5.50E+06	1.15E+06
2-Chloronaphthalene	91-58-7	HPP	6.74E+00	1.70E-02	4.27E-04		1.32E+04
Chrysene	218-01-9	HPP	1.80E-03	6.30E-09	1.05E-06	2.00E+05	4.07E+05
Dibenz(a,h)anthracene	53-70-3	HPP	5.00E-04	1.00E-10	7.33E-08	3.30E+06	6.31E+06
1,2,7,8-Dibenzopyrene	189-55-9		1.01E-01			1.20E+03	4.17E+06
7,12-Dimethylbenz(a)anthracene	57-97-6		4.40E-03			4.76E+05	8.71E+06
Fluoranthene	206-44-0	HPP	2.06E-01	5.00E-06	6.46E-06	3.80E+04	7.94E+04
Fluorene (2,3-Benzidene)	86-73-7	HPP	1.69E+00	7.10E-04	6.42E-05	7.30E+03	1.58E+04

Table 4-23. Water Solubility, Vapor Pressure, Henry's Law Constant, K_{oc}, and K_{ow} Data for Selected Chemicals (3) (Continued)

Chemical Name	CAS #	EPA	Water Solubility (mg/L)	Vapor Pressure (mm Hg)	Henry's Law Constant (atm-m^3/mol)	K_{oc} (mL/g)	K_{ow}
Indene	95-13-6						8.32E+02
Indeno(1,2,3-cd)pyrene	193-99-5	HPP	5.30E-04	1.00E-10	6.86E-08	1.60E+06	3.16E+06
2-Methylnaphthalene	91-57-6	HSL	2.54E+01			8.50E+03	1.30E+04
Naphthalene (Naphthene)	91-20-3	HPP	3.17E+01	2.30E-01	1.15E-03	1.30E+03	2.76E+03
1-Naphthylamine	134-32-7		2.35E+03	6.50E-05	5.21E-09	6.10E+01	1.17E+02
2-Naphthylamine	91-59-8		5.86E+02	2.56E-04	8.23E-08	1.30E+02	1.17E+02
Phenanthrene	85-01-8	HPP	1.00E+00	6.80E-04	1.59E-04	1.40E+04	2.88E+04
Pyrene	129-00-0	HPP	1.32E-01	2.50E-06	5.04E-06	3.80E+04	7.59E+04
Tetracene (Naphthacene)	92-24-0		5.00E-04			6.50E+05	8.00E+05
Amines and Amides							
2-Acetylaminofluorene	53-96-3		6.50E+00			1.60E+03	1.91E+03
Acrylamide (2-Propenamide)	79-06-1		2.05E+06	7.00E-03	3.19E-10		
4-Aminobiphenyl (p-Biphenylamine)	92-67-1		8.42E+02	6.00E-05	1.59E-08	1.07E+02	6.03E+02
Aniline (Benzenamine)	62-53-3	HSL	3.66E+04	3.00E-01	1.00E-06		7.00E+00
Auramine	2465-27-2		2.10E+00			2.90E+03	1.45E+04
Benzidine (p-Diaminodiphenyl)	92-87-5	HPP	4.00E+02	5.00E-04	3.03E-07	1.05E+01	2.00E+01
2,4-Diaminotoluene (Toluenediamine)	95-80-7		4.77E+04	3.80E-05	1.28E-10	1.20E+01	2.24E+00
3,3'-Dichlorobenzidine	91-94-1	HPP	4.00E+00	1.00E-05	8.33E-07	1.55E+03	3.16E+03
Diethanolamine	111-42-2		9.54E+05				3.72E-02
Diethylaniline (Benzenamine)	91-66-7		6.70E+02				9.00E+00
Diethylnitrosamine (Nitrosodiethylamine)	55-18-5			5.00E+00			3.02E+00
Dimethylamine	124-40-3		1.00E+06	1.52E+03	9.02E-05	4.35E+02	4.17E-01
Dimethylaminoazobenzene	60-11-7		1.36E+01	3.30E-07	7.19E-09	1.00E+03	5.25E+03
Dimethylnitrosamine	62-75-9	HPP	Infinite	8.10E+00	7.90E-07	1.00E-01	2.09E-01
Diphenylnitrosamine	86-30-6	HPP					3,72E+02
Dipropylnitrosamine	621-64-7	PP	9.90E+03	4.00E-01	6.92E-06	1.50E+01	3.16E+01
Methylvinylnitrosamine	4549-40-0		7.60E+05	1.23E+01	1.83E-06	2.50E+00	5.89E-01
m-Nitroaniline (3-Nitroaniline)	99-09-2	HSL	8.90E+02				2.34E+01
o-Nitroaniline (2-Nitroaniline)	88-74-4	HSL	1.47E+04				6.17E+01
p-Nitroaniline (4-Nitroaniline)	100-01-6	HSL	7.30E+02				2.45E+01
N-Nitrosodi-n-propylamine	621-64-7	HSL					
Thioacetamide (Ethanethioamide)	62-55-5		1.63E+05				3.47E-01
o-Toluidine (2-Aminotoluene)	119-93-7		7.35E+01	E+00		4.10E+02	7.58E+02
o-Toluidine hydrochloride	636-21-5		1.50E+04	1.00E-01	9.39E-07	2.20E+01	1.95E+01
Triethylamine	121-44-8		1.50E+04	7.00E+00	1.30E+05		
Ethers and Alcohols							
Allyl alcohol (Propenol)	107-18-6		5.10E+05	2.46E+01	3.69E-06	3.20E+00	6.03E-01
Anisole (Methoxybenzene)	100-66-3		1.52E+03	2.60E+00	2.43E-04	2.00E+01	1.29E+02
Benzyl alcohol (Benzenemethanol)	100-51-6	HSL	8.00E+02	1.10E-01	1.95E-05		1.26E+01
Bis(2-chloroethyl)ether	111-44-4	HPP	1.02E+04	7.10E-01	1.31E-05	1.39E+01	3.16E+01
Bis(2-chloroisopropyl)ether	108-60-1	HPP	1.70E+03	8.50E-01	1.13E-04	6.10E+01	1.26E+02
Bis(chloromethyl)ether	542-88-1		2.20E+04	3.00E+01	2.06E-04	1.20E+00	2.40E+00
4-Bromophenyl phenyl ether	101-55-3	HPP		1.50E-03			1.91E+04
2-Chloroethyl vinyl ether	110-75-8	HPP	1.50E+04	2.67E+01	2.50E-04		1.90E+01
Chloromethyl methyl ether	107-30-2						1.00E+00
4-Chlorophenyl phenyl ether	7005-72-3	HPP	3.30E+00	2.70E-03	2.19E-04		1.20E+04
Diphenylether (Phenyl ether)	101-84-8		2.10E+01	2.13E-02	8.67E-09		1.62E+04
Ethanol	64-17-5		Infinite	7.40E+02	4.48E-05	2.20E+00	4.79E-01
Phthalates							
Bis(2-ethylhexyl)phthalate	117-81-7	HPP	2.85E-01	2.00E-07	3.61E-07	5.90E+03	9.50E+03
Butylbenzyl phthalate	85-68-7	HPP	4.22E+01				6.31E+04
Dibutyl phthalate	84-74-2	HPP	1.30E+01	1.00E-05	2.82E-07	1.70E+05	3.98E+05
Diethyl phthalate	84-66-2	HPP	8.96E+02	3.50E-03	1.14E-06	1.42E+02	3.16E+02

Table 4-23. Water Solubility, Vapor Pressure, Henry's Law Constant, K_{oc}, and K_{ow} Data for Selected Chemicals (3) (Continued)

Chemical Name	CAS #	EPA	Water Solubility (mg/L)	Vapor Pressure (mm Hg)	Henry's Law Constant (atm-m^3/mol)	K_{oc} (mL/g)	K_{ow}
Dimethyl phthalate	131-11-3	HPP	4.32E+03	E-02			1.32E+02
Di-n-octyl phthalate	117-84-0	HPP	3.00E+00				1.58E+09
Ketones and Aldehydes							
Acetone (2-Propanone)	67-64-1	HSL	Infinite	2.70E+02	2.06E-05	2.20E+00	5.75E-01
Acrylic acid (2-Propenoic acid)	79-10-7		Infinite	4.00E+00			1.35E+00
2-Butanone (Methyl ethyl ketone)	78-93-3	HSL	2.68E+05	7.75E+01	2.74E-05	4.50E+00	1.82E+00
Formaldehyde	50-00-0		4.00E+05	1.00E+01	9.87E-07	3.60E+00	1.00E+00
Glycidaldehyde	765-34-4		1.70E+08	1.97E+01	1.10E-08	1.00E-01	2.82E-02
2-Hexanone (Methyl butyl ketone)	591-78-6	HSL	1.40E+04	3.00E+10	2.82E-05		
4-Methyl-2-pentanone (Isopropylacetone)	108-10-1	HSL	1.70E+04	2.00E+01	1.55E-04		
Carboxylic Acids and Esters							
Azaserine	115-02-6		1.36E+05			6.60E+00	8.32E-02
Benzoic acid	65-85-0	HSL	2.70E+03				7.41E+01
Dimethyl sulfate (DMS)	77-78-1		3.24E+05	6.80E-01	3.48E-07	4.10E+00	5.75E-02
Ethyl methanesulfonate (EMS)	62-50-0		3.69E+05	2.06E-01	9.12E-08	3.80E+00	1.62E+00
Formic acid	64-18-6		1.00E+06	4.00E+01			2.88E-01
Lasiocarpine	303-34-4		1.60E+03			7.60E+01	9.77E+00
Methyl methacrylate	80-62-6		2.00E+01	3.70E+01	2.43E-01	8.40E+02	6.17E+00
Vinyl acetate	108-05-4	HSL	2.00E+04				
PCBs							
Aroclor 1016	12674-11-2	HPP	4.20E-01	4.00E-04			2.40E+04
Aroclor 1221	11104-28-2	HPP	1.50E+01	6.70E-03			1.23E+04
Aroclor 1232	11141-16-5	HPP	1.45E+00	4.06E-03			1.58E+03
Aroclor 1242	53469-21-9	HPP	2.40E-01	4.10E-04	5.60E-04		1.29E+04
Aroclor 1248	12672-29-6	HPP	5.40E-02	4.90E-04	3.50E-03		5.62E+05
Aroclor 1254	11097-69-1	HPP	1.20E-02	7.70E-05	2.70E-03	4.25E+04	1.07E+06
Aroclor 1260	11096-82-5	HPP	2.70E-03	4.10E-05	7.10E-03		1.38E+07
Polychlorinated biphenyls (PCBs)	1336-36-3	HPP	3.10E-02	7.70E-05	1.07E-03	5.30E+05	1.10E+06
Heterocyclic Compounds							
Dihydrosafrole	94-58-6		1.50E+03			7.80E+01	3.63E+02
1,4-Dioxane (1,4-Diethylene dioxide)	123-91-1		4.31E+05	3.99E+01	1.07E-05	3.50E+00	1.02E+00
Epichlorohydrin	106-89-8		6.00E+04	1.57E+01	3.19E-05	1.00E+01	1.41E+00
Isosafrole	120-58-1		1.09E+03	1.60E-08	3.25E-12	9.30E+01	4.57E+02
N-Nitrosopiperidine	100-75-4		1.90E+06	1.40E-01	1.11E-08	1.50E+00	3.24E-01
N-Nitrosopyrrolidine	930-55-2		7.00E+06	1.10E-01	2.07E-09	8.00E-01	8.71E-02
Safrole	94-59-7		1.50E+03	9.10E-04	1.29E-07	7.80E+01	3.39E+02
Uracil mustard	66-75-1		6.41E+02			1.20E+02	8.13E-02
Hydrazines							
1,2-Diethylhydrazine	1615-80-1		2.88E+07			3.00E-01	2.09E-02
1,1-Dimethylhydrazine	57-14-4		1.24E+08	1.57E+02	1.00E-07	2.00E-01	3.80E-03
1,2-Diphenylhydrazine (Hydrazobenzene)	122-66-7	PP	1.84E+03	2.60E-05	3.42E-09	4.18E+02	7.94E+02
Hydrazine	302-01-1		3.41E+08	1.40E+01	1.73E-09	1.00E-01	8.32E-04
Miscellaneous Organic Compounds							
Aziridine (Ethylenimine)	151-56-4		2.66E+06	2.55E+02	5.43E-06	1.30E+00	9.77E-02
Carbon disulfide	75-15-0	HSL	2.94E+03	3.60E+02	1.23E-02	5.40E+01	1.00E+02
Diethyl arsine	692-42-2		4.17E+02	3.50E+01	1.48E-02	1.60E+02	9.33E+02
Dimethylcarbamoyl chloride	79-44-7		1.44E+07	1.95E+00	1.92E-08	5.00E-01	4.79E-02
Mercury and alkyl compounds	7439-97-6	PP					
Methylnitrosourea	684-93-5		6.89E+08			1.00E-01	1.54E-04
Mustard gas (Bis(2-chloroethyl)sulfide)	505-60-2		8.00E+02	1.70E-01	4.45E-05	1.10E+02	2.34E+01
Phenobarbital	50-06-6		1.00E+03			9.80E+01	6.46E-01
Propylenimine	75-55-8		9.44E+05	1.41E+02	1.12E-05	2.30E+00	3.31E-01
Tetraethyl lead	78-00-2		8.00E-01	1.50E-01	7.97E-02	4.90E+03	

Table 4-23. Water Solubility, Vapor Pressure, Henry's Law Constant, K_{oc}, and K_{ow} Data for Selected Chemicals (3) (Continued)

Chemical Name	CAS #	EPA	Water Solubility (mg/L)	Vapor Pressure (mm Hg)	Henry's Law Constant (atm-m^3/mol)	K_{oc} (mL/g)	K_{ow}
Thiourea (Thiocarbamide)	62-56-6		1.72E+06			1.60E+00	8.91E-03
Tris-BP (2,3-Dibromopropanol phosphate)	126-72-7		1.20E+02			3.10E+02	1.32E+04
Inorganics							
Ammonia	7664-41-7		5.30E+05	7.60E+03	3.21E-04	3.10E+00	1.00E+00
Antimony and compounds	7440-36-0	PP		1.00E+00			
Arsenic and compounds	7440-38-2	PP		0.00E+00			
Barium and compounds	7440-39-3						
Beryllium and compounds	7440-41-7	PP		0.00E+00			
Cadmium and compounds	7740-43-9	PP		0.00E+00			
Chromium III and compounds	7440-47-3	PP		0.00E+00			
Chromium VI and compounds	7440-47-3	PP		0.00E+00			
Copper and compounds	7440-50-8	PP		0.00E+00			
Cyanogen chloride	506-77-4		2.50E+03	1.00E+03	3.24E-02		1.00E+00
Hydrogen cyanide	74-90-8		Infinite	6.20E+02			5.62E-01
Hydrogen sulfide	7783-06-4		4.13E+03	1.52E+04	1.65E-01		
Lead and compounds	7439-92-1	PP		0.00E+00			
Mercury and compounds (inorganic)	7439-97-6	PP	3.00E-02	2.00E-03	1.10E-02		
Nickel and compounds	7440-02-0	PP		0.00E+00			
Potassium cyanide	151-50-8		5.00E+05				
Selenium and compounds	7782-49-2	PP		0.00E+00			
Silver and compounds	7440-22-4	PP		0.00E+00			
Sodium cyanide	143-33-9		8.20E+05				
Thallium chloride	7791-12-0	PP	2.90E+03	0.00E+00			
Thallium sulfate	7446-18-6	PP	2.00E+02	0.00E+00			
Thallium and compounds	7440-28-0	PP		0.00E+00			
Zinc and compounds	7440-66-6	PP		0.00E+00			

PP = Priority Pollutant
HSL = Hazardous Substance List parameter
HPP = PP and HSL parameters

4.4 Treatability Studies

Bench- and pilot-scale treatability studies are valuable means for determining the feasibility of candidate treatment processes for removing contaminants from ground water and leachate. Treatability screening allows a quick, relatively inexpensive evaluation of many different treatment processes when searching for the optimal applicable solution. Bench- and pilot-scale studies also yield basic design data for subsequent use in the design of full-scale facilities and for other technical and economic evaluations.

The need for treatability studies should be considered by comparing the advantages of these studies with their limitations, as discussed in Sections 4.4.3 and 4.4.4.

A well-planned treatability study test program should strive to provide:

- Technically feasible design criteria for full-scale applications.
- Data for estimating full-scale capital and operational costs.
- A basis for equipment performance specifications.
- A nonbiased technical solution.

These considerations are more fully described below.

4.4.1 Types of Treatability Tests

4.4.1.1 Bench Tests

Bench-scale treatability tests are usually performed in the laboratory on actual samples of ground water or leachate. Sample size may vary from 5 to 55 gal (19 to 208 L). Studies performed in the laboratory are more convenient because all of the necessary testing equipment and glassware are readily available; both biological and physical/chemical tests can be routinely performed in the laboratory. Under special circumstances, it may be necessary to run the bench treatability tests in the field. Field tests are common when waste characteristics can change quickly, sample requirements make shipping the water impractical, or the testing needs to be performed over a long period. The engineer can perform a substantial array of bench tests

Table 4-24. Henry's Law Constant (H_l) Groupings (4)

High H_l^a—2×10^2 to 10^{-1}	Medium H_l^a—10^{-1} to 10^{-3}	Low H_l^a—10^{-3} to 10^{-8}
Benzene (0.19)	Acenaphthene (0.0079)	Bis(2-chloroethyl)ether (5.4×10^{-4})
Carbon tetrachloride (1.0)	Acrolein (0.004)	2-Chloroethyl vinyl ether (1.04×10^{-4})
Chlorobenzene (0.17)	Acrylonitrile (0.0026)	Bis(2-chloroethoxy)methane (1.17×10^{-5})
1,1,1-Trichloroethane (0.15)	1,2-Dichloroethane (0.046)	Nitrobenzene (5.46×10^{-4})
Chloroethane (0.21)	Hexachloroethane (0.046)	2,4-Dinitrotoluene (1.87×10^{-4})
1,1-Dichloroethane (0.62)	1,1,2-Trichloroethane (0.032)	2,6-Dinitrotoluene (3.29×10^{-4})
Chloroform (0.14)	1,1,2,2-Tetrachloroethane (0.017)	Phenol (1.89×10^{-5})
Chloromethane (1.67)	Methylene chloride (0.085)	2-Chlorophenol (4.29×10^{-4})
Vinyl chloride (3.4)	1,2-Dichloropropane (0.096)	2,4-Dichlorophenol (1.17×10^{-4})
1,1-Dichloroethene (7.92)	1,3-Dichloropropene (0.055)	2,4,6-Trichlorophenol (1.67×10^{-4})
1,2-trans-Dichloroethene (2.79)	Dibromochloromethane (0.041)	Pentachlorophenol (1.17×10^{-4})
Trichloroethene (0.379)	Tribromomethane (0.023)	2-Nitrophenol (3.15×10^{-4})
Tetrachloroethene (0.638)	Bis(chloromethyl)ether (0.00875)	2,4-Dinitrophenol (2.69×10^{-8})
Hexachloro-1,3-butadiene (1.07)	Bis(2-chloroisopropyl)ether (0.00458)	2,4-Dimethylphenol (7.08×10^{-4})
Hexachlorocyclopentadiene (0.667)	4-Chlorophenyl phenyl ether (0.00912)	p-Chloro-m-cresol (1.04×10^{-4})
Bromomethane (8.21)	4-Bromophenyl phenyl ether (0.00417)	Dimethyl phthalate (8.96×10^{-5})
Bromodichloromethane (0.100)	1,2-Dichlorobenzene (0.080)	Diethyl phthalate (5×10^{-5})
Dichlorodifluoromethane (124.2))	1,2,4-Trichlorobenzene (0.096)	Di-n-butyl phthalate (1.17×10^{-5})
Trichlorofluoromethane (4.58)	Hexachlorobenzene (0.028)	Di-n-octyl phthalate (7.08×10^{-4})
1,3-Dichlorobenzene (0.150)	4-Nitrophenol (0.0010)	Bis(2-ethylhexyl)phthalate (1.25×10^{-5})
1,4-Dichlorobenzene (0.125)	4,6-Dinitro-o-cresol (0.0017)	Butyl benzyl phthalate (3.46×10^{-4})
Ethylbenzene (0.275)	Acenaphthylene (0.0604)	Benzo(a)anthracene (4.17×10^{-5})
Toluene (0.277)	Anthracene (0.0036)	Benzo(b)fluoranthene (5.08×10^{-4})
	Benzo(k)fluoranthene (0.0016)	Benzo(g,h,i)perylene (6×10^{-6})
	Fluorene (0.00267)	Benzo(a)pyrene (2.04×10^{-5})
	Naphthalene (0.0191)	Chrysene (4.38×10^{-5})
	Phenanthrene (0.0094)	Di-benzo(a,h)anthracene (3.04×10^{-6})
	Dimethylnitrosoamine (0.0014)	Fluoranthene (2.71×10^{-4})
	Diphenylnitrosoamine (0.0275)	Indeno(1,2,3-d)pyrene (2.89×10^{-6})
		Pyrene (2.12×10^{-4})
		Di-n-propylnitrosamine (2.62×10^{-4})
		Benzidine (1.25×10^{-5})
		3,3-Dichlorobenzidine (3.33×10^{-5})
		1,2-Diphenylhydrazine (1.41×10^{-7})

[a] H_l is expressed as the ratio of mass per unit volume in air to mass per unit volume in water ($mg/m^3/mg/m^3$).

in the field using portable treatability equipment. Some field analytical equipment should be made available to assist in the testing process.

4.4.1.2 Pilot Tests

Pilot-scale treatability tests use scaled-down replicates of full-size treatment equipment to gather treatability data. The skid-mounted or mobile pilot equipment is used to field-verify initial bench-scale design parameters under actual continuous flow operations. The field tests are normally run under multiple conditions to study the effect of each parameter on treatment results.

Pilot-scale tests require appropriate equipment and skilled operators for successful results. Large, expensive, full-scale installations are usually pilot-tested to optimize the design and minimize risk. The full-scale equipment cost typically justifies the pilot-scale treatability tests because the results are used as the design

Table 4-25. Classes of Organic Compounds Adsorbed on Carbon (5)

Organic Chemical Class	Examples of Chemical Class
Aromatic hydrocarbons	Benzene, toluene, xylene
Polynuclear aromatics	Naphthalene, anthracenes, biphenyls
Chlorinated aromatics	Chlorobenzene, polychlorinated biphenyls, aldrin, endrin, toxaphene, DDT
Phenolics	Phenol, cresol, resorcenol, polyphenyls
Chlorinated phenolics	Trichlorophenol, pentachlorophenol
High molecular weight aliphatic and branch-chain hydrocarbons[a]	Gasoline, kerosene
Chlorinated aliphatic hydrocarbons	1,1,1-Trichloroethane, trichloroethylene, carbon tetrachloride, perchloroethylene
High molecular weight aliphatic acids and aromatic acids[a]	Tar acids, benzoic acid
High molecular weight aliphatic amines and aromatic amines[a]	Aniline, toluene, diamine
High molecular weight ketones, esters, ethers, and alcohols[a]	Hydroquinone, polyethylene glycol
Surfactants	Alkyl benzene sulfonates
Soluble organic dyes	Methylene blue, indigo carmine

[a] High molecular weight includes compounds in the range of 4 to 20 carbon atoms.

basis. In addition to optimizing equipment selection and chemical requirements, the pilot tests can be used to identify potential operating problems. Examples include scale buildup, sludge bulking, and postprecipitates. In these cases, corrective action can be taken before full-scale operations.

Field analysis kits are commonly used to analyze treated samples for quick results to guide the tests; however, these data are typically supported by laboratory analyses using EPA-approved methods. The laboratory results serve as the basis for full-scale equipment design and selection.

4.4.1.3 Vendor Treatability Tests

Vendors commonly agree to perform treatability tests with their equipment at the project site or in their laboratories. By sending samples of ground water or leachate to multiple equipment vendors for treatability tests, the best vendor of a selected technology can be chosen. The advantages of proprietary chemicals and design show up in the test results. Vendors may be subcontracted to perform the treatability tests, or they can be requested to test their products at their own expense as a prequalification for bidding. Duplicate samples are usually submitted to an unbiased laboratory for a confirming analysis at the owner's expense.

4.4.1.4 Independent Treatability Tests

Many qualified consultants and laboratories can perform independent treatability tests under contract. In these circumstances, there is less bias toward process selection of a specific equipment design or proprietary technology. Combination processes can be incorporated into treatment trains that result in improved contaminant removal over single processes. Although independent treatability testing does not benefit from the advantages of proprietary processes and chemical compounds, the results are unbiased. The technology recommendations are based on performance, economics, reliability, and true client needs.

4.4.2 Treatability Testing Strategies

4.4.2.1 Technology Screening

The objectives of the initial technology screening are to:

- Verify the suitability and effectiveness of candidate treatment technologies in meeting treatment objectives.
- Identify the treatment process steps and the order in which these steps are performed.
- Obtain treatment process data (e.g., chemicals needed, dosages, reaction times, separation rates) and preliminary cost information.

The first step is to develop a test plan. A testing plan may be developed to present a detailed description of the processes to be tested and to show how the tests will be conducted. Because the tests are only valid if the samples are representative, flow and concentration data must be collected over as long a period as possible. The testing plan should contain specific information on:

- A sampling strategy that addresses variation with time.
- The numbers and types of experiments proposed.
- The volume of ground water or leachate required for each test.
- A list of parameters that will be chosen to optimize operation of the treatment arrangement.
- The sampling and analytical requirements for each test series.
- A basis for selecting the numbers and types of experiments.

Health and safety plans and quality assurance project plans may also need to be developed before testing begins.

Table 4-26. Summary of Carbon Adsorption Capacities (5)

Compound	Adsorption Capacity (mg/g)[a]
Acenaphthene	190
Acenaphthylene	115
Acetophenone	74
2-Acetylaminofluorene	318
Acridine orange	180
Acridine yellow[b]	230
Acrolein	1.2
Acrylonitrile	1.4
Adenine[b]	71
Aldrin	651
4-Aminobiphenyl	200
Anethole[b]	300
o-Anisidine[b]	50
Anthracene	376
Aroclor 1221	242
Aroclor 1232	630
Benzene	1.0
alpha-Benzene hexachloride (alpha-BHC)	303
beta-Benzene hexachloride (beta-BHC)	220
gamma-Benzene hexachloride (gamma-BHC) (Lindane)	256
Benzidine dihydrochloride	220
Benzo(k)fluoranthene	181
3,4-Benzofluoranthene	57
Benzoic acid	0.76
Benzo(g,h,i)perylene	11
Benzo(a)pyrene	34
Benzothiazole[b]	120
Bis(2-chloroethoxy)methane	11
Bis(2-chloroisopropyl)ether	24
Bis(2-ethylhexyl)phthalate	11,300
Bromoform	20
4-Bromophenyl phenyl ether	144
5-Bromouracil	44
Butylbenzyl phthalate	1,520
N-Butylphthalate	220
Carbon tetrachloride	11
Chlordane	245
Chlorobenzene	91
p-Chloro-m-cresol	124
Chloroethane	0.59
2-Chloroethyl vinyl ether	3.9
Chloroform	2.6
2-Chloronaphthalene	280
1-Chloro-2-nitrobenzene	130
2-Chlorophenol	51
4-Chlorophenyl phenyl ether	111
5-Chlorouracil[b]	25
Cyclohexanone[b]	6.2
Cytosine[b]	1.1
Dibenzo(a,h)anthracene	69
Dibromochloromethane	4.8
1,2-Dibromo-3-chloropropane	53
1,2-Dichlorobenzene	129
1,3-Dichlorobenzene	118
1,4-Dichlorobenzene	121
3,3-Dichlorobenzidine	300
Dichlorobromomethane	7.9
Dichlorodiphenyldichloroethylene (DDE)	232
Dichlorodiphenyltrichloroethane (DDT)	322
1,1-Dichloroethane	1.8
1,2-Dichloroethane	3.6
1,2-trans-Dichloroethene	3.1
1,1-Dichloroethylene	4.9
2,4-Dichlorophenol	157
1,2-Dichloropropane	5.9
1,2-Dichloropropene	8.2
Dieldrin	606
Diethyl phthalate	110
4-Dimethylaminoazobenzene	249
N-Dimethylnitrosamine	6.8×10^{-5}
2,4-Dimethylphenol	78
Dimethylphenylcarbinol[b]	210
Dimethyl phthalate	97
4,6-Dinitro-o-cresol	169
2,4-Dinitrophenol	33
2,4-Dinitrotoluene	146
2,6-Dinitrotoluene	145
Diphenylamine	120
1,1-Diphenylhydrazine	135
alpha-Endosulfan	194
beta-Endosulfan	615
Endosulfan sulfate	686
Endrin	666
Ethylbenzene	53
Ethylenediaminetetraacetic acid	0.86
Fluoranthene	664
Fluorene	330
5-Fluorouracil[b]	5.5
Guanine[b]	120
Heptachlor	1,220
Heptachlor epoxide	1,038
Hexachlorobenzene	450
Hexachlorobutadiene	258
Hexachloroethane	97
Isophorone	32

Table 4-26. Summary of Carbon Adsorption Capacities (5) (Continued)

Compound	Adsorption Capacity (mg/g)[a]
4,4'-Methylene-bis-(2-chloroaniline)	190
Methylene chloride	1.3
Naphthalene	132
alpha-Naphthol	180
beta-Naphthol[b]	200
alpha-Naphthylamine	160
beta-Naphthylamine	150
p-Nitroaniline[b]	140
Nitrobenzene	68
4-Nitrobiphenyl	370
2-Nitrophenol	99
4-Nitrophenol	76
N-Nitrosodiphenylamine	220
N-Nitrosodi-n-propylamine	24
p-Nonylphenol	250
Pentachlorophenol	150
Phenanthrene	215
Phenol	21
Phenylmercuric acetate	270
Styrene	120
1,1,2,2-Tetrachloroethane	11
Tetrachloroethene	51
1,2,3,4-Tetrahydronaphthalene	74
Thymine[b]	27
Toluene	26
1,2,4-Trichlorobenzene	157
1,1,1-Trichloroethane	2.5
1,1,2-Trichloroethane	5.8
Trichloroethene	28
Trichlorofluoromethane	5.6
2,4,6-Trichlorophenol	155
Uracil[b]	11
p-Xylene	85
Not Adsorbed	
Acetone cyanohydrin	
Adipic acid	
Butylamine	
Choline chloride	
Cyclohexylamine	
Diethylene glycol	
Ethanol	
Hexamethylenediamine	
Hydroquinone	
Morpholine	
Triethanolamine	

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[a] Adsorption capacities are calculated for an equilibrium concentration of 1.0 mg/L at neutral pH.

[b] Compounds prepared in "mineralized" distilled water containing the following composition:

Ion	Conc. (mg/L)	Ion	Conc. (mg/L)
Ca^{++}	100	Cl^{-}	177
K^{+}	12.6	SO_4^{--}	100
Mg^{++}	25.3	Alkalinity	200
Na^{+}	92	PO_4^{--}	10

After the test plan has been developed, bench-scale jar tests should be performed in accordance with the test plan. Consideration should be given to technology selection and proper treatment sequence after a review of the characterization data is complete.

For most treatment steps, a series of small-scale jar tests can be performed to select effective treatment chemicals and to determine an appropriate range of dosages and reaction times for further tests. Standardized bench tests are then performed on larger volumes (usually 1 L) to obtain design factors that are effective in the planning and design of pilot plant and full-scale treatment equipment. Based on these test results, a larger sample is commonly treated to provide sufficient sample for the next treatment step. Preparation of treated samples for the performance of a standardized bench test always starts with raw sample, and the preliminary treatment tests are performed in such a manner as to minimize the inadvertent loss of sample components important for the evaluation of data from the bench test.

4.4.2.2 Optimization Testing

In-depth optimization testing on the selected processes or treatment trains should be provided before the equipment is selected. This additional test sequence provides further insights into how the technology will react under varying water characteristics and flow rates. Also, operating parameters can be evaluated to improve performance and/or reduce costs. To achieve this level of testing, it may be necessary to initiate pilot plant testing.

4.4.2.3 Design Verification

Data derived from treatability studies are very useful for full-scale treatment system design. Chemical doses, pH, settling rates, oxygen requirements, air-to-water ratios, sludge production, and retention times are examples of process parameters that can be determined directly from treatability testing. Full-scale equipment can be sized after applying the appropriate scaleup factors. Space requirements can then be accurately determined. Capital cost estimates of full-scale treatment systems based on well-performed treatability tests should be within 20 to 30 percent of actual cost. Operating cost estimates should also be reasonably accurate because chemical and power needs will scale up directly. If performed properly, the treatability study should lay a solid foundation to minimize the risks involved in meeting established cleanup goals.

4.4.3 *Advantages of Treatability Testing*

In the absence of literature or database performance statistics, treatability testing provides the remediation designer with preliminary information on whether or not the selected process(es) will meet expected removal goals. A candidate process can be evaluated with regard to size and operating parameters. New or innovative processes of interest can be applied to the ground water or leachate without excessive risk of time or funds. The time element of treatment for many processes can be estimated in a shorter period than if full-scale tests are performed. Examples would be GAC and ion exchange, where a small amount of medium would be depleted quickly to establish breakthrough time.

4.4.4 *Limitations of Treatability Tests*

Experienced and skilled personnel are required to perform treatability tests. These personnel typically have treated water matrices for many years and can select proper chemical dosages, sequences, and treatment trains to meet the project objectives. Samples resulting from treatment must be preserved and sent to qualified laboratories for analysis. Shipment and analysis require a few days to several weeks before the treatability results are known. The time and cost of performing the testing and laboratory analysis must be considered. The collection of representative treatability test samples is critical. Samples that are too dilute or too concentrated could result in a treatment system that is undersized or oversized. Long periods of bench or pilot testing may also be required for those sites with matrix characteristics that vary significantly.

Bench-scale treatability tests can be used to provide preliminary guidance on technology selection. They also may prove useful in the initial identification of pretreatment requirements and in estimation of the expected magnitude of treatment efficiency, effluent quality, and chemical dosages. Selection of basic design criteria for more comprehensive pilot plant testing should also be achievable. When evaluating the data from a treatability test, however, it must be remembered that the samples collected to perform the tests usually represent only a single point in time. Because the treatment system design may operate for years, even decades, long-term sampling changes must be considered. Usually, no allowance is made in the sample collection methodology for such factors as seasonal variations in ground water or leachate strength or the impact of runoff or rainfall. Furthermore, the appropriate scaleup factors must be applied to the bench test results so that the results can be correctly interpreted. Thus, readers are cautioned not to rely solely on the results of the bench-scale treatability study to provide sufficient technical information for a successful engineering design. Rather, the bench test results should be used in combination with subsequent continuous flow-through pilot plant tests, other available site data, and related experience to ensure that a well-operating, full-scale system is designed and constructed consistent with the goals of the project.

4.5 References

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Chapter 5
Case Studies

In this chapter, examples of ground-water or leachate problems at four sites illustrate how treatment technologies were evaluated, selected, designed, and implemented. Each case study covers the following topics:

- Background information about the site
- Evaluation of treatment alternatives
- Project design
- Results and summary

The purpose of these selected case studies is to show that many factors play a role in a decision. Site-specific factors, including regulatory issues, are part of the evaluation and selection process. For example, in Case Study 1 air is allowed to be discharged directly to the atmosphere, while in Case Study 4 the state required air emissions controls. In Case Study 1, the state required a temporary treatment system. Case Study 3 illustrates the importance of treatability studies for process selection. Figure 5-1 presents a brief description of each case study.

Case Study 1: Ground-Water and Landfill Leachate Treatment
Physical/chemical treatment to remove metals, volatile organic compounds (VOCs), and ammonia

Case Study 2: Ground-Water Treatment
Biological fluidized bed reactor to remove organics

Case Study 3: Landfill Leachate Treatment
Chemical pretreatment and biological treatment to remove metals and organics

Case Study 4: Ground-Water Treatment
High-temperature air stripping to remove VOCs

Figure 5-1. Case studies in Chapter 5.

5.1 Case Study 1: Ground-Water and Landfill Leachate Treatment—Physical/Chemical Treatment To Remove Metals, VOCs, and Ammonia

5.1.1 Background

This project involved a 75-acre (30.4-hectare) landfill that was developed in the early 1940s. A 21-acre (8.5-hectare) double-lined expansion area was permitted and placed in operation in the eastern portion of the site during the summer of 1987; however, the older, western portion of the facility was unlined. Leachate from this unlined portion of the landfill had affected the ground water in the immediate vicinity. The landfill had recently been sold, but the previous owner, under a Consent Agreement with the state, was required to extract and treat the leachate/ground-water mixture from the western portion of the site. The method of treatment selected was lime pH adjustment and biological oxidation in an aerated lagoon.

Later, a leachate and ground-water extraction system for the eastern portion of the site was installed. Lime addition was unnecessary due to the self-neutralizing character of leachate volatile acids; however, the existing aerated lagoon treatment system was grossly undersized to treat the additional water effectively. The new owner contracted with a consulting engineer to design a new physical/chemical treatment system to remove metals, VOCs, and ammonia from the extracted ground water and leachate. The projected ground-water/leachate flow rate for design was 350 gal/min (0.5 million gal/day) (1,325 L/min). Effluent from the landfill leachate treatment system flowed into a small creek that was classified for warm water fishery, recreation, water supply, and aquatic life. Stringent effluent limits were set, and a rigid schedule for compliance was made part of the Consent Agreement with the previous owner.

Leachate/ground-water analysis data collected from the eastern site indicated that samples from the landfill wells had biochemical oxygen demand (BOD) concentrations ranging from 300 to 400 mg/L. Therefore, the state required the owner to include biological treatment, in addition to physical/chemical treatment, to meet the effluent limits (see Table 5-1). The state threatened to close the landfill if the effluent limits were not met on schedule.

Table 5-1. Comparison of Temporary System Effluent With Consent Agreement Discharge Limits

Analysis	System Effluent	Limit (Monthly Average)
The following parameters except pH are in mg/L:		
pH	6.45	6-9
BOD_5	<2	10
Suspended solids	<1	10
NH_4-N, summer	—	1
NH_4-N, winter	<1	3
Total phosphorus	2.35	2
Iron	0.10	1.5
Manganese	0.02	1.0
Zinc	0.15	0.3
Copper	0.02	0.07
Lead	<0.1	0.03
Nickel	<0.1	0.013
The following parameters are in µg/L:		
trans-1,2-Dichloroethylene	<1.0	0.05
Trichloroethylene	<1.0	27.0
1,1-Dichloroethylene	<1.0	3.0
Methylene chloride	<1.0	1.9
Carbon tetrachloride	<1.0	4.0
Tetrachloroethylene	<1.0	8.0

Because the state would not grant an extension for the design and construction of the new leachate/ground water treatment system, the owner proposed to install and operate a 200-gal/min (757-L/min) temporary treatment system. A plan was submitted to the state for approval with a fast-track design and construction schedule for the biological treatment system and completion of the physical/chemical treatment system. Operation of the temporary treatment system to maintain compliance with the Consent Agreement during construction was the key to state approval of the plan.

Together with the consulting engineer, the new owner met with state regulators to explain the plan and the temporary system. Treatability studies were performed to convince the regulators that the temporary treatment system would meet effluent limits. The new owner, the consulting engineer, and regulators continued to meet to expedite approval of the biological treatment system design and permitting for construction and operation.

5.1.2 Evaluation of Treatment Alternatives

The owner was presented with three alternatives to maintain the quality of water in the stream flowing past the landfill.

- Close the landfill.
- Haul leachate/ground water to a distant landfill with a leachate treatment system or to a municipal wastewater treatment system.
- Install the 200-gal/min (757-L/min) temporary treatment system and operate it until the 350-gal/min (1,325-L/min) permanent system could be completed.

Obviously, the owner wished to remain in business, so closing the landfill, even temporarily, was not an option. The daily revenue was necessary to pay for improvements and meet the payroll.

Hauling leachate/ground water for treatment elsewhere was impractical due to the large volume and expense of trucking. Treatment elsewhere also presented technical problems due to the metals content of the leachate/ground water.

By installing a temporary treatment system, the new owner could comply with the terms of the Consent Agreement. Treatment and effluent quality would be under the owner's control. The consultant's engineers would hire and train new treatment system operators while operating the temporary system. This experience would be useful when the new 350-gal/min (1,325-L/min) system was finally completed.

The capital and operating costs of the temporary treatment system were minor compared with going out of business or hauling the ground water/leachate for treatment elsewhere. The owner and consultant, after some negotiation, were able to convince the state to approve the temporary treatment plan.

5.1.3 Project Design

The consulting engineer was contracted to design, build, and operate a temporary ground-water/leachate treatment system that would meet the following objectives:

- Design and construction must be complete and the system ready to operate in 1 month.
- The system must operate at the lowest cost possible due to its short life span, scheduled to be 6 months.
- The system must meet discharge limits for BOD, VOCs, and metals as defined in the Consent Agreement (see Table 5-1).
- Operation must be easy and similar to the 350-gal/min (1,325-L/min) system.

The processes required to duplicate the 350-gal/min (1,325-L/min) system included aeration pretreatment to oxidize iron, chemical precipitation and filtration for metals removal, air stripping for VOC removal, and sludge dewatering. Due to lenient air emission standards in that part of the state, no air stripper off-gas treatment was required. Aqueous-phase carbon was added to the temporary system as an effluent polishing step to assure the state that effluent would meet the discharge limits.

Wastewater treatment engineers assigned to the project met the challenging design objectives in the following manner:

- Rolloff boxes were used as tanks for clarification, sludge thickening, and filter backwash water storage. The boxes had reuse value later for trash pickup.
- Sketches replaced formal drawings to detail the design for shop fabrication and field assembly. Valuable time was saved for earlier fabrication of equipment, piping, and site preparation.
- Carbon canisters and an air stripper package unit were rented for the temporary system to reduce capital cost and design time. An option to buy/lease was arranged but was never exercised.
- The consultant's technicians procured and mounted package filters on a skid. PVC piping was quickly installed in the shop and was ready for field deployment in 2 weeks.
- All connections were made with hoses and quick-couplings to eliminate field piping.
- Controls were rudimentary. All pumps and motors were operated with simple on-off manual switches. Some plug-in float switches were used to energize alarms on high or low tank level. A pH meter with on/off control/alarm switches operated the caustic soda pump, the only automatic subsystem.
- A package precoat vacuum filter was rented to dewater the metal hydroxide sludge. Precoating the filter with diatomaceous earth eliminated iron fouling of the filter media.
- The site was prepared by leveling and paving with crushed limestone. Railroad ties supported the equipment. Terraces cut into the hillside where the tanks were installed provided the hydraulic gradient required for gravity flow of water from one process to another, eliminating transfer pumps.
- An inexpensive pole barn was erected over the equipment for cold weather operation after the system proved to operate satisfactorily without any modifications. Kerosene-fueled space heaters provided ample heat during winter operation.
- Special tanks (rapid mix tank and flocculator) were constructed of carbon steel. To reduce costs and save time, only the outside surfaces of the tanks were painted, because the tanks would have little salvage value at the conclusion of the project.

A layout of the temporary system is shown in Figure 5-2. The 200-gal/min (757-L/min) temporary treatment system was operated for 6 months at a cost of approximately $500,000. The flow rate during operation averaged 120 gal/min (454 L/min). At the end of the project, the temporary system was dismantled and the rental package units returned. The consultant claimed the equipment with salvage value, and the rolloff boxes were given to the landfill owner.

5.1.4 Results and Summary

Effluent samples from the temporary ground-water/leachate treatment system were analyzed weekly and compared with the discharge limits set forth in the Consent Agreement. The results of the effluent sampling and analysis program are shown in Table 5-1, along with the state discharge standards for this landfill. The outfall monthly averages met the discharge limits.

The use of a temporary system enabled the landfill owner to complete the construction of a new, permanent 350-gal/min (1,325-L/min) ground-water/leachate treatment system that had already been designed. A new, additional biological (activated sludge) system was designed and constructed during the operation of the temporary system. The full-scale treatment system diagram is shown in Figure 5-3. The temporary treatment system provided training for the new operators while they became familiar with the new treatment system being constructed nearby. Although the owner did not have to address air quality, the water quality in the creek was preserved. (In other states, air stripper off-gas treatment would have been required.)

5.1.5 Source

Blenk, J.P., and R.A. Kormanik. 1987. Full-scale treatment of leachate and ground water at a sanitary landfill: A case study. Presented at the Water Pollution Control Federation Annual Conference (October).

5.2 Case Study 2: Ground-Water Treatment—Biological Fluidized Bed Reactor To Remove Organics

5.2.1 Background

A chemical manufacturer had contaminated ground water under a retention pond used as a cooling water source. It was determined, however, that this system would be unable to meet stringent water quality discharge standards proposed by the state. The company undertook development of a biological treatment system.

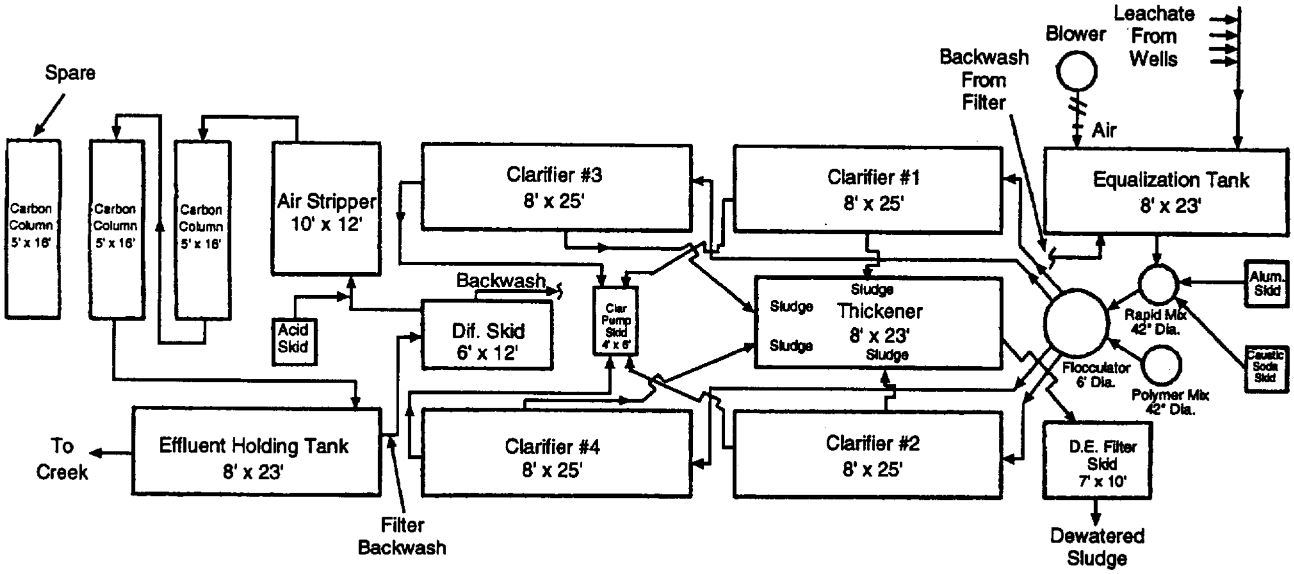

Figure 5-2. Layout of temporary system.

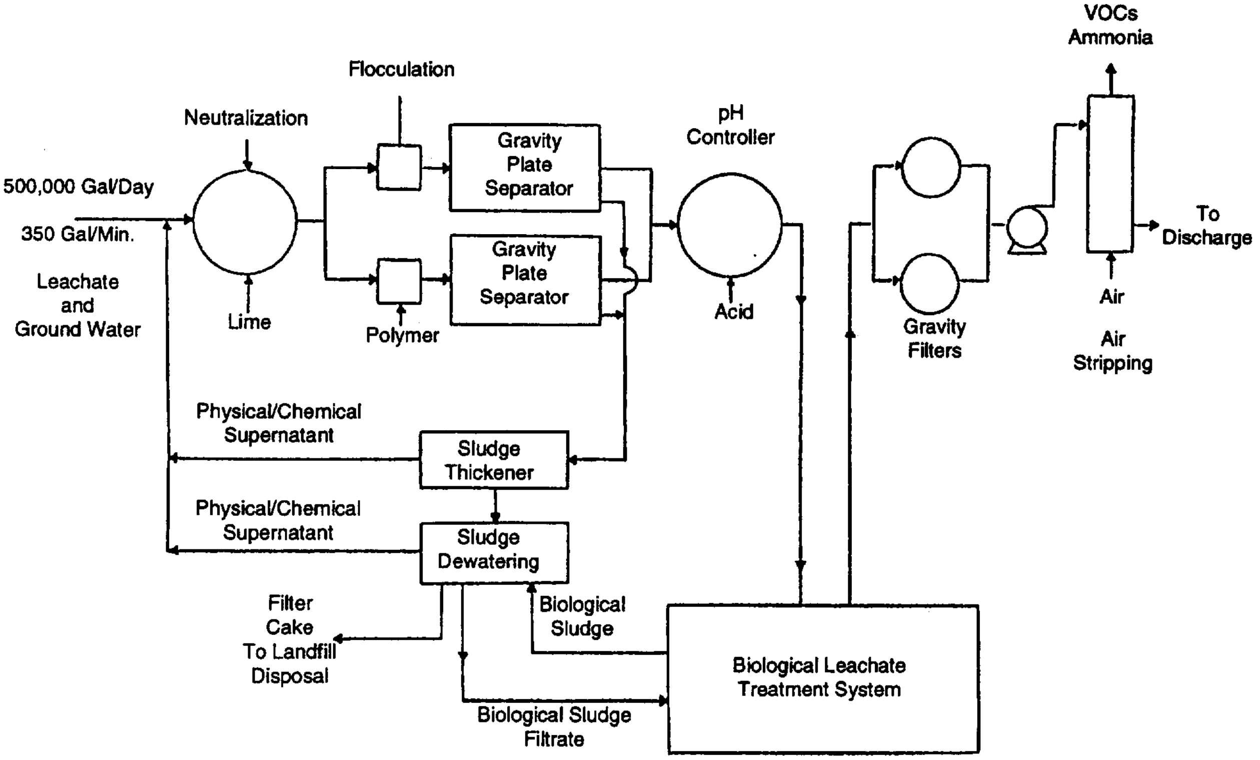

Figure 5-3. The integrated physical/chemical and biological treatment system.

The regulated chemicals of most concern included methanol (CAS number 67-56-1), acetone (67-64-1), methylene chloride (75-09-2), tert-butyl alcohol (75-65-0), chlorobenzene (108-90-7), 1,2-dichloroethane (107-06-2), tetrahydrofuran (109-99-9), and toluene (108-88-3).

A bench-scale treatability study indicated that a biological fluidized bed reactor (FBR) showed promise for treating these compounds. This encouraged the chemical manufacturer to commission a pilot-scale unit, which was used to finalize process design parameters for a full-scale system.

5.2.2 Evaluation of Treatment Alternatives

Three alternative systems were initially evaluated on a bench-scale:

- An FBR with sand as the support medium
- An FBR with GAC as the support medium

- A submerged fixed-media biofilter

The bench-scale studies compared these systems' ability to handle startup, steady-state operation, and shock loads.

During startup, it was found that the sand and carbon fluidized bed reactors performed similarly with regard to maximum hydraulic and organic loading rates, with both over five times better than the biofilter. During steady-state operation, the sand and carbon FBRs performed equally well, with the biofilter found to be inferior due to a significantly lower hydraulic/organic loading rate. During a spike event, reactors operating at steady state were subjected to shock loads of the chemicals listed previously. All reactors responded well to the shock loads of the degradable compounds (e.g., methanol, acetone, and toluene), but the carbon FBR was clearly superior for the less readily degradable compounds (e.g., tert-butyl alcohol, tetrahydrofuran, and 1,2-dichloroethane). Stripping was clearly the lowest in the carbon FBR compared with those that had no adsorptive capabilities. The conclusion was to proceed with pilot-scale testing of a carbon fluidized bed reactor.

5.2.3 Project Design and Pilot-Scale Test

The carbon FBR pilot system used in this test is shown in Figure 5-4. The system included:

- Means for separately delivering a steady feed, influent water, and nutrients.
- Recirculation through the reactor to maintain fluidizing flux.
- Oxygen dissolution to the feed.
- An agitator to aid sloughing of excess microorganisms from the activated carbon.

The FBR unit was designed and constructed as a prototype of a full-scale reactor. The reactor was 20 in. (50.8 cm) in diameter and 14 ft (4.3 m) tall, providing 32 ft^3 (0.9 m^3) empty bed volume. The recirculation flow was set to maintain fluidization and was provided by a centrifugal pump. Oxygen was supplied in a somewhat purified state by passing a compressed air stream through a molecular sieve. Injecting the gas followed by trapping and reinjecting the bubbles enabled the influent to be oxygenated to levels four to five times greater than normal atmospheric saturation levels.

The test used three feed solutions. Two of these combined a base organic feed with a nutrient solution, both of which were needed to maintain a microbial population capable of handling shock loads. The base organic mixture included methanol, acetone, and methylene chloride, standard components of the wastewater. The third solution was another organic feed that was used to simulate shock loads. This feed contained projected peak levels of tert-butanol, 1,2-dichloroethane, tetrahy-

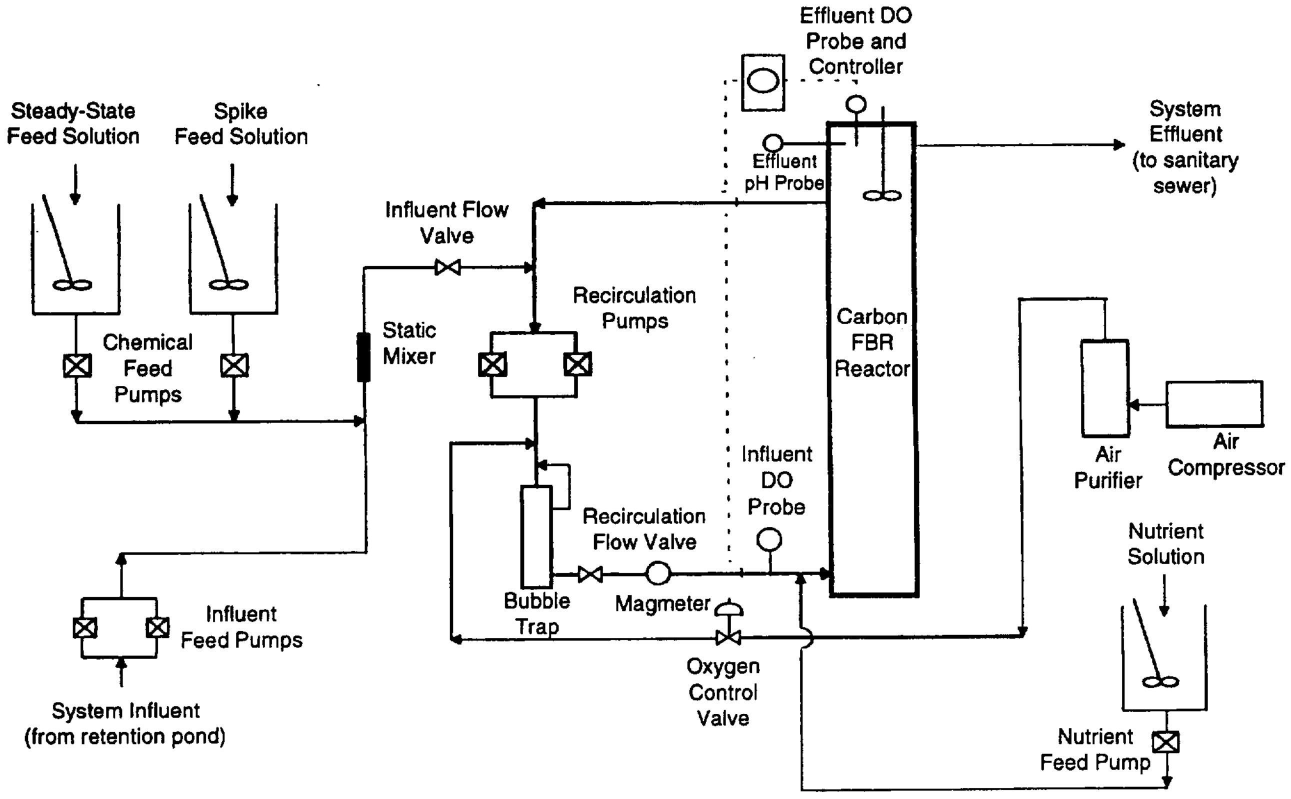

Figure 5-4. Carbon FBR pilot system.

drofuran, toluene, methanol, acetone, and methylene chloride.

The test included three phases: startup, verification of operating point, and a general performance assessment.

The startup phase involved the cultivation of appropriate bacteria in a seed tank. The initial population was obtained from sediment in the retention pond, supplemented with activated sludge from a municipal wastewater treatment plant. The culture was fed a mix of all targeted compounds and nutrients and was aerated. After seed was added to the system, infinite recirculation was implemented for several hours to provide time for microbial attachment to the activated carbon granules.

After the reactor was seeded, continuous operation was initiated. The initial goals were development of a viable biomass in the system and verification of the steady-state operating conditions determined in the bench-scale studies. The steady-state conditions included an organic loading rate (OLR) of 120 lb COD/1000 ft^3-day (1,922 kg COD/1,000 m^3-day), an influent COD of 25 mg/L, and an empty bed contact time (EBCT) of 18.7 min, with a reactor volume of 32 ft^3 (0.9 m^3) and an influent flow rate of 12.8 gal/min (48.4 L/min). The influent COD and flow rate represented a blend of the feed solution and retention pond water. After steady-state conditions were established, the reactor was periodically given a shock load to simulate the effects of rainfall events and subsequent release of additional compounds to the system.

The purpose of the performance assessment was to optimize the design for full-scale operation. This was carried out by incrementally increasing the steady-state load, followed by a shock load. The OLR was scheduled to be increased stepwise from 120 lb COD/1,000 ft^3-day (1,922 kg COD/1,000 m^3-day) to 150, 180, and 210 lb COD/1,000 ft^3-day (2,403, 2,883, and 3,364 kg COD/1,000 m^3-day) based on a recommendation from Envirex. The EBCT and flow rate were then modified to maintain an influent COD concentration of 25 mg/L. Gases were also collected and analyzed during this phase to determine whether air emissions could be a problem for a full-scale unit.

5.2.4 Results

Specific results are summarized in Table 5-2. The startup of the pilot-scale unit took approximately 6 weeks to complete. The steady-state operating parameters were verified successfully. Under the conditions outlined earlier, average influent and effluent COD values of 28 and 2.3 mg/L, respectively, were obtained, producing an overall COD removal efficiency of 92 percent. The bed height increased during the steady-state operation and stabilized near 11 ft (3.3 m), representing a bed expansion of 30 percent. This indicated that the populations in the reactor were healthy and viable. The oxygen utilization rate confirmed this observation.

Table 5-2. Results of Pilot-Scale Tests

	Influent	Effluent	% Removal
Steady-State Parameter:			
COD (mg/L)	28	2.3	92
Methanol (mg/L)	11.6	<0.5	>96
Methylene chloride (µg/L)	33	12	64
Shock Loading Parameter:			
Methanol (mg/L)	28	<1	>99
Acetone (µg/L)	350	20	96
Methylene chloride (µg/L)	160	15	91
t-Butyl alcohol (µg/L)	200	36	82
1,2-Dichloroethane (µg/L)	30	3	90
Tetrahydrofuran (µg/L)	120	25	92
Toluene (µg/L)	27	1	96

The shock load performance of the system was excellent. On a mass basis, methanol and toluene were removed to the greatest extent (greater than 95 percent), followed by acetone, 1,2-dichloroethane, tetrahydrofuran, and methylene chloride (90 to 95 percent). Tert-butyl alcohol was removed to the least extent (80 percent).

Difficulties were encountered at the outset of the next performance assessment. When the OLR was increased to 150 lb COD/1000 ft^3-day (2,403 kg COD/1,000 m^3-day), the bed depth rose to the system design maximum of 11.5 ft (3.5 m). This indicated that the bed was fully loaded; thus, while treatment could continue, additional food would only produce wasted cells. The ability of the system to handle shock loads was also generally better at the 120 lb COD/1,000 ft^3-day rather than 150 lb COD/1,000 ft^3-day (1,922 rather than 2,403 kg COD/1,000 m^3-day), especially with regard to less degradable compounds such as tert-butyl alcohol. The OLR of 120 lb COD/1,000 ft^3-day (1,922 kg COD/1,000 m^3-day) was finally deemed to be optimal because it produced a good balance between biomass growth and sloughing.

The off-gas analysis also produced good results. All seven target compounds were below detection levels in the gas phase during a shock load test.

5.2.5 Summary

Activated carbon treatment is well suited for removing low concentrations of organic compounds from water. In combination with biological destruction, the process has the potential to be extremely useful in situations such as this. The key element in the procedure was the initial treatability study. That study established that microorganisms likely to thrive in the system were able to degrade wastes such as tetrahydrofuran that were not previously described in the literature as biodegradable. Had the treatability results indicated potential difficulties with such treatment, one or more pretreatment processes would have been required, or use of microorganisms would have been abandoned. Because the initial treatability study was successful, moving on to pilot-scale studies followed standard chemical and environmental engineering design procedures.

5.2.6 Source

Kang, S.J., C.J. Englert, T.J. Astfalk, and M.A. Young. 1990. Treatment of leachate from a hazardous waste landfill. In: Proceedings of the 44th Purdue Industrial Waste Conference. Chelsea, MI: Lewis Publishers.

5.3 Case Study 3: Landfill Leachate Treatment—Chemical Pretreatment and Biological Treatment To Remove Metals and Organics

5.3.1 Background

A hazardous waste landfill had historically received both domestic refuse and industrial wastes. Pretreatment of the landfill leachate before discharge to the local publicly owned treatment works was required to meet the local sewer use ordinance. The pretreatment could use a combination of biological and physical-chemical processes. Analysis of the leachate indicated significant concentrations of pollutants as measured by COD, BOD, total Kjeldahl nitrogen (TKN), ammonia nitrogen, phenol, cyanide, methylene chloride, arsenic, and nickel.

5.3.2 Evaluation of Treatment Alternatives

Bench-scale treatability tests were performed on the leachate to identify processes suitable for reducing its strength and toxicity. The processes evaluated included activated carbon adsorption, ammonia stripping, metals removal, and aerobic and anaerobic biological treatment. All tests proved to be successful except for anaerobic treatment.

Based on what had to be removed from the waste, it was determined that a chemical pretreatment step was required before biological treatment. The purpose of chemical pretreatment was to reduce metals and other toxicants that could potentially interfere with biological activity and to prevent discharge exceeding the sewer use ordinance limits. Chemical treatment consisted of metals precipitation with subsequent settling of the metal sludge and addition of growth nutrients. Two biological systems were selected for pilot testing: conventional activated sludge and activated sludge containing powdered activated carbon. The last pretreatment step was activated carbon adsorption to polish the remaining low concentration of organics. The effluent from the carbon system was of sufficient quality to be discharged directly to the sanitary sewer.

5.3.3 Project Design

Leachate from several cells was collected into separate tanks. This provided equalization before feeding to the treatment system. The equalized feed was processed through the metals removal system, then transferred to the biological system.

The chemical treatment step consisted of three mix tanks, where pH was adjusted, metal precipitate particles were coagulated and flocculated, and nutrients were added to encourage microbial growth. This chemical treatment step resulted in nickel removal of 15 to 75 percent, depending on the chemicals selected. Use of ferrous and ferric hydroxides as sweep coagulants gave the best removal but generated large quantities of slow-settling sludge. Use of oxidants such as hydrogen peroxide or potassium permanganate also gave high removals but made the leachate foam. Simple pH adjustment with sodium hydroxide generated small quantities of nonfoaming sludge and was the preferred method operationally, despite the fact that it removed only about 40 percent of the nickel.

The biological reactor pilot tests examined two treatment methods: conventional activated sludge and the powdered activated carbon process. The systems were set up as two-stage operations, with the second stage designed to test reactor performance when much of the possible high-strength loading was removed. (Staging has other operational advantages for both leachate and ground-water treatment, as outlined below). The removal performances of these two systems are compared in Table 5-3. Overall, the pilot results indicated that both BOD and COD removals in excess of 90 percent were possible with either of these techniques. This indicated that the leachate test samples had little toxicity for activated sludge bacteria and that little non-degradable adsorbable material was present in the feed.

The full-scale system used the conventional activated sludge process with necessary features to add powdered activated carbon. The treatment plant was designed for 30,000 gal/day (113,562 L/day) and is shown in Figure 5-5. The system featured flexibility in adding powdered activated carbon when needed; the effluent was also routed through carbon columns when polishing was required for compliance.

5.3.4 Results and Summary

Operating data for the system, which was installed in 1990, demonstrate its effectiveness. These data are

Table 5-3. Comparison of Conventional Activated Sludge and Powdered Activated Carbon Reactor Performance

Parameter	Influent	Conventional A.S. Effluent			Powdered Activated Carbon Process Effluent		
		Stage 1	Stage 2	%[a]	Stage 1	Stage 2	%[a]
HRT (days)	—	20	10	—	20	10	—
SRT (days)	—	20	20	—	20	20	—
Carbon dose (mg/L)	—	—	—	—	7,500	0	—
OLR (lb COD/10^3 ft^3-d)	—	75	32	—	75	21	—
COD (mg/L)	24,000	2,750	2,120	91	1,750	1,670	93
BOD_5 (mg/L)	12,700	576	478	96	703	432	97
MLSS (mg/L)	—	5,810	5,000	—	13,800	10,400	—
MLVSS (mg/L)	—	3,100	2,550	—	8,470	6,840	—
TKN (mg/L)	880	663	623	29	637	517	41
Ammonia-N (mg/L)	345	257	131	62	213	181	48
Ortho-phosphate (mg/L)	43	2	4	91	4	11	74
Nickel (mg/L)	16	7.95	7.6	53	8.7	8.4	48
Phenol (mg/L)	290	0.85	0.29	>99	0.36	0.06	>99
Cyanide (mg/L)	10.7	6.1	5.1	52	4.1	2.1	80

[a] Overall removal efficiency
HRT = hydraulic retention time
MLSS = mixed liquor suspended solids
MLVSS = mixed liquor volatile suspended solids
SRT = solids retention time

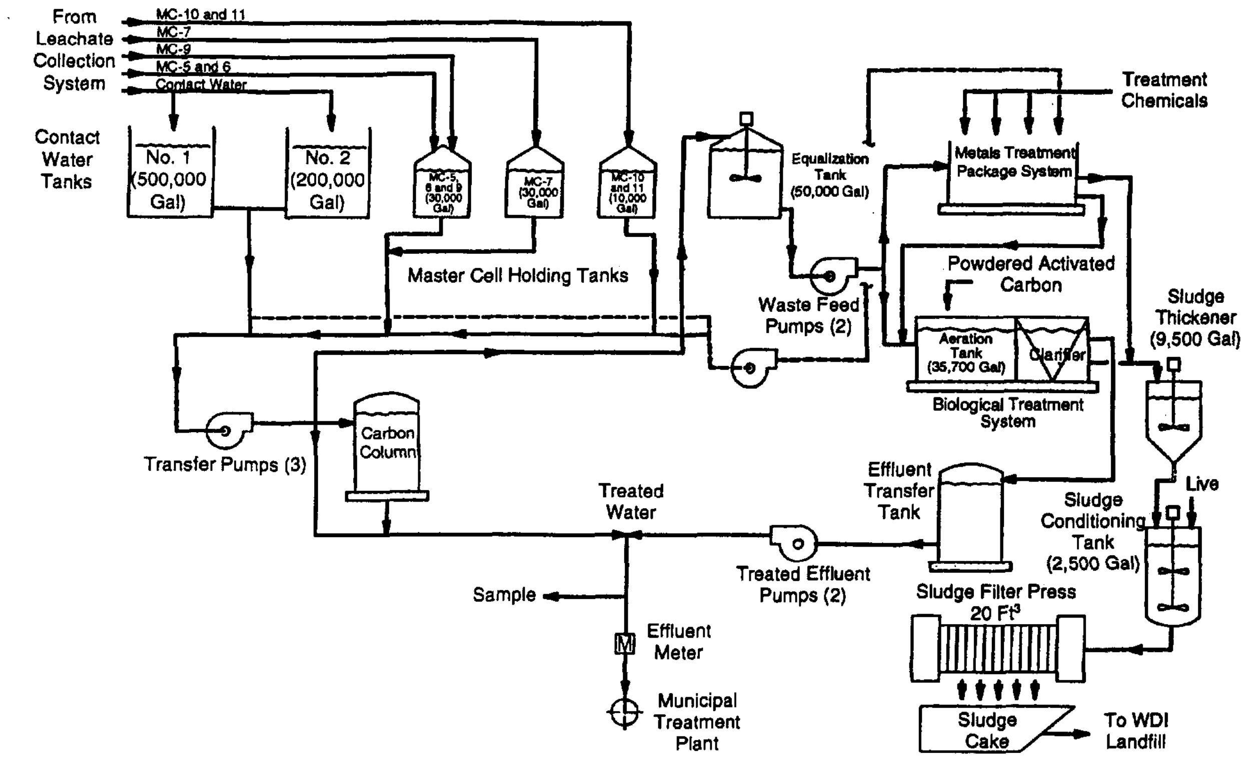

Figure 5-5. Full-scale system using the conventional activated sludge process.

summarized in Table 5-4. The COD and BOD removals were generally excellent in the full-scale system.

Table 5-4. Full-Scale Operating Data

Parameter	Influent	Effluent	% Removal
COD (mg/L)	3,571	420	88
BOD (mg/L)	715	32	96
Ammonia-N (mg/L)	261	44	83
Ortho-P (mg/L)	2.99	1.64	45

The leachate in this case study was typical of many leachates emanating from hazardous waste facilities: very high strength with a mixture of metals and organic compounds. Initial treatability studies were critical in determining what processes would work in this case. Other systems may not need the same combination of processes. For example, a nonhazardous waste leachate may not need metals removal. Another point that the treatability studies showed was that anaerobic treatment was unworkable. Because some conventional wisdom would suggest that anaerobic treatment should be used for high-strength wastes, proceeding to pilot scale with an anaerobic system in this case would have produced unacceptable results. Once the necessary processes had been identified, standard environmental and chemical engineering design techniques were used to produce the pilot-scale tests and the full-scale design.

5.3.5 Source

Kuljian, A.H., Jr., P.A. Van Meter, C.D. Fifield, J. O. Thaler, and T.-P. Chen. 1994. Remedial biodegradation of low organic strength cooling water using carbon fluidized bed reactor. In: Proceedings of the 49th Annual Purdue Industrial Waste Conference (May).

5.4 Case Study 4: Ground-Water Treatment—High-Temperature Air Stripping To Remove VOCs

5.4.1 Background

The ground water beneath McClellan Air Force Base in Sacramento, California, was contaminated with fuel and solvents from spills and storage tank leaks. Volatile and semivolatile organics, such as acetone and methyl ethyl ketone, had been reported at ppm levels. A treatment system consisting of air stripping and liquid-phase carbon adsorption was installed to eliminate these compounds from the ground water. (Blaney and Branscome, 1988). This system is described briefly below.

5.4.2 Project Design

The air stripping system employed at McClellan Air Force Base is a high-temperature process. The facility was built in 1986 for a cost of approximately $3.1 million. The process is diagrammed in Figure 5-6. The contaminated ground water is pumped to a storage tank which provides flow and waste strength equalization. Water from the storage tank is then fed to a series of heat exchangers. Heating increases the air stripping efficiency for the VOCs. In this case, the ground water is pumped through a water-to-water plate and frame, single-pass heat exchanger, which raises the temperature from about 65°F (18.3°C) to approximately 95°F (35°C). The water temperature is elevated an additional 7 to 10°F (3.8°C to 5.5°C) in a single-pass fin-tube air-to-water heat exchanger. The ground water is then pumped to the stripping tower.

The water flow rate to the air stripper is approximately 270 gal/min (1,021 L/min) with an air-to-water ratio of 30:1. The packing materials consist of 2-in. (5-cm) plastic balls. The height of the packing media is 25 ft (7.6 m). The tower effluent contains trace concentrations of the VOC pollutants. For example, concentrations of 1,2-dichloroethane, cis-1,2-dichloroethene, 1,1,1-trichloroethane, and trichloroethene are nearly equal to the practical quantitation limits (PQLs) of 0.5 µg/L. The liquid effluent enters a wet well, where it is subsequently pumped to two GAC units in series. The purpose of the GAC is to remove the trace quantities of other organic pollutants that are not amenable to air stripping. The effluent from the GAC is finally discharged to a nearby creek.

The stripper off-gas is preheated in two air-to-air heat exchangers in series, where its temperature is brought to approximately 1,200°F (649°C) before being incinerated. The temperature inside the incinerator is maintained at 1,815°F (990.5°C). The incinerator gases are recycled to preheat both the stripper off-gas and the ground-water stream fed to the stripper. Once the heating value of the waste gases is recovered, the gas is fed to a caustic scrubber to neutralize hydrochloric acid before being discharged into the atmosphere.

5.4.3 Results and Summary

One of the major operating problems encountered was the potential for calcium and magnesium carbonate precipitation to foul the packing material. The original 1-in. (2.5-cm) packing material was replaced with 2-in. (5-cm) balls to decrease the likelihood of fouling. Corrosion within the incinerator is also a problem because of the extreme off-gas temperature combined with the presence of hydrochloric acid. Mechanical failures resulting from corrosion are common. As parts wear out, they are replaced with new components constructed using special metals and alloys.

The facility is continually undergoing design modifications. An early corrective action was to equalize plant flows in an attempt to eliminate downtime when the

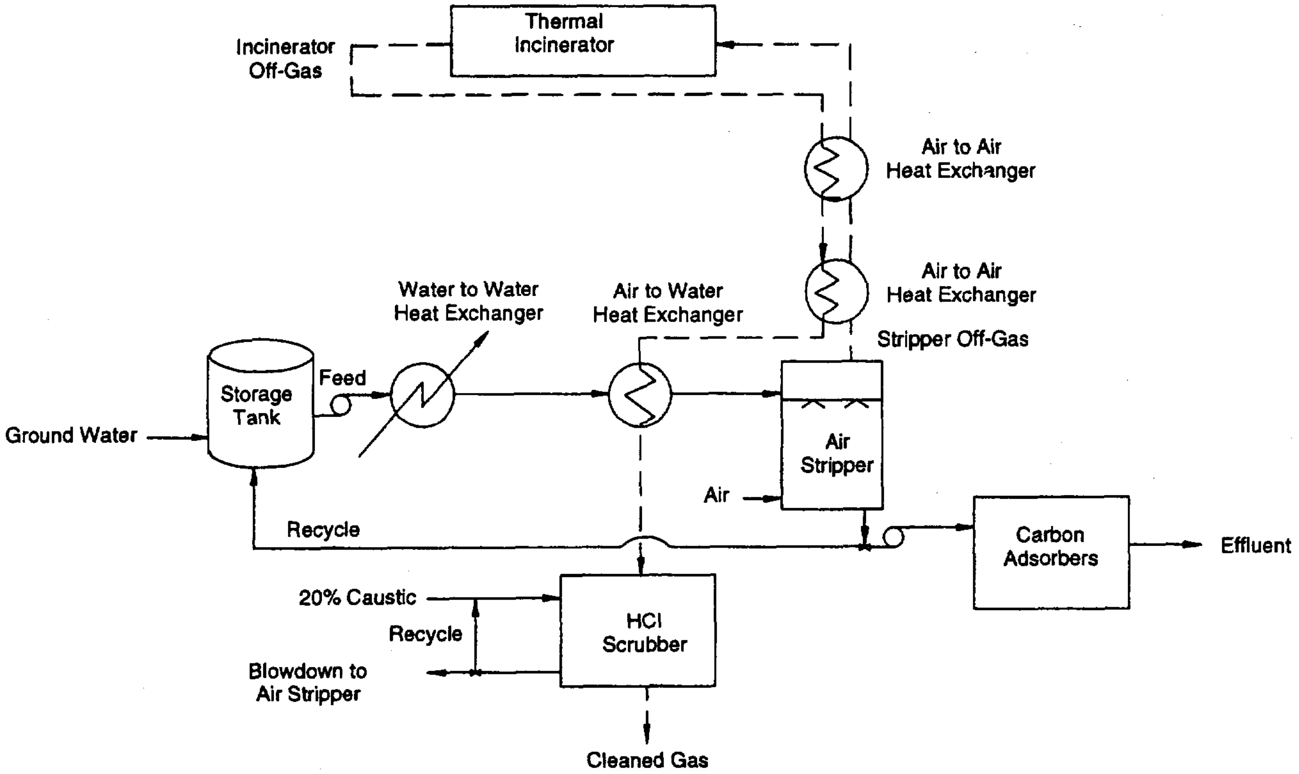

Figure 5-6. Ground-water treatment system, McClellan Air Force Base.

influent flow control valve and the stripper level control valve failed. Each valve works independently, but each one senses changes in plant flow and makes the changes necessary to maintain its preset operating level either by opening or closing the valve.

Over time, the facility staff have fine-tuned the controllers operating the level control valves until the range and span were set in tune with the flow of the plant.

As far as polishing the stripper effluent is concerned, the efficiency and economics of the GAC may need to be re-evaluated against an alternative process, such as chemical oxidation.

Appendix A

Compendium of Ground-Water and Leachate Treatment Technologies

This appendix presents information about the most common technologies for treating contaminated groundwater and landfill leachates. Figure A-1 lists the technologies that are described. Each treatment technology summary addresses the following topics:

- A brief technology description
- A process flow diagram
- Pretreatment/chemical requirements
- Parameters of interest
- Key design considerations and criteria
- Residuals generation
- Major cost elements

The technology descriptions that follow discuss percentage removal for gross waste parameters such as COD, BOD, and nitrogen, as well as organics not included in the list of 20 compounds frequently found at hazardous waste sites. For specific contaminant removal data for these 20 compounds, the reader should consult Tables 4-3 through 4-22. The ranges listed for the design criteria are keyed to the specific references cited and not to the process.

Note that because cost data are difficult to obtain, cost units or cost figures may vary from summary to summary. The cost data are not presented in any uniform fashion, such as cost per unit mass of contaminant removed. The cost data are presented as they are reported in the literature or as available from vendors. In most instances, no adjustments using an index value have been made from the years reported in the references. Therefore, direct comparisons using these cost data are discouraged. The reader is encouraged to consult the original references. Abbreviations used throughout the Appendix are defined on page ix.

Conversion from nonmetric to metric units can be accomplished using the following conversion factors:

To convert from:	To:	Multiply by:
gal	L	3.785412
gal/ft^2	L/m^2	42.1
gal/ft^3	L/m^3	139.8
gal/min	m^3/hr	0.227
gal/min	L/sec	0.06309
ft	m	0.3048
ft^2	m^2	0.0929
ft^3	m^3	0.0283
lb	kg	0.4536
lb/ft^2	kg/m^2	4.8824
lb/ft^3	kg/m^3	16.0184
in.	cm	2.54
ac	km^2	4.0468×10^{-3}

Biological
- Activated sludge system
- Sequencing batch reactor
- Powdered activated carbon
- Rotating biological contactor
- Aerobic fluidized bed biological reactor

Physical/Chemical
- Air stripping
- Activated carbon
- Ion exchange
- Reverse osmosis
- Chemical precipitation of metals
- Chemical oxidation
- Chemically assisted clarification (polymer only)
- Filtration

Radiation
- Ultraviolet radiation

Figure A-1. Compendium of ground-water and leachate treatment technologies.

Biological

A.1 Activated Sludge System

A.1.1 *Technology Description*

The activated sludge process is a suspended-growth, biological treatment system that uses aerobic microorganisms to biodegrade organic contaminants. Influent is introduced into an aeration tank, where a mixed culture of bacteria is maintained in suspension. In the presence of oxygen, nutrients, organic compounds, and acclimated biomass, a series of biochemical reactions is carried out in the reactor that degrades the organics and generates new biomass. Diffused or mechanical aeration is used to maintain aerobic conditions and good mixing in the reactor. After a specified period, the mixture of new cells and old cells is passed into a settling tank, where the cells are separated from the treated water. A portion of the settled cells is recycled to maintain the desired concentration of organisms in the reactor, and the remainder is wasted and sent to sludge handling facilities.

Variations in the conventional activated sludge process have been developed to provide greater tolerance for shock loadings, to improve sludge settling characteristics, to achieve higher BOD_5 removals, and to achieve integrated biological nutrients removal.

A.1.2 *Common Modifications*

Complete mixing, plug flow, step aeration, modified aeration, extended aeration, contact stabilization, pure oxygen aeration, and anoxic/aerobic sequential reactors.

A.1.3 *Technology Status*

The activated sludge process was developed in England in 1914 and was so named because it involved the production of an activated mass of microorganisms capable of stabilizing a waste aerobically. Activated sludge has been widely used for municipal and industrial wastewater treatment but not for ground-water treatment.

A.1.4 *Applications*

Most suitable for soluble organics, adequate for nutrient removal. Easily degrades alkanes, alkenes, and most aromatics. Widely tested for leachate treatment.

A.1.5 *Process Limitations*

Limited BOD loading capacity. Equalization may be required for extreme fluctuating flow and loading conditions. VOCs may be driven off to a certain extent during aeration. Relatively high sludge production. May not be suitable for low-strength ground-water treatment. Some contaminants are known to be nonbiodegradable aerobically, such as TCE, PCE, carbon tetrachloride, and chloroform.

A.1.6 *Typical Equipment*

General: aeration tank, air diffuser or mechanical aerator, mixer, air blowers, submersible or screw sludge pumps, aeration basin, clarifier, sludge dewatering equipment.

A.1.7 *Flow Diagram*

Figure A-2.

A.1.8 *Chemical Requirements*

Nutrients (N or P) if they are not sufficient in the leachate; polymer if required for sludge settling.

A.1.9 *Design Criteria*

Parameter	Range	Reference
MLSS (mg/L)	3,000-6,000	1
MLVSS (mg/L)	2,500-4,000	1
F/M (lb BOD/lb MLVSS/day)	0.01-1.0	2
Maximum volumetric COD loading (lb COD/1,000 ft^3/day)	10-30	2
SRT (days)	2-40	1, 2
RT (days)	0.1-20	1-4

A.1.10 *Performance*

Compound	Influent (mg/L)	Removal %	Reference
COD	23,900	89-91	1
	1,296	93+	2
BOD_5	12,700	95-96	1
NH_4-N	564	98+	2
	387	99	3
	345	25-97	1
TKN	880	25-29	1

A.1.11 *Residuals Generated*

Aerobic process: 01-0.6 lb sludge/lb COD removed, at about 1.0% solids concentration.

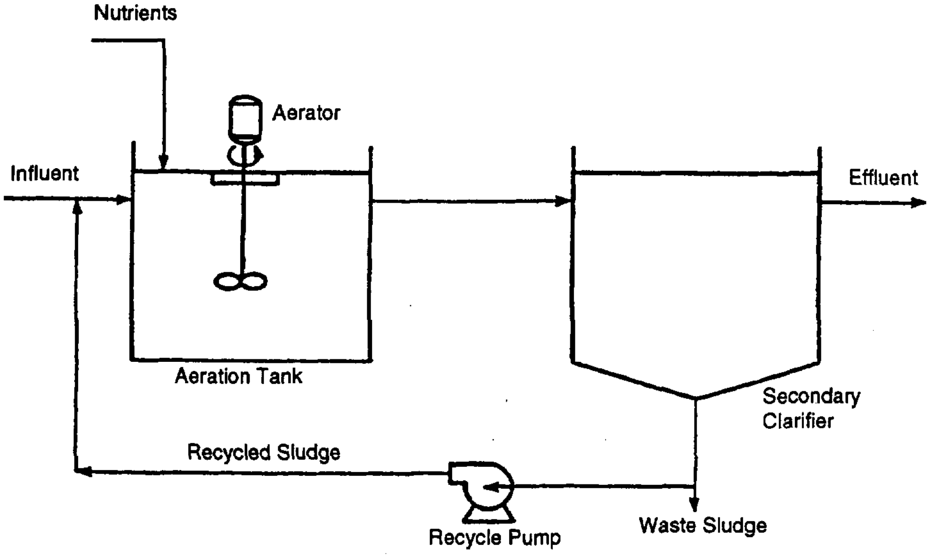

Figure A-2. Activated sludge system.

A.1.12 Process and Mechanical Reliability

Expected to have high process and mechanical reliability. Single or dual reactor design provides on-line reliability and flexibility.

A.1.13 Environmental Impact

Reactor can be enclosed to minimize gas release, and an off-gas treatment can be installed where needed.

A.1.14 Major Cost Elements

Capital costs for the activated sludge process for leachate treatment are estimated to be $2.5 to $5.1 million per million gal/day treatment capacity; O&M costs are estimated to be $0.33 to $0.5 million per million gal/day capacity (5). The aeration basin design assumes a detention time of 6 hours based on an aerator power input of 0.1 hp per 1,000 gal. The clarifier design is based on an operation of 600 gal/day/ft^2.

Breakdown of Capital Costs	
Aeration basin	28%
Clarifier	29%
Aerators	1%
Pumps and piping	12%
Residuals management	30%

Breakdown of O&M Costs	
Power	9%
Labor	12%
Chemicals	19%
Residuals management	60%

A packaged activated sludge reactor with 0.02 million gal/day design capacity had a capital cost of $150,000, which includes equalization tank, feed tank, system control, pumps and pipings, and installation. This application was for high-strength ground-water treatment, with 1,296 mg/L and 546 mg/L average influent COD and BOD_5, respectively (2).

A.1.15 References

1. Kang J.S., J.C. Englert, J.T. Astfalk, and A.M. Young. 1990. Treatment of leachate from a hazardous waste landfill. 44th Purdue Ind. Waste Conf. Proc. 44:573-579.
2. Molchan, A.G., and S.J. Kang. 1992. Onsite portable bioremediation unit. Presented at the Air and Waste Management Association 85th Annual Meeting and Exhibition, Kansas City, MO.
3. Brouns, M.T., S.S. Koegler, K.J. Fredrickson, P.S. Luttrell, and A.K. Borgeson. 1991. Biological treatment of Hanford ground water: Development of an ex situ treatment process. In: Hinchee and Olfenbuttel, eds. Onsite bioremediation. Butterworth-Heinemann.
4. Mueller, G.J., E.S. Lantz, D. Ross, J.R. Colvin, P.D. Middaugh, and H.P. Pritchard. 1993. Strategy using bioreactor and specially selected microorganisms for bioremediation of ground water contaminated with creosote and pentachlorophenol. Environ. Sci. Technol. 27:691-698.
5. McArdle, J.L., M.M. Arozarena, and E.W. Gallagher. 1987. Handbook on treatment of hazardous waste leachate. EPA/600/8-87/006.

A.1.16 Additional Source

1. Flathman, E.P., E.D. Jerger, and M.P. Woodhull. 1992. Remediation of dichloromethane (DCM) contaminated ground water. Environ. Prog. 11(3):202-209.

A.2 Sequencing Batch Reactor

A.2.1 Technology Description

The sequencing batch reactor (SBR) is a periodically operated, suspended growth, activated sludge process. The only conceptual difference between the SBR and the conventional continuous-flow activated sludge system is that each SBR tank carries out functions such as equalization, biological treatment, and sedimentation in a time rather than in a space sequence. Because of the flexibility associated with working in time rather than in space, the SBR can be operated as either a labor-intensive, low-energy, high-sludge-yield system or a minimal-labor, high-energy, low-sludge-yield system for essentially the same physical plant. The actual operating policy can be adjusted in accordance with prevailing economic conditions by simply modifying the settings of the control mechanism. Labor, energy, and sludge yield can also be traded off with initial capital costs. The cycle for each tank in a typical SBR is divided into five discrete periods: FILL, REACT, SETTLE, DRAW, and IDLE, as shown in Figure A-3. Each tank in the SBR system is filled during a distinct period. During this FILL period, organism selection can be controlled by manipulating the actual specific growth rates of the microbes and by regulating the oxygen tension in the reactor (e.g., from anaerobic to aerobic). After a tank is filled, treatment continues with the SBR operating as a batch reactor. During this REACT period, further organism selection is achieved by controlling the length of time the organisms are subjected to starvation conditions. After treatment, the microbes are allowed to separate by sedimentation during a period called SETTLE. The treated effluent is subsequently drawn from the reactor during an additional, distinct DRAW period. The time between FILL periods for a given tank is called IDLE. Sludge wasting may take place near the end of REACT or during SETTLE, DRAW, and IDLE. FILL and REACT may have several possible different phases based on aeration and mixing policies. Overall control of the system is accomplished with level sensors an a timing device or microprocessor. A floating mixer and/or motored decanter is used, as well as submerged diffusers.

By using a single tank, SBR not only saves the land requirement (no return activated sludge [RAS] pump station or clarifiers), it also provides exceptional flexibility in the readily changeable time and mode of aeration in each stage. SBR is flexible enough to tolerate loading/flow fluctuations as well as to achieve complete nitrification/denitrification and phosphorus removal.

A.2.2 Common Modifications

Different operating strategies, multiple-stage SBRs.

A.2.3 Technology Status

Aerated fill-and-draw reactor technology was developed in the 1920s. In the 1970s, the latest wave of re-discovering the fill-and-draw treatment technology was initiated at the University of Notre Dame. The first full-scale SBR for the treatment of leachates from a hazardous waste disposal site was initiated in 1980 (1). Since then, it has become a well-established technology for a variety of wastewater and leachate treatment applications. Over 800 full-scale SBRs have been designed and constructed worldwide.

A.2.4 Applications

Widely used for leachate treatment. Most suitable for soluble organics and nutrient removal. Treatment of leachate contaminated with phenols, benzoic acids, chlorobenzoic acids, other aromatics, halogenated aliphatics, aliphatics, or general BOD and COD reduction. This technology has not been widely applied to low-strength ground-water treatment.

A.2.5 Process Limitations

During FILL, the SBR has the same dilution advantage as a continuous-flow activated sludge system. As a result, it is subject to toxic interferences only if it is not designed properly. Equalization may be required under highly variable flow and loading conditions, or for treatment of continuous flow with single reactor installation.

A.2.6 Typical Equipment

SBR tank, microprocessor-based control system, floating mixer, floating/motorized decanter, diffused/jet aeration system, air blowers, submersible sludge pumps. Tank insulation and a supplemental heat source may be required for winter operation.

A.2.7 Flow Diagram

Figure A-3.

A.2.8 Chemical Requirements

Nutrients (N or P) if they are not sufficient in the leachate; polymer may be required for sludge settling.

A.2.9 Design Criteria

Parameter	Range	Reference
Cycles/tank (d^{-1})	1-3	2-4
MLSS (mg/L)	3,500-10,000	2-4
SRT (days)	10-30	3, 4
F/M (lb COD/lb MLVSS/day)	0.05-0.54	3, 4
Volumetric COD loading (lb COD/1,000 ft^3/day)	30-135	2, 3
HRT (days)	1-10	2-4

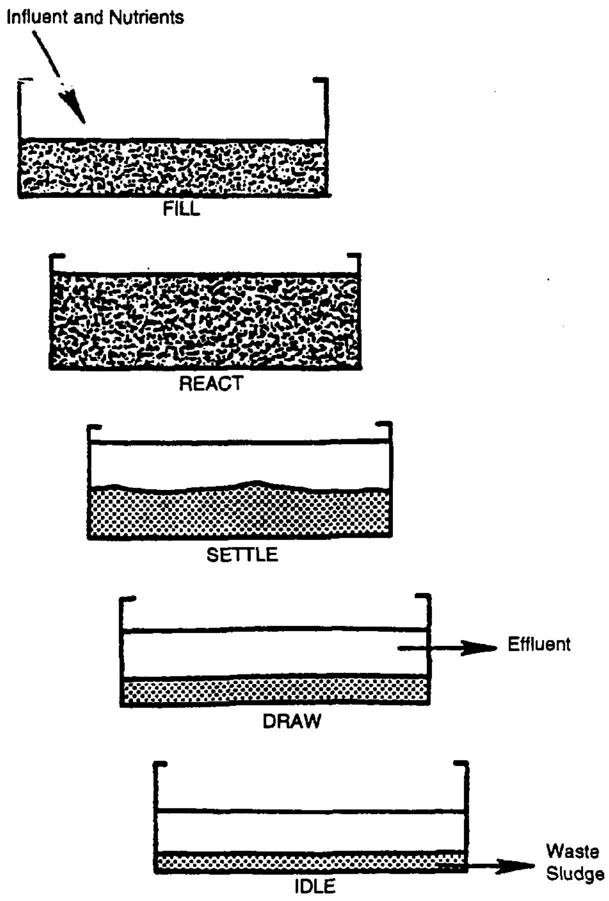

Figure A-3. Sequencing batch reactor.

A.2.10 Performance

Compound	Influent Strength (mg/L)	Removal Percentage (%)	Reference
COD	1,000-5,300	85-92	2-4
SCOD	8,000	94	4
BOD_5	818-6,000	95-99	2-4
$SBOD_5$	5,200	95-99+	4
TOC	2,500	90-95+	4
TOX	325	28-66	2
TSS	155-1,500	70-99+	3
NH_4-N	7-310	74-99+	3, 4
NO_3-N	332	97+	3
TKN	5-250	96-98	3

A.2.11 Residuals Generated

Aerobic process: 0.1-0.6 lb sludge/lb COD removed at about 1.0 percent solids concentration.

A.2.12 Process and Mechanical Reliability

Expected to have high process and mechanical reliability; loading/flow fluctuations are generally tolerable.

A.2.13 Environmental Impact

Reactor can be enclosed to minimize venting gas release. Sludge yield is relatively low.

A.2.14 Energy Notes

For SBR, the aerator and mixer are the major power-consuming items. The sludge pump and water pump may add 10 to 20 percent extra. From 0.014 million gal/day to 0.167 million gal/day SBR, 500-1,000 hp power consumption per million gal/day capacity is typical, but these devices do not run 24 hr/day (3).

A.2.15 Major Cost Elements

For capital costs, see the table on page 84.

Routine O&M includes daily check of equipment status, sampling and analysis for process parameters and the effluent, dewatering where applicable, and periodic maintenance. In all cases, these duties require less than one full-time operator. Chemical costs are additional.

A.2.16 References

1. Herzbrun, P.A., R.L. Irvine, and K.C. Malinowski. 1985. Biological treatment of hazardous waste in the SBR. J. Water Poll. Control Fed. 57:1,163.
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Capital Costs (2)

Design Flow (million gal/day)		Level of treatment (mg/L)					Metals Removal	Sludge De-watering	Building Enclosure	Holding Tank	Total Capital ($Million)	SBR Capital ($Million)	No. of Units
		COD	BOD_5	TSS	TKN	P							
0.014	Inf.	-	850	1,500	332[a]	-	N	N	N	Y	1.0	0.13	1
	Eff.	-	10	10	10[a]	-							
0.0167	Inf.	-	4,500	1,000	300[b]	-	N	Y	N	Y	7.2	-	2
	Eff.	-	200	200	20[b]	-							
0.0288	Inf.	1,000	500	100	5	-	Y	Y	Y	N	1.6	0.16	2
	Eff.	150	20	20	-	-							
0.043	Inf.	-	5,000	200	250	-	Y	Y	N	Y	2.8	-	-
	Eff.	-	60	60	5	-							
0.053	Inf.	4,730	2,350	-	552[b]	-	N	Y	Y	Y	3.1	-	-
	Eff.	764	<30	<200	<5[b]	-							
0.085	Inf.	-	820	155	7[b]	4	N	Y	N	N	1.6	0.36	2
	Eff.	-	<10	<15	<2[b]	<2							

[a] As NO_3-N
[b] As NH_4-N
+ = Plus sludge conditioning and oil/water separation.
[ ] = Required by state to have 30-day influent and effluent storage capacity.

A.3 Powdered Activated Carbon, Biological (Biophysical)

A.3.1 Technology Description

This biophysical system involves the controlled addition of powdered activated carbon to an activated sludge system. The mixture of influent, activated sludge, and powdered carbon is held in the aeration basin for a hydraulic detention time adequate for the desired biological treatment. After aeration, the mixture flows to a clarifier. Settled solids are fed back to the aeration tank to maintain the necessary concentrations of microorganisms and carbon, and the clear supernatant is discharged. Fresh carbon is added to the aeration basin at a rate dependent on influent characteristics and desired effluent quality. Excess solids are wasted directly from the recycle stream. Wasted solids can be processed by simple dewatering and disposal or by wet-air oxidation, or for destruction of organics and regeneration of the activated carbon. For small installations, however, carbon regeneration is typically handled off site. The powdered activated carbon system is also operated in fill-and-draw mode, similar to SBR operation.

The powdered activated carbon system combines physical adsorption with biological treatment, achieving a higher degree of treatment than possible by either mode alone. The presence of carbon in the aeration basin removes some refractory organics that are difficult for microorganism to attack, enhances solids settling, and buffers the system against loading fluctuation and toxic shocks.

By using the fill-and-draw operating mode, the system provides exceptional flexibility because of the readily adjustable time and aeration mode in each stage, which is important for treatment of leachate with variable composition and strength.

A.3.2 Common Modifications

Different operating strategies, continuous or batch systems, multiple-stage powdered activated carbon, aerobic/anaerobic powdered activated carbon. Pretreatment units of metal precipitation, oil/water separation, and postcarbon adsorption.

A.3.3 Technology Status

The practice of adding powdered carbon into the activated sludge process was started during the early 1970s. Applications in leachate treatment started in the 1980s.

A.3.4 Applications

Widely used for leachate treatment and high-strength ground water (particularly with low BOD to COD ratio). Most suitable for soluble organics and nutrient removal. Better color and refractive organics removal than conventional process. Treatment of leachate contaminated with phenols, other aromatics, volatile acids, halogenated aliphatics, aliphatics, color removal, or general BOD and COD reduction.

A.3.5 Process Limitations

Metals removal may require pretreatment. Other applications may require equalization tank, oil/water separator, sludge dewatering, postcarbon adsorption or filter. Certain applications may require off-gas control system. May be unsuitable for low-strength ground water (COD <40 mg/L).

A.3.6 Typical Equipment

Aeration contact tank, hydraulic carbon delivery system, microprocessor-based control center, aeration blower, decanter (for batch reactor) or clarifier (for continuous reactor), air diffuser and internal air piping, submersible or other type sludge pumps.

A.3.7 Flow Diagram

Figure A-4.

A.3.8 Chemical Requirements

Nutrients (N or P) if they are not sufficient in the leachate; chemicals if metal precipitation is required.

A.3.9 Design Criteria

Leachate

Parameter	Range	Reference
Carbon dosage (mg/L)	50-10,000	1-5
MLSS (mg/L)	2,000-11,000	1
SRT (days)	10-20	1-3, 5-6
F/M (lb BOD/lb MLVSS/day)	0.05-0.3	
Maximum COD loading (lb/1,000 ft^3/day)	200	7
Maximum cycle (days)[a]	2-5	2, 7
Minimum cycle time (hr)[a]	4.8	7
HRT (days)	1-16	1, 2, 5-7
Maximum clarifier overflow rate (gal/day/ft^2)[b]	480-520	6

[a] Batch operation mode parameters
[b] Continuous operation mode parameter

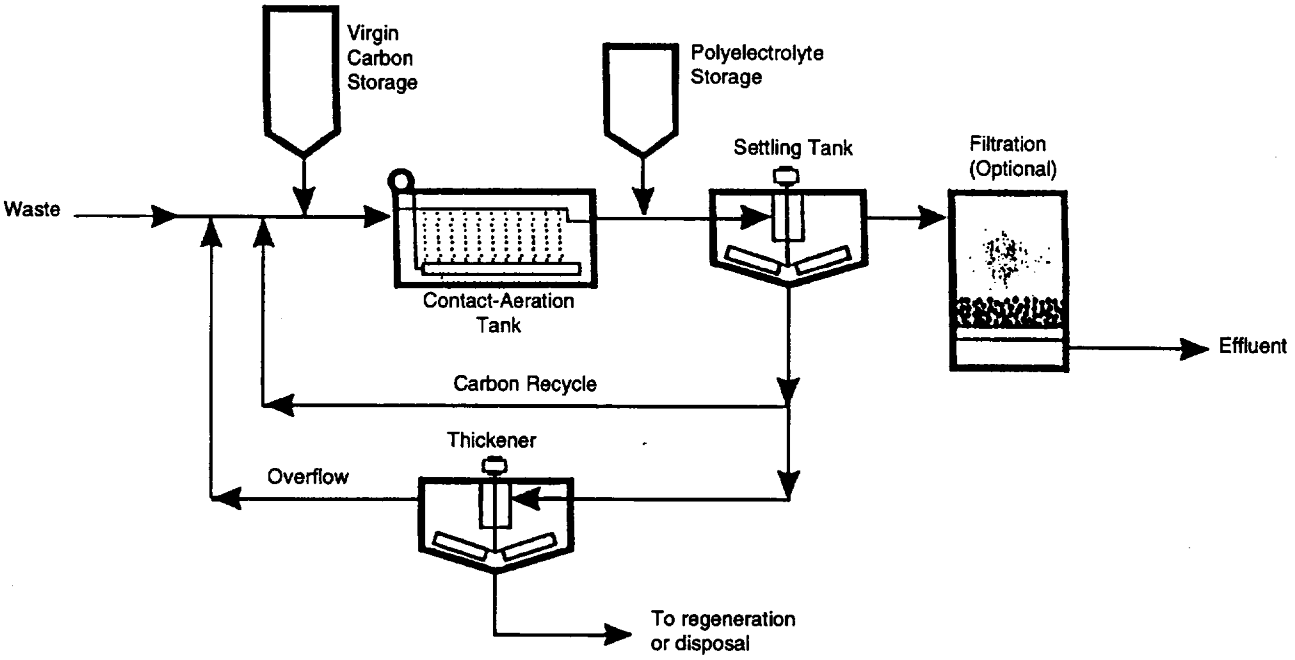

Figure A-4. Powdered activated carbon system general process.

Ground Water

Parameter	Range	Reference
Carbon dosage (mg/L)	10-100	8
MLSS (mg/L)	4,000-20,000	
SRT (days)	10-30	8
F/M (lb BOD/lb MLVSS/day)	0.1-0.7	
Maximum COD volumetric loading (lb COD/1,000 ft^3/day)	200	5, 8
HRT (days)	0.5-2	8
Maximum cycle (days)[a]	5	9
Minimum cycle time (hr)[a]	4.8	9

[a] Batch mode operating parameters

A.3.10 Performance

Leachate

Compound	Influent (mg/L)	Removal (%)	Reference
COD	870-3,237	67-99%+	1-3, 5-7, 9
BOD_5	53-1,600	90-99%+	1, 2, 5-7, 9
NH_4-N	26-315	82-99%+	3, 5, 6, 9
Oil and grease	30	93%	1
Volatile organic acids	20	99%	1
Volatile organic compounds	>3	99%	1

Ground Water

Compound	Influent (mg/L)	Removal (%)	Reference
COD	364-11,500	72-99%	8, 10-14
BOD_5	130-8,260	83-99%	8, 11, 13, 14
Total BTEX	0.75-9.9	93-99%+	11
NH_4-N	200	75-94%	10-12

A.3.11 Residuals Generated

Aerobic process: about 0.24-0.3 lb sludge/lb COD removed (8)

A.3.12 Process and Mechanical Reliability

Expected to have high process and mechanical reliability. Unit has some tolerance to loading and flow fluctuations.

A.3.13 Environmental Impact

The presence of carbon may reduce stripping of VOCs. Aeration tank can be enclosed and off-gas treated, when needed.

A.3.14 Major Cost Elements

See tables on page 87.

Leachate

Design Flow (million/ gal/day)		Level of Treatment (mg/L)					Metals Removal Unit	Sludge Dewatering	System Mode	Capital ($Million)	O&M ($1,000 lb COD)	O&M ($1,000 gal)	Reference
0.035[a]		COD	BOD$_5$	TSS	O&G	Phenolics							
	Inf	843	406	62	150	1.42							
	Eff.	600	300	50	5	0.05	No	Yes	Batch	0.37	28	4.3	15
		COD	BOD$_5$	VOA	O&G	VOC							
0.040[b]	Inf.	1,812	916	20	30	>3							
	Eff.	75	<10	0.02	2	0.02	Yes	Yes	Continuous	-	1.7-2.0	25-30	1, 2
		COD	BOD$_5$	TSS	O&G	NH$_3$-N							
0.033[c]	Inf	1,150	600	300	30	80							
	Eff.	400	<10	<20	<1	<1	No	No	Batch	0.27	0.13	1.2	15

[a] The capital cost included the complete powdered activated carbon system (tankage, blowers, pumps, instruments/controls, MCC, etc.), carbon feed system, sludge storage tank, filter press, O&M manuals, startup and training services, no building. The O&M cost covers the leachate treatment and solids dewatering.

[b] No capital cost information is available. All tanks are covered.

[c] The capital cost included two batch powdered activated carbon systems, two carbon feed systems, O&M manuals, startup and training services. The O&M costs pertain only to the leachate treatment plant.

Ground Water

Design Flow (million/ gal/day)		Level of Treatment (mg/L)					Sludge Dewatering	Solids Disposal	Carbon Regeneration	Capital ($Million)	O&M ($/lb COD)	O&M ($1,000 gal)	Reference
1.8[a]		COD	NH$_3$-N	OCA	DCB		No	Yes	Yes	-[b] (Continuous)	0.04-0.6	2-3	10, 12
	Inf.	6,000	200	53	12								
	Eff.	<100	<10	<0.01	0.002								
0.0245[c]		COD	BOD	NH$_3$-N	P	BTEX	No	No	No	0.15 (Batch)	1.6-2.0	1.7-2.2	11
	Inf.	130	10	1.3	0.4	0.75-11							
	Eff.	<50	<6	<1	0.03	0.007							
0.003[d]		COD	BOD	BTEX	MEK	MIK	Yes	Yes	Yes	0.18 (Batch)	1.0	100	13, 14
	Inf	11,500	8,260	300	410	350							
	Eff.	66	16	<5	<10	<5							

[a] Maintenance and operation of single-stage continuous powdered activated carbon system, 10 gal/min wet-oxidation unit, solid disposal, ground-water pumping, neutralization, and effluent discharge. Value is in 1986 U.S. dollars.

[b] No capital cost information is available.

[c] The capital cost includes a batch powdered activated carbon system, ground-water equalization tank, O&M manual, startup and training services, and 6 months of site operational services. O&M costs cover the entire contaminated ground-water cleanup operation, including analytical.

[d] The capital cost includes covered tank, carbon feed system. O&M costs cited are for ground-water treatment, air emissions control/treatment, sludge dewatering/disposal, and analytical.

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A.4 Rotating Biological Contactor

A.4.1 Technology Description

The rotating biological contactor (RBC) is an aerobic fixed-film biological treatment process. The RBC consists of a series of closely spaced plastic (polystyrene, polyvinyl chloride, or polyethylene) disks on a horizontal shaft. The assemblage is mounted in a contoured-bottom tank to partially immerse (about 40 percent) the disks in the waste stream. The disks, which develop a slime layer over the entire wetted surface, rotate slowly through the wastewater and alternately contact the biomass with the organic matter in the waste stream and then with the atmosphere for absorption of oxygen. Excess biomass on the media is stripped off by rotational shear forces, and the stripped solids are held in suspension with the wastewater by the mixing action of the disks. The sloughed solids are carried with the effluent to a clarifier, where they are settled and separated from the treated waste. Staging, which employs a number of RBCs in series, enhances biological treatment efficiency, improves shock-handling ability, and could aid in achieving nitrification.

RBCs provide a greater degree of flexibility for meeting the changing needs of a leachate treatment plant than do trickling filters. The modular construction of RBCs permits their multiple staging to meet increases or decreases in treatment demands.

Factors affecting the treatment efficiency of RBC systems include the type and concentration of organics present, hydraulic residence time, rotational speed, media surface area exposed and submerged, and pre- and posttreatment activities.

A.4.2 Common Modifications

Multiple staging; use of dense media for latter stages in train; use of molded covers or housing of units; various methods of pretreatment and posttreatment of wastewater; use of air-driven system in lieu of mechanically driven system; addition of air to tanks; addition of chemicals for pH control; and sludge recycle to enhance nitrification.

A.4.3 Technology Status

RBCs were first developed in Europe in the 1950s. Commercial applications in the United States did not occur until the late 1960s, mostly for municipal and industrial wastewater. EPA sponsored several treatability studies for RBC treating leachate in the 1980s. There have been rare applications since then.

A.4.4 Applications

Widely tested for leachate treatment but with few installations. Suitable only for soluble organics, and adequate for nitrification. Effective for treating solvents, halogenated organics, acetone, alcohols, phenols, phthalates, cyanides, ammonia, and petroleum products. No applications for ground-water treatment have been identified.

A.4.5 Process Limitations

Low-rate system, limited loading capacity, and not efficient for degrading refractory compounds or removing metals. Toxic constituents (such as heavy metals, pesticides, etc.) may require pretreatment. Use of dense media in earlier stages can result in media clogging. Off-gas treatment may be required if aeration is provided. May require supplemental aeration and alkalinity addition. Vulnerable to climate changes and low temperature if not housed or covered. Not suitable for treatment of low-strength ground water (less than 40 mg/L BOD_5).

A.4.6 Typical Equipment

Rotating disk system, tank, clarifier, hydraulic delivery system, water pumps, sludge pumps.

A.4.7 Flow Diagram

Figure A-5.

A.4.8 Chemical Requirements

Nutrients (N or P) if they are not sufficient in the leachate or ground water; alkalinity adjustment chemicals.

A.4.9 Design Criteria

Parameter	Range	Reference
MLVSS (mg/L)	3,000-4,000	11
MLVSS (mg/L)	1,500-3,000	1
F/M (lb BOD/lb MLVSS/day)	0.05-0.3	
Maximum BOD volumetric loading (lb BOD/1,000 ft^3/day)	15-60	2
Maximum BOD surface loading (lb BOD/1,000 ft^2/day)	0.05-0.7	1
Number of stages per train	1-4	2
Hydraulic surface loading (gal/day/ft^2)	0.3-1.5	2
HRT (days)	1.5-10	1

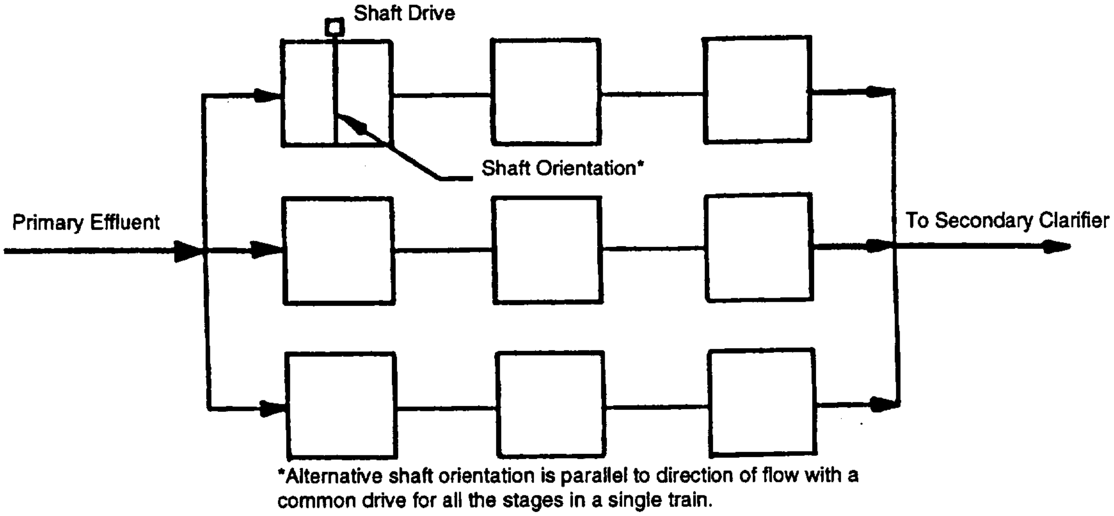

Figure A-5. Typical staged rotating biological contactor configuration.

A.4.10 Performance

Compound	Influent (mg/L)	Removal (%)	Reference
SCOD	800-5,200	55-99	1, 3-5
$SBOD_5$	100-2,700	95-99+	1, 3-5
$TBOD_5$	3,000	99+	3
TOC	2,100	99	3
DOC	300-2,000	63-99	3-5
NH_4-N	100	80-99	1, 2

A.4.11 Residuals Generated

Aerobic process: 0.2-0.5 lb/lb COD removed at about 2.0 percent solids concentration.

A.4.12 Process and Mechanical Reliability

Expected to have high process and mechanical reliability.

A.4.13 Environmental Impact

Reactor can be enclosed to minimize off-gas release.

A.4.14 Major Cost Elements

The construction cost of RBC is estimated to be about $0.6 million per million gal/day capacity (using ENR index of 2,475). Costs include RBC disks, RBC shafts (standard media, 100,000 ft^2/shaft), motor drives (5 hp/shaft), molded fiberglass covers, and reinforced concrete basins; clarifiers are not included, assuming a surface loading rate of 1.0 gal/day/ft^2 and carbonaceous oxidation only. O&M costs are estimated at $0.01 to $0.1 million per million gal/day capacity (using ENR index of 2,475). Specific applications to leachate or groundwater treatment will yield different costs, but no such data are available at present.

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A.4.16 Additional Sources

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A.5 Aerobic Fluidized Bed Biological Reactor

A.5.1 Technology Description

An aerobic fluidized bed biological reactor (FBR) is a fixed-film biological treatment technology. The microorganisms are grown on either granular activated carbon (GAC) or sand media. Dedicated pumps provide desired fluidization and control the reactor internal flux. Influent enters the bottom of the reactor through a distributor, which is designed to provide uniform fluidization of the media and to prevent short-circuiting or plugging. The media bed expands farther as the biofilm grows in thickness and reduces the media density. An internal growth control system intercepts the rising bed at a desired height, removes the bulk of biomass from the particle, and returns the media back to the reactor. The aerobic/GAC FBR is most widely used for ground-water treatment. In a proprietary system design, an oxygen preparation unit enriches the oxygen in the air supply to about 90 percent, and the oxygen-enriched air is then predissolved in the influent.

Using GAC media integrates biological removal and carbon adsorption, which has the advantage of tolerating loading or flow fluctuations, and may speed system startup, compared with other types of media. The fluidization and high oxygen transfer capacity in the aerobic/GAC FBR make the process extremely efficient. The high surface area of the media supports a reactor biomass concentration three to 10 times greater than in conventional suspended growth processes. The vertical installation and high loading capacity reduce the land requirement. The short hydraulic retention time makes this process suitable for low to moderate levels of contaminated ground-water treatment. Typically, GAC offers easier/faster startup than the sand media.

A.5.2 Common Modifications

Anoxic, anaerobic process; combination of aerobic/anoxic; sand/GAC media.

A.5.3 Technology Status

The technology was developed in the 1970s.

A.5.4 Applications

Most suitable for soluble organics. Aerobic/GAC FBR has been widely used for treatment of ground water contaminated with BTEX, other aromatics, halogenated aliphatics, aliphatics, or general BOD and COD reduction. This technology has not been widely applied to leachate treatment.

A.5.5 Process Limitations

Free products may simply pass through or cover the biofilm surface. Iron levels above 20 mg/L may require pretreatment to avoid plugging problems. Calcium and magnesium may cause scaling problems. Not designed for TSS removal; pretreatment is required for influent containing high solids content. GAC FBR is not efficient for low-yield, nonbiodegradable organics because it is often operated as a high loading system and has very short retention time.

A.5.6 Typical Equipment

General: fluidization reactor and internals, reactor hydraulic distribution system, internal growth control system, weir/baffle, and nutrient feed system. Aerobic mode addition: oxygen source or preparation unit, pressurized bubble contactor, and dilution chamber. Anoxic: supplemental carbon source feed system as needed.

A.5.7 Flow Diagram

Figure A-6.

A.5.8 Aerobic/GAC FBR Reactor Sizing

Figure A-7 provides a general sizing curve for BTEX treatment in GAC/FBR based on flow rate, at 35 mg/L influent COD and 14-foot design bed height. The curve would be different for other contaminants or COD levels.

A.5.9 Chemical Requirements

Aerobic process: nutrients (N or P) if not sufficient in the ground water.

Anoxic process: external carbon source if needed.

A.5.10 Design Criteria

Maximum loading	Aerobic process: 400 lb COD/1,000 ft^2/day
	Anoxic process: 300-500 lb NO_3-N/1,000 ft^2/day
Minimum HRT	5-10 minutes

A.5.11 Performance

Compound	Influent Range (mg/L)	Removal Range (%)	Reference
Total BTEX	2.0-7.8	99-99+	2-7
Total volatile hydrocarbons	9.42	99+	7

A.5.12 Residuals Generated

Aerobic process: 0.3-0.5 lb sludge/lb COD removed at about 1 to 2 percent solids concentration.

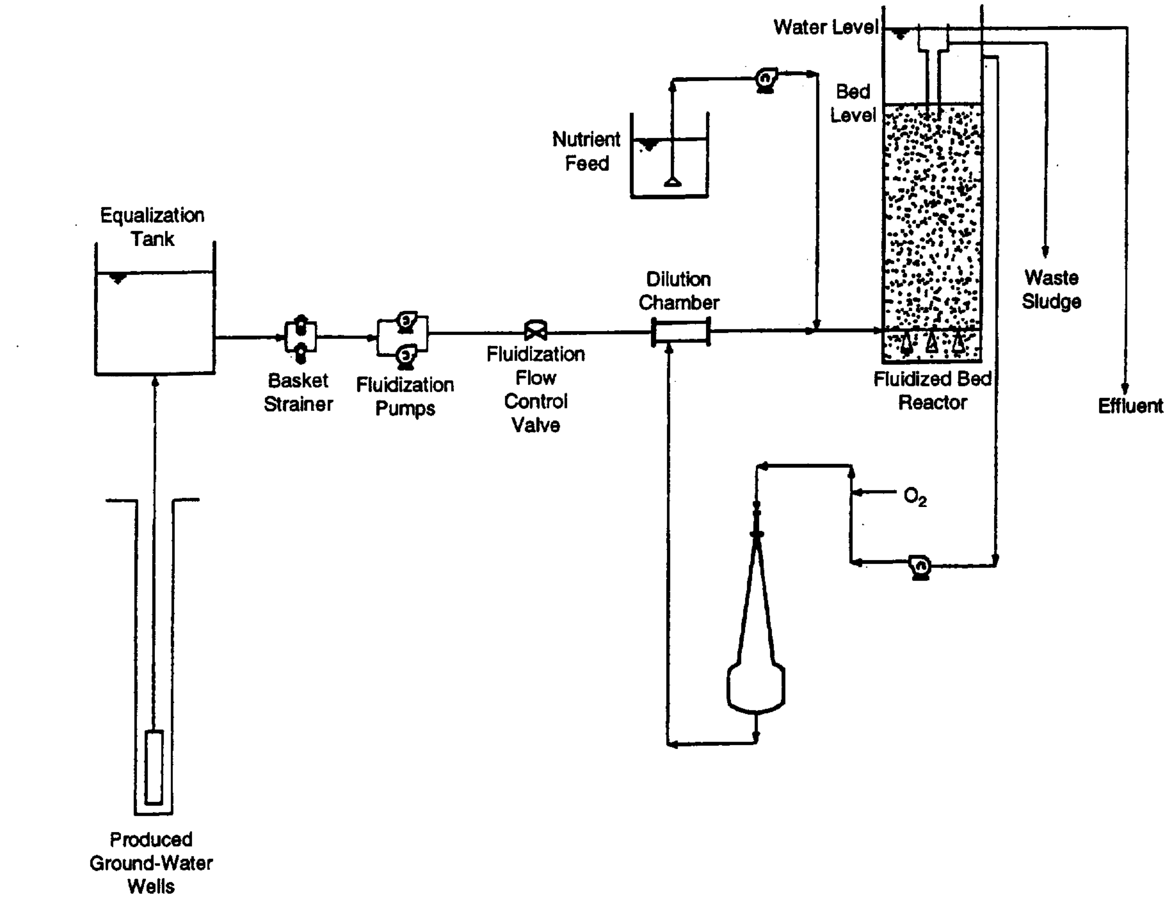

Figure A-6. Aerobic fluidized bed biological reactor (1).

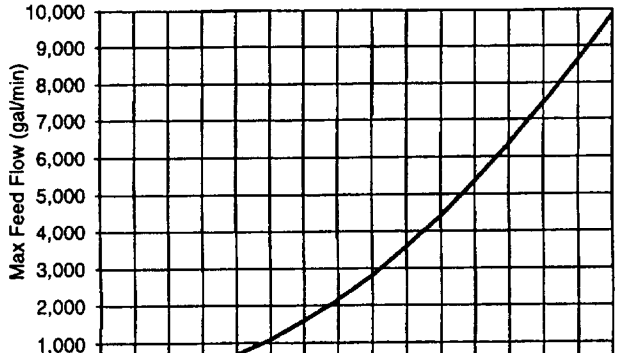

Figure A-7. Fluid bed sizing curve, ground-water aerobic application (1).

Anoxic process: 0.6-0.8 lb sludge/lb nitrate nitrogen removed at about 1 to 2 percent solids concentration.

A.5.13 Process and Mechanical Reliability

Expected to have high process and mechanical reliability. Single or dual reactor design provides on-line reliability and flexibility. GAC FBR offers the advantage of stable performance under fluctuating loading conditions.

A.5.14 Environmental Impact

Applying oxygen enriching and predissolving mechanism, GAC/FBR minimizes off-gas generation. In low-strength ground-water application, only nominal carbon replacement is needed to compensate for physical loss.

A.5.15 Major Cost Elements

Capital costs (as shown in Figure A-8) include all general equipment listed above plus carbon media, general engineering, and startup cost. The costs do not include intake and discharge piping, sludge dewatering, and building. Estimation is based on 35 mg/L influent COD and bed height of 14 feet (4.3 m).

Energy cost (as shown in Figure A-9) is based on the electrical power consumption for fluidization pumps, internal growth control system, air compressor and preparation systems, and control system.

Labor cost is estimated at 0.5 to 1.5 full-time operator and chemist. Duties include daily maintenance checkup, sampling, and routine analysis.

A.5.16 References

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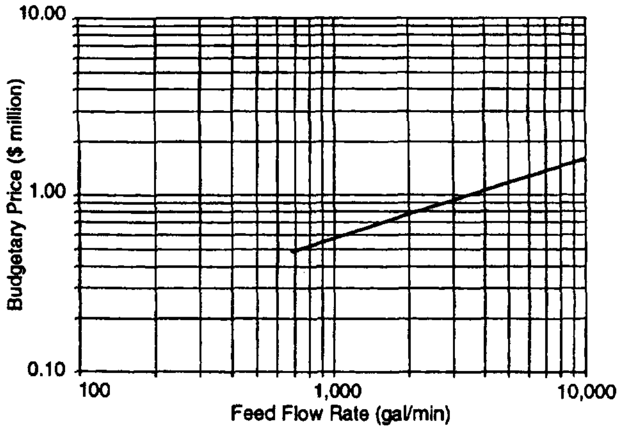

Figure A-8. **Granular activated carbon/fluid bed budgetary price, ground-water aerobic application (1).**

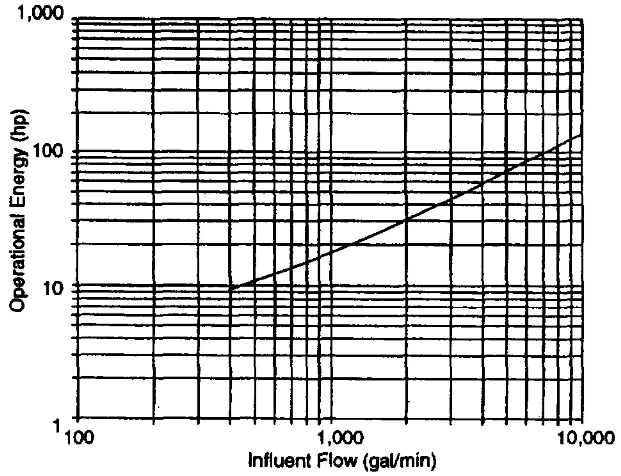

Figure A-9. **Granular activated carbon/fluid bed energy requirement, influent flow versus operational energy (1).**

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A.6 Air Stripping

A.6.1 Technology Description

Stripping occurs when a gas, such as air or steam, is introduced into a water containing volatile constituents.

Volatile organic compounds (VOCs) are released from the water phase to the gas phase, proportional to the differential in concentration of the volatile constituent between the two phases. The interphase transfer of a VOC will continue until equilibrium is established. At equilibrium, the concentration (or partial pressure) of a substance in the gas phase is proportional to its concentration in the liquid phase. This relationship is known as Henry's Law, and is unique for each compound. Air stripping involves optimization of Henry's Law to transfer aqueous contaminants into an air phase. The contaminated air may be released or can be treated by flaring or other oxidation method, by activated carbon adsorption or by scrubbing. The air stream must be reduced to between 40 and 50 percent humidity before entering the carbon adsorption system.

The residual concentrations of volatile contaminants that remain in the water phase depend in part on system temperature, total pressure, and molecular interactions occurring between the dissolved contaminant(s) and water.

The rate of transfer of VOCs can be modeled using Fick's Law:

$$r_{VOC} = -K_L a_{VOC} (C - C_S), \qquad (1)$$

where

r_{VOC} = rate of VOC mass transfer ($\mu g/ft^3 \cdot h$)
$K_L a$ = overall VOC mass transfer coefficient (h^{-1})
C = concentration of VOC in liquid ($\mu g/ft^3$)
C_S = saturation concentration of VOC in liquid ($\mu g/ft^3$)

Values for $K_L a$ can be found in the literature for many specific compounds.

The saturation concentration of the VOC, C_S, is a function of the partial pressure of the VOC in the gas phase in contact with the wastewater. This relationship is given by Henry's Law as

$$\frac{C_g}{C_S} = H_c, \qquad (2)$$

where

C_g = concentration of VOC in gas phase ($\mu g/ft^3$)
H_c = Henry's Law constant (unitless)

Typically, Henry's Law constants (H) are tabulated in units of volume x pressure/mole. A value of H_c is then calculated from

$$H_c = \frac{H}{RT}, \qquad (3)$$

where R is the ideal gas law constant and T is the absolute temperature.

A.6.2 Process Flow Diagram

A schematic of an air stripper is shown in Figure A-10. Contaminated water is pumped to a storage tank (Point 1) along with any recycle from the air stripper. Water from the storage tank is then fed to the air stripper (Point 3) at ambient temperature, although in some cases the feed stream may be heated in a heat exchanger (Point 2). If required, the liquid effluent from the air stripping tower is further treated (Point 4) with carbon adsorption or other appropriate technologies. The off-gas can also be treated (Point 5), using gas phase carbon adsorption, thermal incineration, or catalytic oxidation (1).

A.6.3 Pretreatment Requirements

To avoid fouling column packing, obtain uniform flow, and maintain evenly distributed contaminant concentrations, influent ground water or leachate may be pretreated using the following unit operations:

- Hydraulic and/or waste strength equalization, to adjust for variable flow and contaminant concentrations (2).
- TSS removal by settling, filtration, skimming, etc.
- Separation of immiscible liquids (LNAPL, DNAPL) by gravity separation or flotation.
- Iron/manganese or hardness removal by precipitation or ion exchange.
- Dissolved heavy metals removal by precipitation or ion exchange.
- pH adjustment to minimize precipitation of dissolved metals, biological fouling, and corrosion, and possibly enhance system performance.
- Disposal of TSS and chemical precipitation treatment sludges, LNAPL, DNAPL, and any other waste pretreatment residuals.

A.6.4 Parameters of Interest

Several significant parameters for design and process control, in addition to flow, are listed in Table A-1.

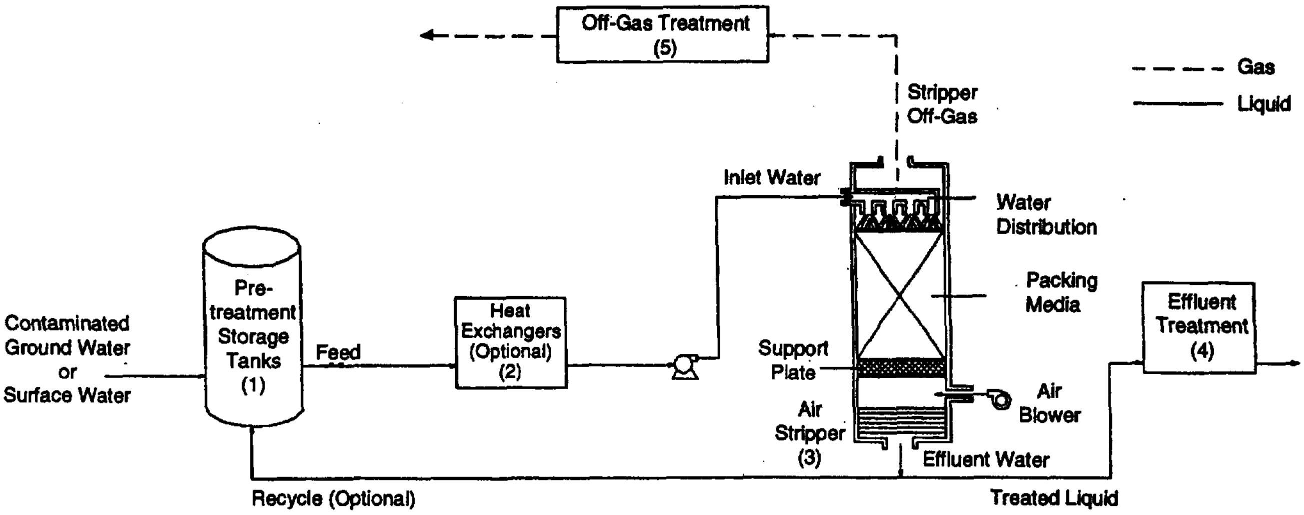

Figure A-10. Air stripping system.

Table A-1. Significant Treatment Parameters for Design of Air Stripping Units

Parameter	Rationale
Contaminants present	Only VOCs and some SVOCs with H_c>0.003 can be removed by air stripping. Other dissolved chemicals can degrade effectiveness of stripper by fouling or precipitating on packing material.
Contaminant concentration	For given operating conditions, an air stripper provides a fixed chemical-dependent removal efficiency. The variation in the influent concentration must be known to determine the maximum target removal efficiency for the chemical chosen.
Temperature	Temperature is an important determinant of removal efficiency. Henry's Law constants depend on the water temperature. Freezing conditions may foul packing.
Composition	Some naturally occurring constituents, such as iron or calcium carbonate, can foul or plug air stripper media.
Water pH	Precipitation of certain metals depends strongly on the solution pH.
Target effluent concentration	For this technology, a suitable VOC with a target removal efficiency can be selected as the basis for designing an air stripper.

A.6.5 Applications and Design Considerations

The design of air strippers is based on the type of contaminant present, the contaminant concentration, the required effluent concentration, water temperature, and water flow rate. Major design variables include gas pressure drop, air-to-water ratio, hydraulic loading rate, and type of packing (1). Example design parameters (3) are listed in Table A-2 for several common ground-water organic contaminants.

Goodrich et al. (4) have presented several example applications of air stripping for ground water using a packed tower (see Table A-3). Table A-3 compares influent concentrations versus several design parameters. Air stripping applications for leachates that contain high VOC concentrations have also been recommended (5).

A second type of stripping device is a "low profile" stripping unit. Low profile tray air strippers have smaller dimensions than the conventional packed tower. One example configuration is a modular design in which the trays are inside a fitted rectangular shaped tower, shown schematically in Figure A-11. The trays are made of sheet metal (aluminum or steel). The tower itself is less than 6 feet tall. Low profile strippers have been used with liquid flow rates of 600 to 1,600 ft^3/min. Because these systems use high air-to-water ratios, they are best suited for treatment of water containing highly volatile organic compounds. Several advantages include lower pressure pumps, better liquid distribution characteristics, low maintenance, resistance to fouling, lower buildings for enclosure, increased retention time, and portability. One disadvantage may be the higher operating costs associated with the high blower power needed to overcome the high static head of moving air through layers of water.

A.6.6 Major Cost Elements

Figures A-12 and A-13 present estimated capital costs and annual O&M costs associated with 99 percent removal of several VOCs and radon using packed tower air stripping. The costs presented are a function of daily flow, in millions of gallons per day.

A.6.7 Residuals Generated

The primary residual generated by an air stripping process itself is the contaminated off-gas stream. VOC

Table A-2. Typical Air Stripping Design Parameters for Removal of 12 Commonly Occurring Volatile Organic Chemicals[a] (3)

Compound	Henry's Law Constant	Air-to-Water Ratio	Air Stripper Height ft (m)	Diameter of Packed Column ft (m)
Benzene	0.106	32.7	36.2 (10.9)	8.4 (2.5)
Carbon tetrachloride	0.556	6.2	44.9 (13.5)	5.0 (1.5)
Chlorobenzene	0.069	50.3	37.6 (11.3)	22.7 (6.8)
1,2-Dichlorobenzene	0.090	38.7	40.4 (12.1)	8.9 (2.7)
1,2-Dichloroethylene	0.023	150.6	33.5 (10.0)	14.9 (4.5)
cis-1,2-Dichloroethylene	0.093	37.1	34.9 (10.5)	8.7 (2.6)
Dichloromethane	0.048	71.6	28.6 (8.6)	11.1 (3.3)
Tetrachloroethylene	0.295	11.8	43.8 (13.1)	6.0 (1.8)
Toluene	0.117	29.6	39.0 (11.7)	8.1 (2.4)
1,1,1-Trichloroethane	0.172	20.1	40.1 (12.0)	7.1 (2.1)
Trichloroethylene	0.116	29.9	38.0 (11.4)	8.1 (2.4)
m-Xylene	0.093	37.3	40.5 (12.1)	18.3 (5.5)

[a] Water flow rate, 2.16 million gal/day (8.17×10^6 L/day); inlet water concentration, 100.0 µg/L; water treatment objective, 1.0 µg/L; air stripper temperature, 50°F (10°C); air stripper packing pressure drop, 50.0 (N/m^2)/m packing; air stripper packing, 3-in. plastic saddles.

Table A-3. Applications of Packed Tower Aeration (4)

Location (Number of Towers)	Flow (million gal/day)	Contaminants	Total Influent Concentration (µg/L)	Tower Air-to-Water Ratio	Tower Height (ft)
Hartland, WI (1)	1.4	TCE, PCE, DCE	170	50:1	35
Schoefield, WI (1)	1.1	TCE, PCE, DCE, TCA	100	28:1	40
Rothschild, WI (2)	4	TCE, PCE, DCE, benzene	100	40:1	55
Wausau, WI[a] (2)	8	TCE, PCE, DCE	200	35:1	25
Elkhart, IN[a] (3)	10	TCE, carbon tetrachloride	100	30:1	55

[a]Superfund site

emissions from a stripping tower are calculated with the formula (3)

$$\text{Emission rate (lb/hr)} = (C1-C2) * V * (5E-7), \quad (4)$$

where

C1 = influent concentration of the VOC (µg/L)
C2 = effluent concentration of the VOC (µg/L)
V = water flow rate (gal/min)

Often, off-gas treatment, such as by dehumidification followed by gas-phase carbon adsorption, is employed to segregate contaminants from the off-gas stream. Alternatively, if the gas has a high BTU content, it may be piped to a flare or incinerated, if properly permitted. Other options include catalytic oxidation and scrubbing.

A.6.8 References

1. U.S. EPA. 1991. Air stripping of aqueous solutions. EPA/540/2-91/022. Washington, DC.
2. Patterson, J.W., and J.P. Menez. 1984. Simultaneous wastewater concentration and flow rate equalization. Environ. Prog. 3:81-87.
3. U.S. EPA. 1990. Technologies for upgrading existing or designing new drinking water treatment facilities. EPA/625/4-89/023. Cincinnati, OH.
4. Goodrich, J.A., B.W. Lykins, Jr., R.M. Clark, and E. Timothy Oppelt. 1991. Is remediated groundwater meeting SDWA requirements? JAWWA 83:55-62.
5. Eckenfelder, W.W., Jr., and J.L. Musterman. 1994. Leachate treatment technologies to meet alternative discharge requirements. Nashville, TN: Eckenfelder, Inc.

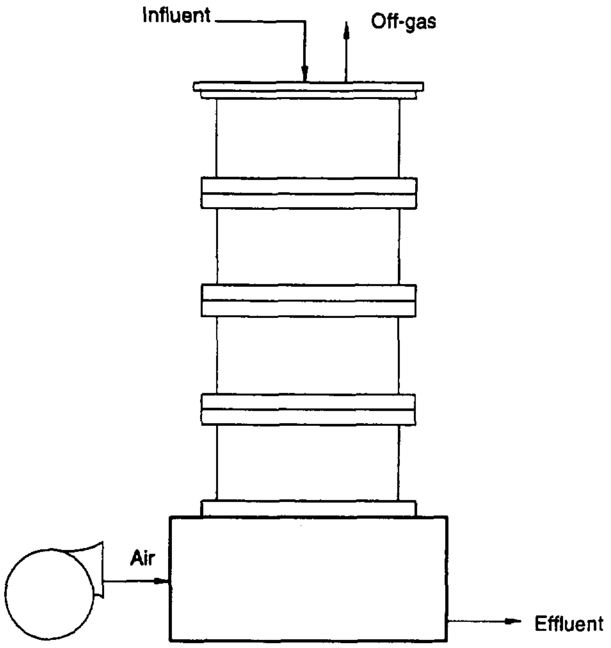

Figure A-11. Low-profile tray-type air stripper.

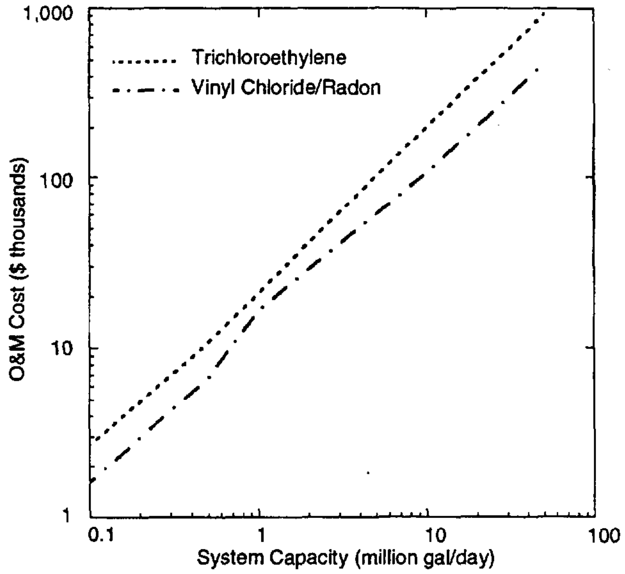

Figure A-13. O&M cost curve for 99-percent removal of several VOCs and radon using packed tower aeration, in 1989 dollars (3).

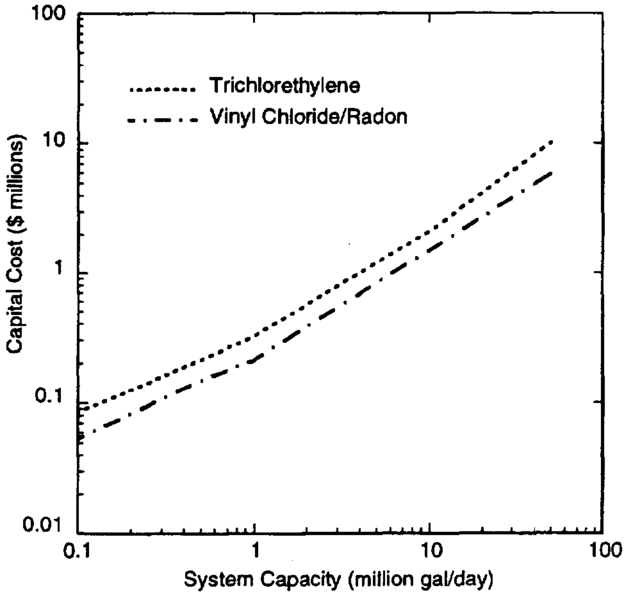

Figure A-12. Capital cost curve for 99-percent removal of several VOCs and radon using packed tower aeration, in 1989 dollars (3).

A.7 Activated Carbon

A.7.1 Technology Description

Activated carbon is effective in removing many contaminants from leachate and ground water. Removal is accomplished by adsorption, which is a phenomenon of physical attraction of molecules to the surface of the carbon. Activated carbon is made from coal, wood, coke, or coconuts, and has over 100 m^2 of surface area per gram. Adsorption capacities of 0.5 to 10 percent by weight are typical, and the carbon can be regenerated for reuse.

Activated carbon purifies ground water or leachate directly when the water is pumped through containers of liquid-phase carbon. If air stripping or soil vapor extraction is used as the primary means of water purification, activated carbon may be used to remove the contaminants from the air discharge. In this case, the off-gases are passed through vapor-phase carbon.

Permanent carbon treatment systems use carbon steel vessels that are epoxy lined. Disposable carbon canisters are also available. Drum sizes can contain from 150 to 2,400 lb of carbon for liquid- or vapor-phase use. The canisters are suitable for shipment and disposal, and are easily handled by fork truck. Other types of containers are available with hopper bottoms for removal of the carbon for regeneration. Carbon vendors will exchange spent carbon with fresh carbon. Large carbon vessels are drained and refilled with bulk carbon from tank trucks or on-site carbon storage silos. On-site regeneration may be cost-effective for large users of carbon.

A.7.2 Process Flow Diagram

Carbon canisters can be piped for upflow, downflow, parallel, or series operation. A typical carbon process flow diagram is presented in Figure A-14.

A.7.3 Application

Many organic compounds and some metals are removed from contaminated ground water and leachate by activated carbon.

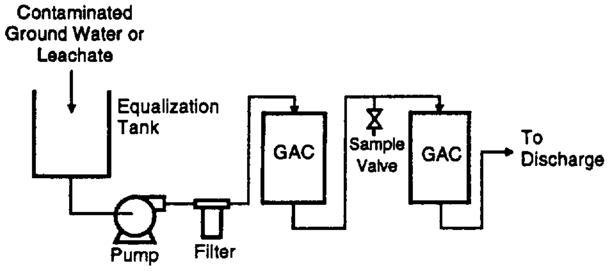

Figure A-14. Liquid-phase granular activated carbon process.

A.7.4 Pretreatment Requirements

Water high in suspended solids (>50 mg/L) should be filtered before activated carbon treatment (1). The carbon surface provides an ideal condition for bacterial growth. In some cases, growth of bacteria may become excessive. In these cases, pretreatment is necessary to minimize operating problems.

A.7.5 Parameters of Interest

Some parameters of interest that may assist in the selection of activated carbon systems are shown below.

Contaminant data	Type and concentration of pollutants to be removed; required removal efficiency; suspended solids in feed stream.
Iodine number	Quantity of iodine adsorbed (mg) by 1 g of carbon, usually 900-1,100.
Carbon isotherm data	Lab tests that predict the amount of specific contaminant adsorbed per gram of carbon.
Carbon selection	Bituminous, lignite, coconut, wood, etc.

A.7.6 Design Considerations and Criteria

Breakthrough is defined as the volume of water that has passed through the carbon bed before the maximum allowable concentration appears in the effluent. Provide sample valves in the piping along the carbon vessels to monitor for breakthrough. For canister applications, arrange piping, valves, and connections to allow replacement of the primary canister with the secondary canister in a series arrangement. New canisters should always replace the secondary canister. Allow space to store fresh and spent carbon, and for fork truck access. Other design considerations are (2, 3):

Pressure drop	2 to 15 in. H_2O per canister (air); 0.1 to 1 psi per canister (water).
Total pressure	Sum of strainers, cartridge filters, canisters, piping; typically 5 to 15 psi
Empty bed contact time (EBCT)	15 to 60 min typical for liquid systems; determined from pilot tests or from carbon supplier. Contact with vapor-phase carbon results in nearly instantaneous removal.
Volume of carbon	Calculated from EBCT and flow rate. Vol = flow rate x EBCT.
Hydraulic loading rate	2-8 gal/min/ft^2 common; used to calculate area of carbon vessels. Area required = flow rate divided by loading rate (gal/min/ft^2)
Adsorption capacity	$X/M = KC^{1/n}$, where X = amount contaminant adsorbed (mg) M = unit weight of carbon (g) K, n = empirical constants C = concentration of contaminant (mg/L) Note: The above equation applies to liquid- and vapor-phase carbon. Different constants must be inserted.
Impurity loading rate	Amount of contaminant adsorbed per gram of carbon.

Humidity	Decreases vapor-phase carbon effectiveness. Curves available.
Temperature	Decreases vapor-phase carbon effectiveness, but will offset negative effect of humidity if air is preheated, for a net gain of carbon effectiveness. See supplier performance curves.
Flow direction	Downflow mode is most common for liquid flow. Upflow variation used for high suspended solids waters. Series or parallel selection based on characteristics of adsorption wave front.
Backwash	Permanent carbon installations are normally equipped with a backwash system to purge entrapped suspended solids from the carbon bed. Air scour may be included to detach foulants or biological growth from the carbon.
Safety	Consider dust when handling bulk carbon. Spontaneous combustion is possible at certain conditions of temperature and humidity.
Material of construction	Use carbon steel vessels with epoxy coating.

A.7.7 *Treatment Ranges*

The effectiveness of activated carbon to adsorb contaminants varies inversely with contact time, contaminant concentration, temperature, and humidity. See Tables 4-3 to 4-22 for ranges of contaminant removal.

A.7.8 *Major Cost Elements*

Estimated costs for liquid-phase carbon and vapor-phase carbon adsorption are listed as follows:

Liquid-Phase Carbon Costs

Nominal Flow Rate

Gal/Min	Million Gal/Day	Capital Cost[a]	Annual O&M Cost[b]	Cost per 1,000 Gal
10	0.014	$5,000	$7,100	$1.40
50	0.072	$13,000	$15,100	$0.60
100	0.144	$20,000	$22,300	$0.40
300	0.288	$39,000	$53,300	$0.35

Vapor-Phase Carbon Costs

Nominal Flow Rate

Ft^3/Min	Capital Cost[c]	O&M Cost[d]	Cost per 1,000 Gal[e]
100	$6,000	$2,700	$0.55
500	$18,000	$9,800	$0.40
1,000	$36,000	$19,200	$0.35
3,000	$58,000	$47,800	$0.30

[a] Capital cost estimated on the basis of two pressure vessels on a prepiped, prewired skid, no installation included.

[b] Based on $0.08/kWh power, $10/hour labor for 1 hour per day, 360 days annual operation, 1 mg/L contaminant and 5 percent adsorption by weight, $1.00/pound carbon, 5 percent of capital for maintenance, and 5-yr life at 8 percent interest.

[c] Capital cost basis is 2 to 4 skid-mounted, reusable carbon vessels with hose connections, initial fill of carbon, sizes of 400 lb, 2,000 lb, and 10,000 lb as required for rated flow at 5-in. H_2O pressure drop or less.

[d] Operating cost based on 99+ percent removal of all VOCs from water with 1 mg/L VOC, 75:1 air water ratio (volume based), 5 percent adsorbency, $10.00/hr operator, 40 hr/yr changeover time, no power, no freight, 5-yr life at 8 percent interest, 5 percent of capital for maintenance, and $1.00/lb regeneration or replacement carbon.

[e] Costs per 1,000 gal correspond to flow rates for liquid-phase carbon, ft^3/min divided by 10 (i.e., 1,000 ft^3/min 10 = 100 gal/min).

A.7.9 *Residuals Generated*

Residuals consist of bulk spent carbon, disposable canisters (including spent carbon), or reusable vessels containing spent carbon. If cartridge pre- and postfilters are used, spent cartridge filter elements will be generated. Carbon fines and backwash water are generated at startup.

A.7.10 *References*

1. Hagar, D.G., J.L. Rizzo, and R.H. Zanistch. Advanced waste treatment design seminar: Experience with activated carbon in treatment of textile industry wastewaters. U.S. EPA Technology Transfer Seminar Series.
2. Calgon Carbon Corporation. Adsorption handbook. Pittsburgh, PA.
3. U.S. EPA. No date. Process design manual for carbon adsorption. Technology Transfer Series.

A.7.11 *Additional Source*

1. Carbtrol Corporation. 1990. Technical information data sheets. Westport, CT.

A.8 Ion Exchange

A.8.1 Technology Description

Ion exchange is an adsorption process that uses a resin media to remove contaminants from ground water or leachate. Cation resins adsorb metals, while anion resins adsorb such contaminants as nitrate and sulfate. Some resins are designed to adsorb only specific metals and are used for the recovery of metals in electroplating and metal finishing operations. Chelating resins are selective in adsorbing toxic metals such as copper, nickel, mercury, and lead.

Ion exchange systems consist of pressure vessels containing beds of resin pellets and strainer systems to retain the pellets. The most common mode of operation is continuous downflow using a fixed bed. Other cperating modes include batch and fluidized bed. The method of resin bed regeneration can be cocurrent or countercurrent. In cocurrent regeneration, the regeneration solution flows downward through the resin bed, in a similar manner as the liquid being treated. In countercurrent regeneration, solution flows upward, opposite the direction of water flow, which scours the bed and regenerates the resin with less solution.

A single batch mode ion exchange vessel may be adequate for contaminant removal if continuous operation is not required. Regeneration will, however, require temporary interruption of water treatment. A process flow diagram for a single ion exchange system is shown in Figure A-15. Additional tanks and pumps are required for regeneration, chemical feed, and collection of spent solution. Clean water is also required to flush the regeneration solution from the resin bed before resuming operation.

Ion exchange equipment configurations include parallel and series vessel arrangements. In a parallel ion exchange system, two or more vessels each treat a fraction of the total flow. Any one of the parallel flow vessels may be regenerated while the others remain on line. Series configuration systems have two vessels, each sized for 100 percent of the flow. After the lead vessel is regenerated, it becomes the lag vessel. The series configuration assures passage of contaminated water through at least one bed of freshly regenerated resin.

A.8.2 Application

Ion exchange is useful for removing and recovering metals. This process can also remove sulfates, nitrates, and radionuclides from water.

A.8.3 Pretreatment Requirements

Minimum pretreatment is 10-µm cartridge filtration. Other pretreatment may be required, including:

Carbon adsorption	Removes large organic molecules that foul strong base resins.
Dechlorination	Avoid prechlorination or neutralize chlorine.
Aeration, precipitation, filtration	Remove iron and manganese, which coat resin pellets.

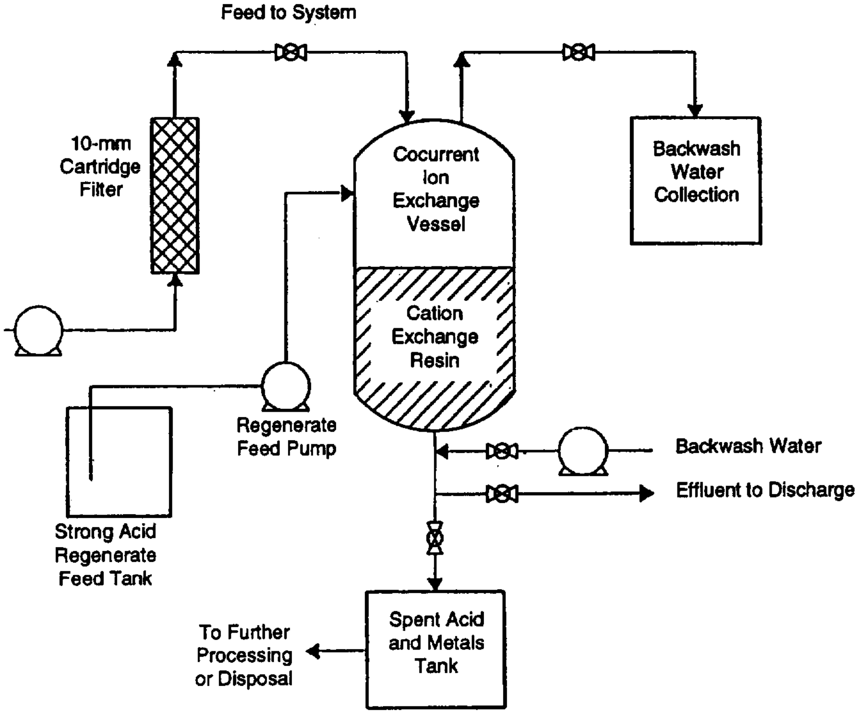

Figure A-15. Typical cocurrent ion exchange system.

A.8.4 Parameters of Interest

The following parameters are important for successful ion exchange operation:

Parameter of Interest	Basis of Interest
Type of contaminant	Basis for selection of resin.
Concentration of contaminant	Determines equipment size and frequency of regeneration.
Resin selection (acid or base resin)	Determines materials of construction, regeneration chemicals.
Flow rate	Volume of bed and area of vessel(s) depend on flow rate. Bed depth ranges from 2 to 5 feet.
Capacity of resin	Breakthrough curves for water with single metal contamination are available from vendors. Complex matrices require bench or pilot breakthrough test to determine impact of other contaminants.
Backwash rate	Sufficient to flush suspended solids from resin bed. Depends on resin density. Provide flow adjustment or consult resin supplier.
Regeneration	Volume required, contact time, flow rate, storage capacity.
Instrumentation	TDS, conductivity, pH, flow rate.

A.8.5 Design Considerations and Criteria

The following design information serves as a guide for evaluation and preliminary ion exchange design (1):

Resin volume	Provide resin bed volume that will result in a service flow of 2 to 4 gal/min/ft^3.
Cross-sectional area	Pressure vessel diameter should provide a cross-sectional area resulting in 5 to 8 gal/min/ft^2.
Backwash rate	Needs to be sufficient to fluidize bed to 50 to 75 percent more than original depth.
Regeneration	Acid or caustic, as required, 1-5N solution: Contact time: 30 min Flow rate (volume based): 0.25 to 0.5 gal/min/ft^3 Flow rate (area based): 1 to 2 gal/min/ft^2
Rinse	Flush at rapid rate. Provide storage for 50 to 100 gal/ft^3 resin volume.
Materials of construction	Tanks—Epoxy coating or rubber lined Pipes—PVC for water, stainless steel or plastic lined steel for acids Pumps—316 stainless steel for acid, carbon steel for caustic, cast iron or plastic for water

A.8.6 Treatment Ranges

Many contaminants, especially metals, can be removed by ion exchange. High concentrations of contaminants result in shorter runs before regeneration is required. Treatment ranges for many contaminants are listed in Chapter 4.

A.8.7 Major Cost Elements

Nominal Flow Rate

Gal/Min	Million Gal/Day	Capital Cost[a]	Annual O&M Cost[b]	Cost per 1,000 Gal[c]
10	0.014	$31,000	$26,000	$5.20
50	0.072	$81,000	$75,000	$3.00
100	0.144	$123,000	$128,000	$2.60
300	0.432	$237,000	$330,000	$2.20

[a] Based on quotation for dual-bed system (anion and cation exchange), completely assembled on a skid, no site work included. Single-bed systems cost approximately one-third as much.

[b] Cost based on one regeneration per day, 2 hours operator attention per day @ $10/hour, 5 percent of capital cost for maintenance, $0.08 per kWh power, and 5-year life at 8 percent capital recovery factor. Acid and caustic use at 5N, 30 minutes' detention time in resin bed. Annual operation of 360 days.

[c] Cost based on annual operation of 360 days, 23 hours per day.

A.8.8 Residuals Generated

The rate of generating residuals is proportional to the concentration of contaminants in the leachate or ground water. Residuals generated by ion exchange include:

- Spent chemicals: acid and/or caustic soda
- Backwash water: dilute acid or basic solution
- Filters: spent cartridges
- Resin: fouled resin granules

A.8.9 Reference

1. Rohm and Haas Company. Technical bulletins: Ion exchange and fluid process. Philadelphia, PA.

A.9 Reverse Osmosis

A.9.1 Technology Description

Reverse osmosis (RO) is a separation process that uses selective semipermeable membranes to remove dissolved solids, such as metal salts, from water. A high-pressure pump forces the water through a membrane, overcoming the natural osmotic pressure, to divide the water into a dilute (product) stream and a concentrated (brine) stream. Molecules of water pass through the membrane while contaminants are flushed along the surface of the membrane and exit as brine.

The most commonly used materials for membranes are cellulose acetate, aromatic polyamide, and thin-film composites. RO membranes (or modules) are configured into tubular, spiral wound, hollow fiber, or plate-and-frame modules. The modules are inserted into long pressure vessels that can contain one or more modules. RO systems consist of a pretreatment pump, a high-pressure feed pump, one or more pressure vessels, controls, and instrumentation.

Membranes have a limited life of approximately 2 years. When product water production declines, the membranes must be restored with a cleaning solution. Tubular and plate and frame membranes can be physically scrubbed with a brush. All membranes can be cleaned chemically by recirculating the cleaning solution through the membranes to restore performance. Membranes can also be removed from the RO system and sent to cleaning centers for flushing and rejuvenation. When cleaning is no longer effective, the membranes must be replaced.

Theoretically, 100 percent of the water pumped into a RO system could be recovered as product water, but the module would soon be fouled beyond restoration. Some brine must flow out of the module to remove concentrated contaminants. This rejected flow may be significant (15 to 25 percent of the feed flow). This is one of the disadvantages of the RO process. To ensure adequate flow of brine over the membrane surface and reduce the volume of the reject, RO modules are arranged in stages. As the raw water is converted to product, brine flow is reduced. Fewer modules in downstream stages maintain the minimum flow necessary for flushing. A typical multistage RO system is shown in Figure A-16.

A.9.2 Applications

Reverse osmosis is widely used for desalination of brackish water as a potable water source. Special membranes have been developed for industrial uses and for purifying wastewater. Metal compounds are readily removed. Reverse osmosis is a commercially mature process available for many special applications.

A.9.3 Pretreatment Requirements

Typical RO membrane pore sizes range from 5 to 20 Angstrom units (0.0005 to 0.002 µm), while pressures of 300 to 400 psi are usually encountered. Therefore, RO feed water needs to be very low in turbidity (generally, less than 1.0 NTU). Pretreatment may be necessary, including chemical addition, clarification, and filtration. Final cartridge filtration using 5-µm filters is standard practice. Some RO membranes are sensitive to chlorine. Activated carbon pretreatment is used when needed to remove chlorine. Biofouling can be prevented by chlorination and dechlorination of the feed water. Use stainless steel and/or plastic piping to prevent iron fouling from contact with steel pipes. Perform a Langelier Index calculation to determine if the water tends to corrode ferrous piping or if deposits and scale may form. Adjust the pH with acid, if necessary, to maintain solubility of metals such as calcium, magnesium, and iron. Chemical requirements are:

pH adjustment	Sulfuric acid, hydrochloric acid.
Bactericide	Chlorine, sodium hypochlorite.
Dechlorination	Activated carbon.
Chelating agents	EDTA, proprietary solutions.

A.9.4 Membrane Maintenance

When RO membranes are not in use, they must not be allowed to dry out or freeze. Fill with recommended preservative solution. Flush before using RO system. When cleaning becomes necessary, cleaning solution is normally recycled through the RO system at high flow with the bypass valve open.

Cleaning solution	EDTA, tripolyphosphate, citric acid, acetic acid, proprietary cleaners.
Storage	Formaldehyde, glutahyde, sodium metabisulphite, proprietary solutions.

A.9.5 Parameters of Interest

A thorough analysis of the water is necessary to determine the pretreatment requirements and values of operating parameters, which are:

Flux	Flow rate of product (permeate) per unit of membrane area, gal/ft^2/day.
Product recovery	Ratio of product flow rate to feed flow rate.
Rejection	Percent removal of contaminant(s).

A.9.6 Design Considerations and Criteria

Membrane fouling can be reduced by proper design, based on analysis of ground water or leachate samples.

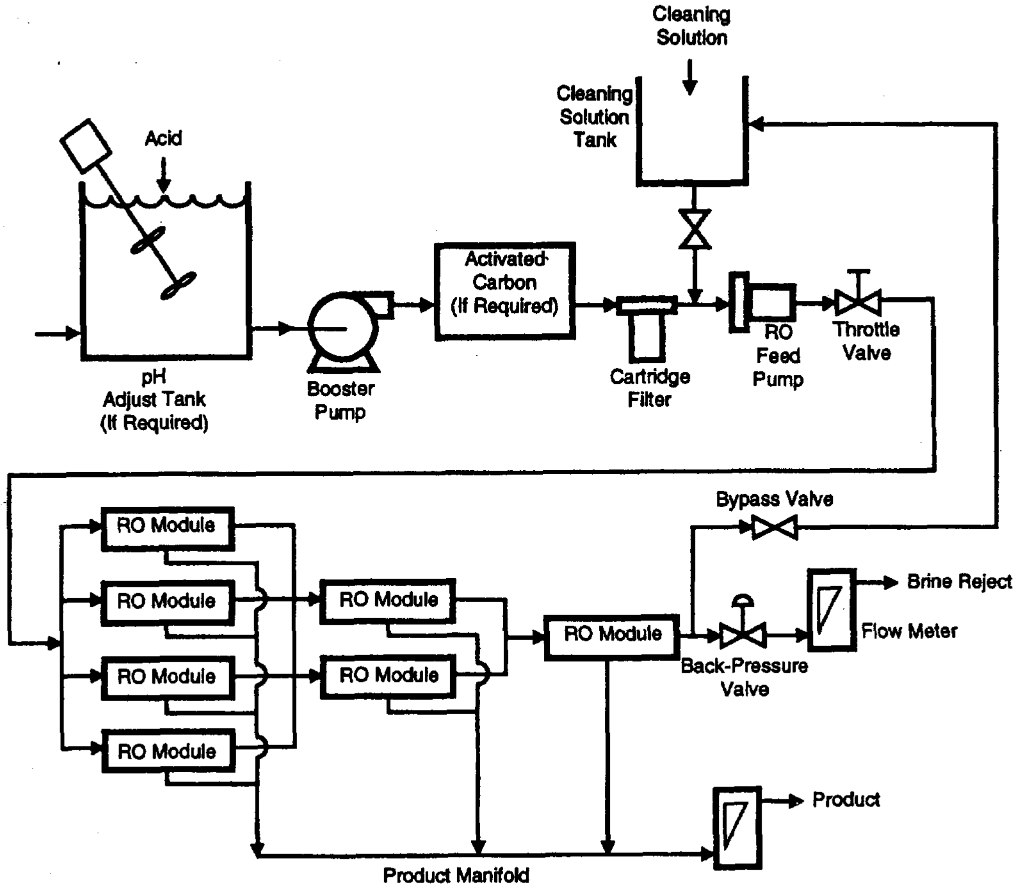

Figure A-16. Reverse osmosis process.

Typical design parameters are (1):

Feed water quality	Less than 50,000 mg/L total dissolved solids. Minimum levels of iron, magnesium sulfates, calcium carbonate, silicates, chlorine, and biological organisms.
Suspended solids	Remove colloids, silt with 5- to 10-µm filters.
Temperature	85°F to 120°F.
Product water flow	1 to 10 gal/ft^2/day.
Recovery	5 to 6 percent per module; 50 to 90 percent per system.
Pressure	400 to 600 psi.
Rejection	70 to 97 percent sodium chloride solution.
Waste stream	Brine flow rate of 10 to 50 percent of feed flow rate.

A.9.7 Treatment Ranges

Treatment efficiency of RO is most sensitive to fouling factors. Pressure, temperature, flow rate, and membrane age also affect removals. See Tables 4-3 to 4-22 for a list of treatment ranges.

A.9.8 Major Cost Elements

Estimated costs for RO systems of various sizes are:

Nominal Flow Rate

Gal/Min	Million Gal/Day	Capital Cost	Annual O&M Cost	Cost per 1,000 Gal
10	0.014	$20,000	$15,100	$2.90
50	0.072	$80,000	$61,600	$2.40
100	0.144	$175,000	$112,500	$2.20
300	0.432	$450,000	$310,600	$2.00

A.9.9 Residuals Generated

Brine is the primary residual, with concentrations of dissolved solids and contaminants approaching 10 times that of the feed water. Flow rate of brine ranges from 10 to 50 percent of feed. Spent carbon and filter cartridges are solid wastes. Batches of cleaning solution, 30 to 50 gal per cleaning event. Spent modules, 2-year life expectancy.

A.9.10 Reference

1. E.I. duPont de Nemours and Co. Permasep engineering manual. Permasep Products, Wilmington, DE.

A.9.11 Additional Source

1. UOP, Inc. Product bulletins. Fluid Systems Division, San Diego, CA.

A.10 Chemical Precipitation of Metals

A.10.1 Technology Description

Chemical precipitation is a principle technology for removing metals contaminants from contaminated ground water.

In general, metals can be precipitated to insoluble metal hydroxides, sulfides, carbonates, or other salts. The chemical precipitation process involves several principle mechanisms, including formation of the metal precipitate species, and coprecipitation or adsorption. The major process variables that influence precipitation reactions are treatment pH; type of treatment chemical(s) and dosage; types of ligands present; wastewater volume and temperature; the number of treatment stages; and the chemical speciation(s) of the pollutant(s) to be precipitated. Each variable can directly influence the degree of treatment performance and cost. Cost factors to be considered include the type of treatment chemicals employed and the volume of sludge generated. If the residual waste (sludge) is deemed hazardous, the cost of disposal can increase by an order of magnitude or more (1).

Precipitation in the most narrow sense involves a shift in chemical conditions to force a soluble species to form an insoluble (or precipitated) salt. This could result, for example, by the addition of sodium sulfide to a cadmium wastewater to precipitate cadmium sulfide. Classically, precipitation for heavy metals treatment is perceived to result through pH adjustment and consequent precipitation of the metal hydroxide. "Precipitation," however, is now recognized to encompass a much broader range of phenomena, including formation of mixed or transient salts and adsorptive coprecipitation. The latter results from adsorption of one metal species onto the highly reactive surface of a solid phase, typiçally formed in situ. Coprecipitation may be induced, for example, by the addition of an iron or alum coagulant, or incidental due to the precipitation of a secondary species already present within the wastewater. The consequence of this broader range of chemical behavior is that residual metal solubility levels far below the theoretical solubility limits of simple metal salts are commonly achieved.

Treatability studies are often needed to optimize treatment variables, such that effluent limits are achieved cost effectively. Volumes and handling characteristics of precipitation treatment sludges frequently override other economic factors in selection or optimization of precipitation treatment variables.

A.10.2 Process Flow Diagram

Example precipitation sequences are shown in Figures A-17 and A-18. The physical/chemical system in Figure A-17 includes the following unit processes: equalization, coarse filtration, chemical oxidation, coprecipitation with lime and ferric chloride, clarification (flocculation and sedimentation), polishing filtration for clarifier supernatant, and sludge dewatering. This sequence may be representative of treatment for arsenic, where preparatory oxidation of arsenite to arsenate enhances coprecipitation treatment efficiency. Chemical reduction, for example, of hexavalent chromate anion to the trivalent chromic cation, may be substituted in this treatment scheme. Figure A-18 shows a treatment sequence employing simple direct precipitation, flocculation, and sedimentation.

A.10.3 Pretreatment Requirements

Design data are needed for each stage of a precipitation treatment sequence. A listing of sequence design elements is given in Table A-4.

Table A-4. Design Elements for Precipitation Treatment

Treatment Stage	Design Elements
Equalization	Waste strength, flow, separate immiscible liquids (LNAPL, DNAPL)
Chemical addition	pH control, type of chemicals used, coprecipitant/adsorbent, reactor design-rapid mix
Flocculation	Flow, flocculent aids, mixing regime, flocculation basin residence time
Sedimentation	Flow, basin configuration, hydraulic loading, precipitate settling characteristics
Effluent filtration	Flow, filter media, filter aids, number of filter units
Sludge thickening and/or dewatering	Sludge volume, conditioning chemicals, dewatering unit type and size

Precipitation processes have been identified for the effective removal of various metals contaminants in ground water (3, 4). Several example processes are given in Table A-5. The effectiveness of chemical precipitation treatment is limited. Nyer (5) suggested that at low influent heavy metals concentration, ion exchange could be a more cost-effective treatment technique. This is especially true at metals concentrations having discharge limits below the solubility limit. The impact of competing nontoxic ions such as calcium on ion exchange process efficiency and cost-effectiveness must be evaluated.

A.10.4 Parameters of Interest

Significant parameters for design and process control are given in Table A-6.

A.10.5 Major Cost Elements

Figures A-19 and A-20 present example construction costs and operation and maintenance costs curves,

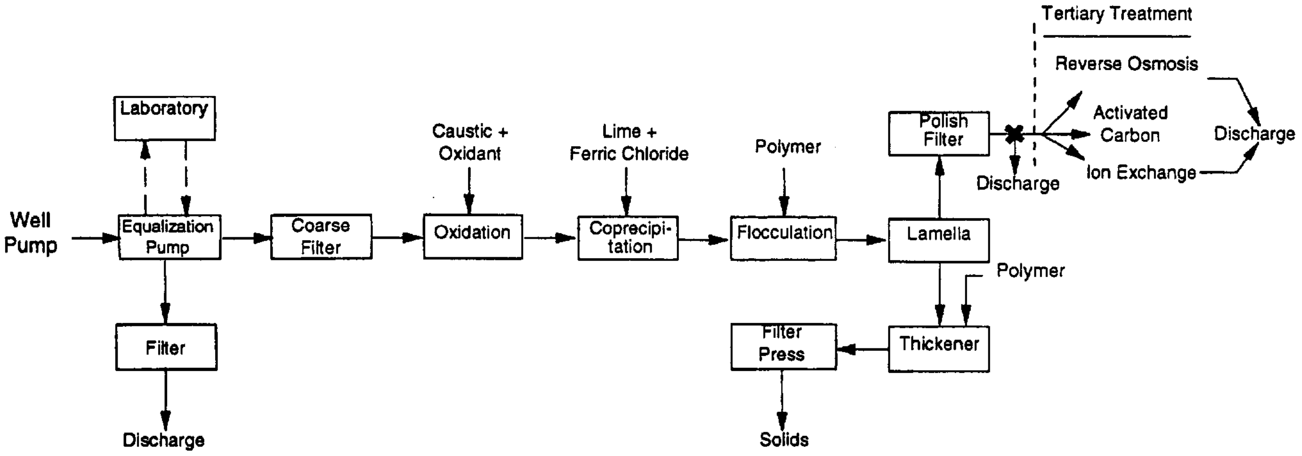

Figure A-17. Physical chemical treatment process.

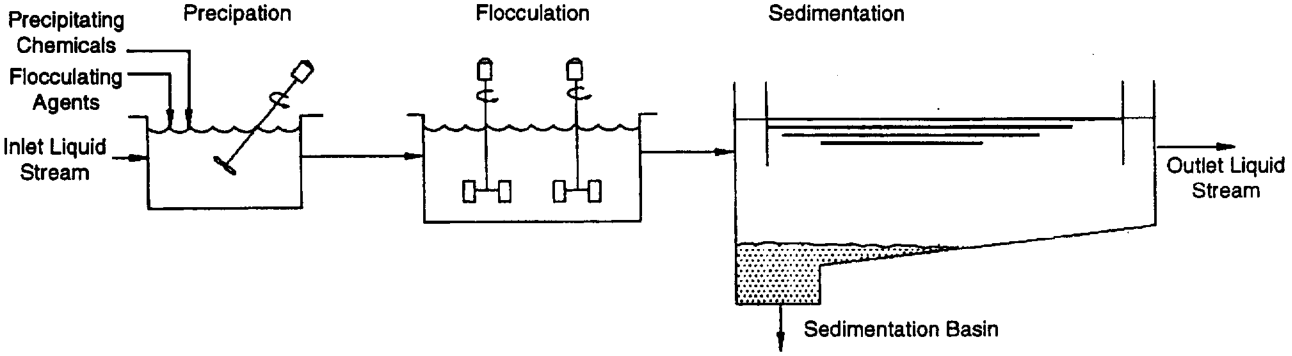

Figure A-18. Representative configuration employing precipitation, flocculation, and sedimentation (2).

respectively, for a package water treatment plant for precipitation, flocculation, sedimentation, and filtration.

A.10.6 Residuals Generated

The quantity of sludge produced depends on the quality of the water being treated and the type of treatment chemical used (e.g., lime, alum, or iron containing sludges). The amount of sludge produced can be approximated from the chemistry and raw water quality (i.e., adding the suspended solids removed to the coagulant added). Better estimates, however, are obtained by treatability studies using the actual ground water or leachate to be treated.

A.10.7 References

1. Patterson, J.W. 1985. Industrial wastewater treatment technology, 2nd ed. Boston, MA: Butterworth Publishers.
2. U.S. EPA. 1982. Handbook for remedial action at waste disposal sites. EPA/625/6-82/006. Cincinnati, OH.
3. U.S. EPA. 1990. Technologies for upgrading existing or designing new drinking water treatment facilities. EPA/625/4-89/023. Cincinnati, OH.
4. American Society of Civil Engineers (ASCE) and American Water Works Association (AWWA). 1990. Water treatment plant design, 2nd ed. New York, NY: McGraw-Hill.
5. Nyer, E.K. 1992. Ground-water treatment technology. New York, NY: Van Nostrand Reinhold Company.
6. U.S. EPA. 1978. Estimating costs for water treatment as a function of size and treatment plant efficiency. EPA/600/2-78/182. Cincinnati, OH.

A.10.8 Additional Sources

1. Dentel, S.K., B.M. Gucciardi, T.A. Bober, P.V. Shetty, and J.J. Resta. 1989. Procedures manual for polymer selection in water treatment plants. Prepared for AWWA Research Foundation, Denver, CO.
2. Eckenfelder, W.W., Jr. 1989. Industrial water pollution control. New York, NY: McGraw-Hill.

Table A-5. Example Precipitation Treatment Methods for Metal Contaminants (1, 4)

Contaminant	Process	pH Range	Comments
Arsenic (+5)	Ferric sulfate coprecipitation	6-8	—
	Alum coprecipitation	6-7	
	Lime softening	>10.5	
Arsenic (+3)	Ferric sulfate coprecipitation	6-8	Oxidation to As^{5+} by chlorination required before coprecipitation
	Alum coprecipitation	6-7	
	Lime softening	>10.5	
Cadmium	"Hydroxide" precipitation	Varies	
	Ferric sulfate coprecipitation	7-8	
	Lime softening	—	Effective over full lime-softening range
Chromium (+3)	"Hydroxide" precipitation	Varies	
	Ferric sulfate coprecipitation	6-9	—
	Alum coprecipitation	6-7	—
	Lime softening	>10.5	—
Chromium (+6)	Ferrous sulfate coprecipitation	7-9.5	—
Lead	"Hydroxide" precipitation	Varies	
	Ferric sulfate coprecipitation	6-9	—
	Alum coprecipitation	5-7	—
	Lime softening	—	Effective over full lime-softening range
Inorganic mercury	Ferric sulfate coprecipitation	7-8	—
Selenium	Ferric sulfate coprecipitation	6-7	—
Silver	Ferric sulfate coprecipitation	7-9	—
	Alum coprecipitation	6.2-6.4	—
	Lime softening	—	Effective over full lime-softening range

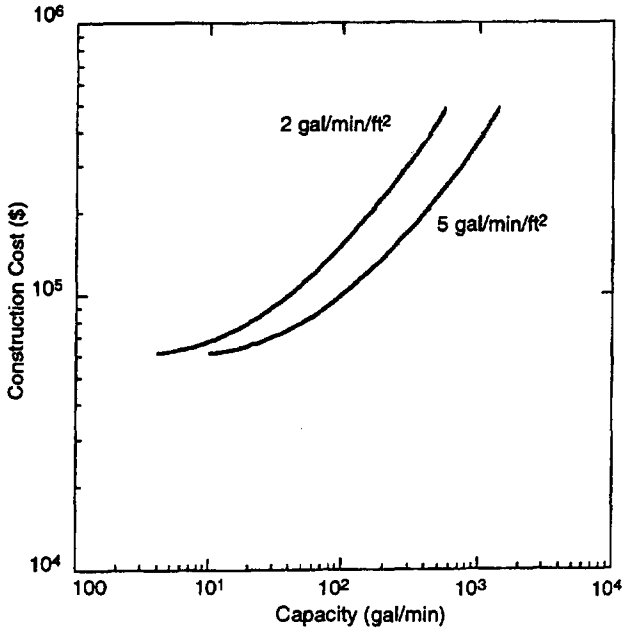

Figure A-19. Construction cost curves for package complete treatment plants, in 1978 dollars (6).

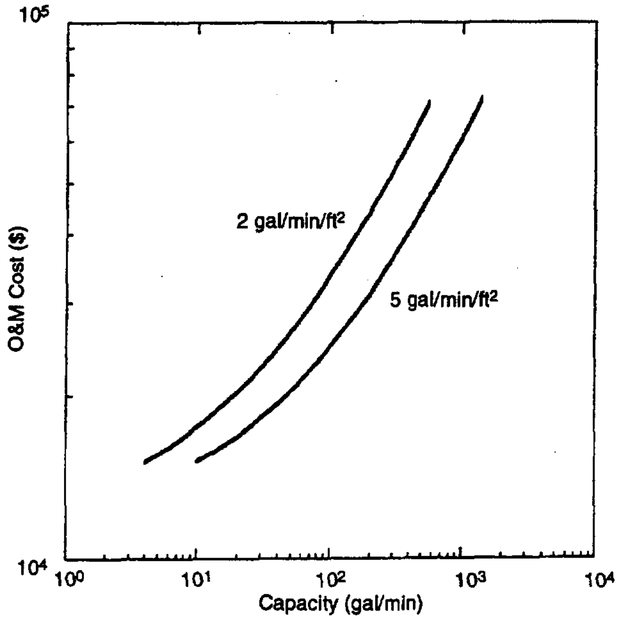

Figure A-20. O&M cost curves for package complete treatment plants, in 1978 dollars (6).

Table A-6. Significant Treatment Variables for Precipitation

Treatment Variable	Potential Effect(s)
Optimum pH	To achieve the necessary effluent limits. the optimal pH must be determined. pH control is a function of the chemical(s) used to precipitate metals in the ground water. The treatment pH can also affect the amount of sludge generated and its settleability. Figure A-21 shows the solubility of various metal hydroxides as a function of pH.
Treatment chemical/dosage	The cost and type of treatment chemical used influences both the amount and type of sludge produced. The use of sulfide, for example, may achieve the lowest effluent residual metals concentrations but make sludge generated hazardous (because of reactivity). Sodium hydroxide, on the other hand, may generate less sludge, but the sludge can have poor settleability. Sodium hydroxide is also expensive. Lime is relatively inexpensive, and the sludge generated has generally good settling characteristics. Lime usually generates a large volume of sludge, however, which affects the cost of disposal.
Treatment chemical coprecipitant/adsorbent used	Typically, ferric iron salts are used to effect coprecipitation/adsorption of trace metals from solution. Ferrous iron salts and alum, however, have also been investigated and are widely used (1).
Wastewater volume	The volume of water to be treated affects the amount of chemical used and sludge produced. Patterson (1) reported that approximately 4 percent of the wastewater volume treated becomes sludge.
Treatment stages	Often multiple-stage precipitation processes enhance metals removals. Dividing precipitation, coprecipitation, and adsorption into several discrete processes allows each to be optimized for a given pollutant(s). This could reduce the amount of sludge produced because each pollutant is removed at its "optimal" chemical dosage, chemical type, and pH. Further, the sludge produced in each step may have reclamation possibilities versus disposal, and sludge volume versus settleability.
Pollutant chemical speciation	The chemical speciation of the pollutant to be removed directly affects the degree of removal. For example, arsenate is readily coprecipitated by lime-ferric chloride addition, but arsenite is not (1). Hence additional treatment steps are required. In this case, chemical oxidation could be used to convert arsenite to arsenate.
Other ions present	The presence of other ions may or may not enhance the precipitation, coprecipitation, and adsorption process. Ions such as sulfate and carbonate may increase chemical demand by reacting with the treatment chemical(s). Ions such as chloride may compete with metals for surface sites on the precipitate or may form other, more soluble metal complexes. Hardness also influences the treatment effectiveness. High lime plus ferric chloride could be required to coprecipitate or adsorb the micropollutant concentrations of metals present to achieve water quality based effluent limits (WQBEL). Hardness as $CaCO_3$ could offset the quantity of lime (CaO) required, for example. The quantity of sludge produced, however, would remain constant.
Wastewater temperature	Wastewater temperature may affect the minimum solubility of the metals present. Generally, as the temperature is increased, the solubility is increased and the soluble metals in the wastewater are not precipitated to their optimal residual concentrations.
Settling velocity and settled sludge volume	A design criteria in the design of sedimentation tank is for the overflow rate to be less than the settling velocity of the feed solids. The manner in which the suspended solids settle depends on the nature of the solids present. The settling of activated sludge and flocculated chemical suspensions usually takes place in the hindered settling regime (6). This type of settling is characterized by the formation of a distinct interface between the clear water (supernatant) and the particles in the settling region. Discrete, flocculant, and hindered settling have different settling characteristics and require different methods of settling velocity determination. The settled sludge volume is the volume of sludge collected at the bottom of a test cylinder after quiescent settling for a given period, normally 30 minutes to 1 hour. It provides information on the expected volume of sludge that will be generated in a settling basin.
Effectiveness of polymers	Polymers act to promote particle aggregation by either reducing charge, bridging, or coagulation-bridging. Polymers may be used either as primary coagulants, in which case they are typically low molecular weight or positively charged, or as coagulant aids, in which case they have a higher molecular weight and a positive, negative, or neutral charge (7). Chemical characteristics of polymers and laboratory (jar) test of polymer performance provide the information that determines the best polymer to use and the optimal dosage level.

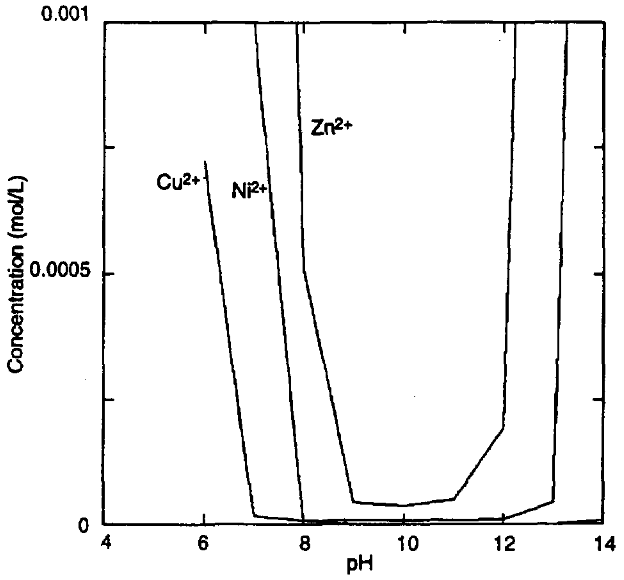

Figure A-21. Solubilities of metal hydroxides at various pHs.

A.11 Chemical Oxidation

A.11.1 Technology Description

Oxidation—reduction or "redox" reactions—can play an important role in the treatment of a contaminated ground water. The chemical behavior of compounds containing carbon, nitrogen, sulfur, iron, and manganese, for example, are largely influenced by redox reactions. Often, redox reactions are employed to facilitate the removal of a pollutant from a given wastewater. For instance, the reduction of hexavalent chromium to the trivalent ion facilitates the removal of chromium by precipitation. Oxidation of arsenite to arsenate can enhance the efficiency of certain arsenic treatment technologies. Similarly, cyanide can be oxidized, using sodium hypochlorite, to carbon dioxide and nitrogen at elevated pH (1).

Chemical oxidation involves the loss of one or more electrons by the element oxidized. The electron acceptor may be another element, including an oxygen molecule, or it may be a chemical species containing oxygen, such as hydrogen peroxide and chlorine dioxide or some other electron acceptor. Oxidation processes for some organic compounds may be too slow to completely oxidize the constituents to CO_2 and water. Weber and Smith (2) categorized organic compounds' amenability to oxidation. For example, high reactivity compounds include phenols, aldehydes, aromatic amines, certain organic sulfur compounds; medium reactivity compounds include alcohols, alkyl-substituted aromatics, nitro-substituted aromatics, unsaturated alkyl groups, carbohydrates, aliphatic ketones, acids, esters, and amines; and low reactivity compounds include halogenated hydrocarbons, saturated aliphatic compounds, and benzene.

Chemical oxidation is a potential treatment option for the removal of certain organic pollutants from a ground water or leachate. The amount of oxidant required in practice is generally greater than the theoretical mass calculated. The reasons for this are numerous and include incomplete oxidant consumption and oxidant demand caused by other species in solution. Often, oxidation reactions are pH dependent, hence pH control may be an important design variable. Economics of treatment and treatability of a specific pollutant also govern the degree of oxidation. For example, partial oxidation of dichlorophenol in a contaminated ground water may be employed to facilitate subsequent removal by activated carbon. Partial oxidation followed by additional treatment options may be more efficient and cost effective than using a complete oxidation treatment scheme alone. An increase in the biodegradability of refractory organics due to chemical oxidation has been reported (3). Examples of common oxidants include ozone, chlorine, hydrogen peroxide, and UV radiation. The use of chlorine to oxidize organic compounds must be closely evaluated due to the potential formation of toxic chlorinated reaction byproducts.

A.11.2 Process Flow Diagram

A simple oxidation treatment schematic, which might be applicable to arsenic, is shown in Figure A-22. This treatment sequence consists of equalization, coarse filtration, the oxidation step, coprecipitation, flocculation, and a polishing step using filtration.

A.11.3 Design Considerations and Criteria

Chemical oxidants such as hydrogen peroxide, chlorine, and ozone are commonly employed in ground-water and leachate treatment. The use of these chemicals is briefly described below.

A.11.3.1 Ozonation Systems

Ozone is an allotrope of oxygen. It is relatively unstable, having a half-life of less than 30 minutes in distilled water at 20°C (4). Ozonation systems have four major components: air preparation or pure oxygen feed, ozone generation, ozone contacting, and off-gas destruction (5).

Ozone is produced by passing air between oppositely charged plates or through tubes in which a core and the tube walls serve as the oppositely charged surfaces. Air is refrigerated to below the dew point to condense out atmospheric humidity. The air is then passed through a silica gel or activated alumina to further lower the dew point to minus 40 to 60°C. The use of dry, clean air results in lower ozone generator maintenance requirements, long-life units, and more ozone produced per unit of power added.

If pure oxygen gas is used as the feed to the ozonator, it should have a purity greater than 95 percent and a dew point lower than -60°C. Oxygen feed can also be produced on site by either pressure swing adsorption of oxygen from air or cryogenic production from air. Pure oxygen feed is generally more cost effective than air for ozonation systems that generate more than 3,500 lb/day of ozone.

Once produced, ozone is bubbled through the ground water or leachate using a diffusion system, such as two-chamber porous plate diffusers, with a 15- to 24-ft water column. Ozone transfer occurs as fine bubbles containing ozone and air (or oxygen) rise slowly inside the column, contacting the contaminated water phase. The correct ozone dose to achieve oxidation must be determined by treatability studies. There are many site specific variables, such as ozone production efficiency and wastewater quality, that must be determined to correlate ozone dosage and contaminant oxidation efficiency. Table A-7 lists some example removal efficiencies obtained by ozone treatment.

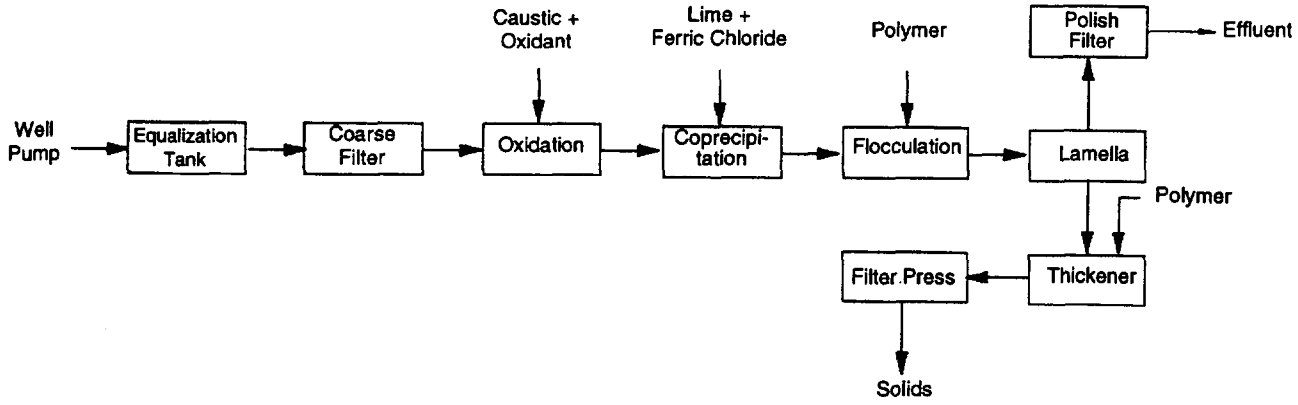

Figure A-22. Simple oxidation process.

Table A-7. Removal Efficiencies by Ozone Oxidation (6)

	Removal Efficiency
Organic Compounds	**Ozone Oxidation at 2 to 6 ppm**
Alkanes	0-30
Alkenes	30-100
Aromatics	30-100
Pesticides	30-100

Any ozone remaining in the off-gas from the diffusion system must be destroyed before release to the atmosphere. It should be noted, however, that the ozone contactor can be designed for 100 percent absorption. The destruction of excess ozone from ozone contactor exhaust gases can be accomplished thermally by heating the off-gases to 300°C to 350°C for 3 seconds; catalytically by using metal catalysts or metal oxides; or by employing a combination of thermal and catalytic destruction (7). It is generally more cost effective to destroy ozone in exhaust gases than to recycle the gases through the feed air preparation and ozone generation systems.

Capital and O&M costs associated with ozone treatment are given in Figures A-23 and A-24, respectively.

A.11.3.2 Hydrogen Peroxide

EPA (7) has reported design criteria for a full-scale ozone/hydrogen peroxide plant treating a ground water contaminated with TCE and PCE. The design parameters for this system are presented in Table A-8. One economic advantage of oxidation over the use of packed tower stripping for this ground water was the absence of off-gas controls because the contaminants were oxidized, not merely stripped from the water phase. Another process for generating hydroxyl radical is the catalyzed decomposition of hydrogen peroxide by iron (II), known as Fenton's reagent. The optimal pH range for the reaction is 3 to 5 (9).

Table A-8. Design Parameters for Hydrogen Peroxide-Ozone Treatment Plant (7)

Parameter	**Value**
Plant flow (gal/min)	2,000
TCE concentration (µg/L)	200
PCE concentration (µg/L)	20
Reaction tank capacity (gal)	6,000
Hydraulic detention time (min)	3
Reaction tank stages (number)	1
Ozone dosage (mg/L)	4
Ozone generator capacity (lb/day)	100
Peroxide dosage (mg/L)	2
Peroxide storage (gal at 50-percent concentration)	1,000

A.11.3.3 Chlorine

Chlorination is widely used in waste treatment for disinfection. Aqueous chlorine owes its oxidizing power to two chemical species: the hypochlorite ion (OCl^-) and hypochlorous acid (HOCl). Chlorine can oxidize both inorganic and organic substances.

The destruction of cyanide can be accomplished by alkaline chlorination. In this process, cyanide is oxidized rapidly by hypochlorite (either as sodium hypochlorite or produced by the reaction of chlorine with sodium hydroxide) to cyanate at pH greater than 10 (1). Further oxidation of cyanate by hypochlorite or chlorine results in the formation of CO_2 and N_2. The recommended pH for this second stage is 8.5. The reaction is complete within 1 hour (1).

The use of chlorine for oxidizing organic compounds can result in the formation of toxic chlorinated byproducts, such as trihalomethanes. Thus, the use of alternative oxidants such as ozone, hydrogen peroxide, and chlorine dioxide may be preferred.

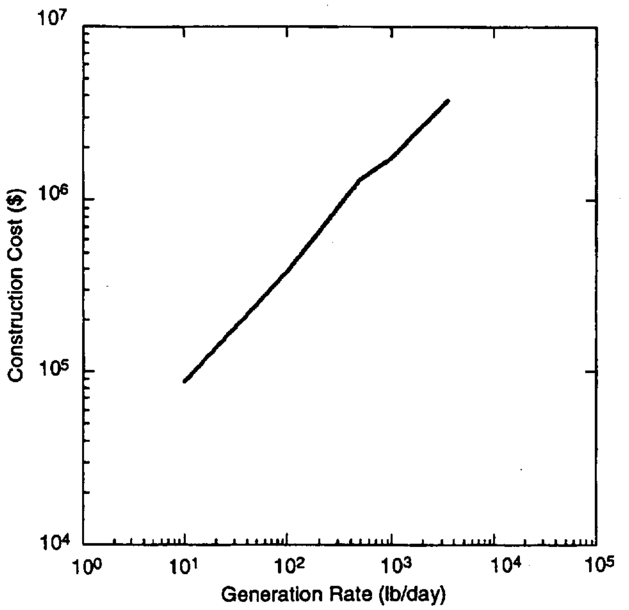

Figure A-23. Construction cost curve for ozone generation systems, updated to 1992 dollars (8).

A.11.4 References

1. Patterson, J.W. 1985. Industrial wastewater treatment technology. Boston, MA: Butterworth Publishers.

2. Weber, W.J., Jr., and E.H. Smith. 1986. Removing dissolved organic contaminants from water. ES&T 20:970-979.

3. Bowers, A.R., F.H. Cho, and A. Singh. 1992. Chemical oxidation of aromatic compounds: Comparison of H_2O_2, $KMnO_4$, and O_3 for toxicity reduction and improvements in biodegradability. In: Eckenfelder, W.W., A.R. Bowers, and J.A. Roth, eds. Chemical oxidation. Lancaster, PA: Technomic Publishing Co. pp. 11-25.

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5. Ferguson, D.W., J.T. Gramith, and M.J. McGuire. 1991. Applying ozone for organics control and disinfection: A utility perspective. JAWWA 83:32-39.

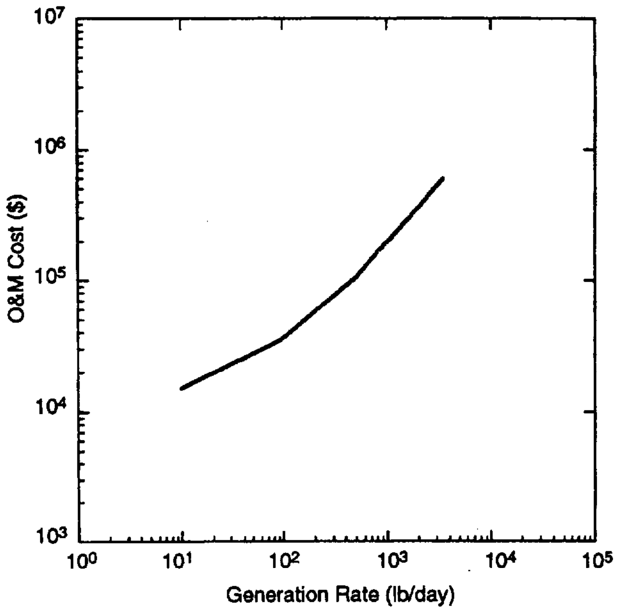

Figure A-24. O&M cost curve for ozone generation systems, updated to 1992 dollars (8).

6. Goodrich, J.A., B.W. Lykins, Jr., R.M. Clark, and E. Timothy Oppelt. 1991. Is remedial ground water meeting SWDA requirements? JAWWA 83:55-62.

7. U.S. EPA, 1990. Technologies for upgrading existing or designing new drinking water treatment facilities. EPA/625/4-89/023. Cincinnati, OH.

8. U.S. EPA. 1978. Estimating costs for water treatment as a function of size and treatment plant efficiency. EPA/600/2-78/182. Cincinnati, OH.

9. Robinson, S.F., and R.M. Monsen. 1992. Hydrogen peroxide and environmental immediate response. In: Eckenfelder, W.W., A.R. Bowers, and J.A. Roth, eds. Chemical oxidation. Lancaster, PA: Technomic Publishing Co. pp. 51-67.

4.11.5 Additional Source

1. Eckenfelder, W.W., Jr. 1989. Industrial water pollution control. New York, NY: McGraw-Hill.

A.12 Chemically Assisted Clarification (Polymer Only)

A.12.1 Technology Description

Polyelectrolytes (polymers) are low or high molecular weight organic compounds that are added to water as a flocculant/coagulant solution to enhance the gravity settling of colloids and suspended solids. Polymers are available as anionic, cationic, and nonionic types in liquid and dry powder form. The effectiveness of polyelectrolytes in water treatment can be quite variable. Polymers are effective in flocculating suspensions of inorganic materials (clays, soil, colloids, metal salts, etc.); however, they are usually not effective alone for flocculating organic suspensions. Rather, they can be used to improve the performance of alum or ferric salts in treating organic suspensions. Dry polymers cost less to ship, but liquid polymers are easier to mix with water. Polymer solutions are viscous and sticky. Special mixing techniques and equipment are necessary to prepare polymer solutions in the field.

Package polymer mixing systems are available with mixers, tanks, dry polymer hoppers, dry feeders, and controls to automatically mix dry polymer with water. Other automatic package systems continuously mix liquid polymer with water in static mixers. The solution is stored in a day tank for use until another batch is required. All polymer systems require a wetting mechanism, batch mix tank, mixer, holding tank, and metering pump. A typical polymer mixing system diagram is presented in Figure A-25. Electrical power and clean water supplies are necessary for polymer solution preparation.

A.12.2 Application

Polymers are used with chemical precipitation and filtration treatment processes. Refer to Tables 4-3 to 4-22 for compounds that are removed by the above processes. Treatability studies should be performed to select the proper type and dosage of polymer, or, at a minimum, the manufacturer should be consulted for recommendations.

A.12.3 Pretreatment Requirements

The polymer manufacturer's instructions should be followed closely for best results. An accurate scale and graduated mix tank are required for proportioning polymer and water. The mixer should be of the low speed type to minimize shear while mixing. An eductor and pressurized water supply efficiently wet dry polymer before mixing. Dry polymer can also be added manually to water in a mix tank by slowly sprinkling the dry powder into the mixer vortex until all powder is dissolved. A separate feed tank is required only if the treatment process cannot be interrupted while polymer is mixing.

A.12.4 Parameters of Interest

The following parameters should be given consideration for a successful polymer application:

Type of polymer	Select anionic, cationic, or nonionic based on a treatability study or vendor recommendations.
Dose	Jar tests will show by visual comparison which dose is appropriate. Poor settling can occur if polymer is overdosed or underdosed.
Temperature	Some polymers mix well in cold water, others require warm water for dispersal. Never freeze polymer.

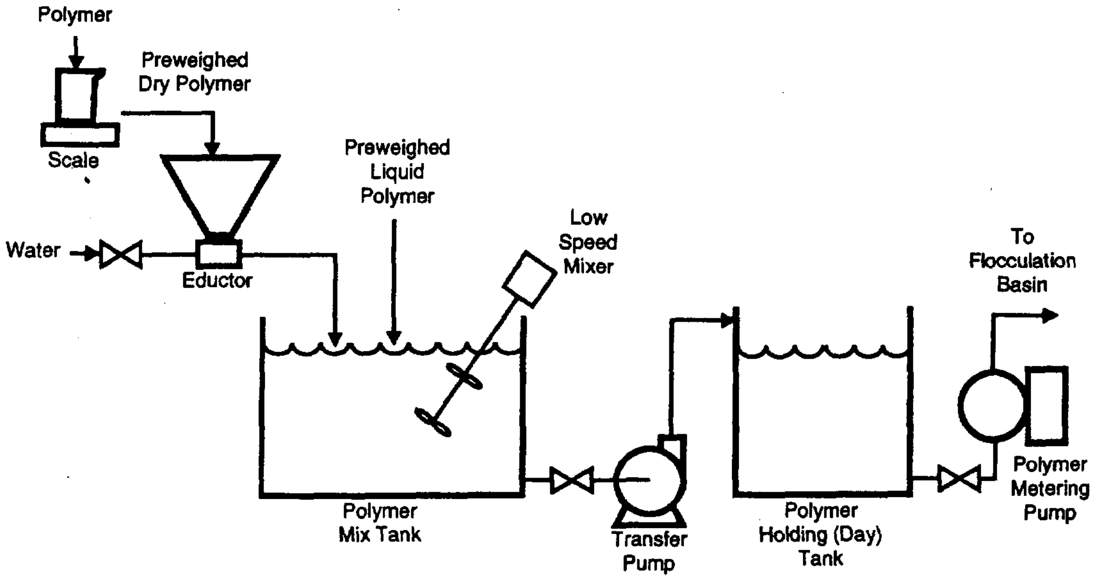

Figure A-25. Polymer mixing and feed system.

Feed concentration	Most polymers must be diluted to 0.1 to 0.5 percent at the injection point.
Time	Mixing time (dilution) and flocculation detention time are critical.
Mixing shear	Overmixing and high speed mixers should be avoided.

A.12.5 Design Considerations and Criteria

Polymer mixing and feed systems should be designed in accordance with the following considerations and criteria (1-4):

Materials of construction	Use stainless steel or fiberglass. Avoid rubber. PVC pipe is suitable.
Storage volume	Mix batches that will be used in 2 to 3 days. Solution shelf life is limited. Storage tank should be 1.5 times mix tank volume.
Stock mixer selection	Low speed mixers are best. Power must be sufficient to prevent motor overload. Vendors can select the most efficient mixer for each application. Provide tank size, power available, type and concentration of polymer, mixing time requirement.
Stock concentration	Dilute with water to 1 to 2 percent for storage. Dilute to 0.1 to 0.5 percent in the pipelines or in a tank before injection.
Stock mix time	Mix for 15 to 30 minutes per manufacturer's instructions. Let solution stand quietly 30 to 60 minutes until all polymer is dissolved.
Water	Clean, under 50 psi pressure desirable. Plentiful supply.

Polyelectrolyte addition

Dosage	For dilute suspensions (say <100 mg/L suspended solids), try 1 to 10 mg/L cationic polymer or 0.5 to 5 mg/L anionic or nonionic polymer. For concentrated suspensions (>1,000 mg/L), try 1 to 300 mg/L cationic polymer or 1 to 100 mg/L anionic or nonionic polymer.
Addition sequence	Slowly add polymers in dilute solutions (usually 0.1 to 0.5 percent) to the water while vigorously agitating for 1 to 2 minutes to ensure dispersal.
Flocculation	Only enough agitation should be applied to keep the developing floc from settling. Flocculate about 5 to 10 minutes. If more flocculation time is needed, try using a higher polymer dosage.
Settling	Polyelectrolytes produce a floc that settles rapidly, usually 0.5 to 1.0 ft/min or more. If the settling rate is less than 0.5 ft/min, increase the polymer dosage. Minimum settling tank detention time should be 4 minutes per foot of depth.
Safety	Eye protection required. See MSDS. Spillage causes slippery floors, falls. Rinse thoroughly, provide nonslip surfaces

A.12.6 Treatment Ranges

Polymer is used with chemical precipitation and filtration. Refer to Tables 4-3 to 4-22 for a range of chemicals removed and the removal efficiencies for those two processes.

A.12.7 Major Cost Elements

Major cost elements for polymer mix systems are the tanks, mixers, and pumps. Typical cost ranges are listed below (5):

Nominal Flow Rate				
Gal/Min	**Million Gal/Day**	**Capital Cost**[a]	**Annual O&M Cost**[b]	**Cost per 1,000 Gal**
10	0.014	$8,000	$4,400	$0.85
50	0.072	$9,000	$6,400	$0.25
100	0.144	$10,000	$8,900	$0.20
300	0.432	$16,000	$19,700	$0.15

[a] Cost is based on catalog prices for mixers, tanks, metering pumps, transfer pumps, and estimated assembly cost for each size.

[b] Based on 1 hour operator attention per 3 days, $2/pound polymer cost, $10/hour operator, 5 mg/L dose, $0.08/kWh, 360 days/year, 24 hours/day operation.

A.12.9 Residuals Generated

The only residual from polymer use is the empty shipping container. The smallest commercial package is 25 lb; therefore, one empty container is generated for every 25 lb of polymer used unless larger shipping containers are ordered. Spillage and tank leftovers can be drained to a sewer.

A.12.10 References

1. Allied Colloids, Inc. Polymer for water pollution control. Product Bulletins. Suffolk, VA.
2. American Petroleum Institute. The chemistry and chemicals of coagulation and flocculation. Committee on Refinery and Environmental Control.
3. Stockhausen, Inc. Clean Water Clean Environment Product Bulletins. Greensboro, NC.
4. U.S. EPA. 1979. Chemical aids manual for wastewater treatment facilities. EPA/430/9-79/018.
5. McMaster-Carr Catalog No. 100. P.O. Box 4355, Chicago, IL 60680.

A.13 Filtration

A.13.1 Technology Description

The filtration process consists of a fixed or moving bed of media that traps and removes suspended solids from water passing through the media. Monomedia filters usually contain sand, while multimedia filters include sand, anthracite, and possibly garnet. In multimedia filters, a layer of granular anthracite (coal) is provided above the sand to trap large particles that would quickly blind the sand media. This results in extended runs between backwash cycles. Garnet sand is very fine and is commonly used as a final polishing media when extremely low turbidity effluent is required. The garnet rests on the support media below the sand layer.

Two types of fixed bed filters are available. Pressure filters contain media in an enclosed, watertight pressure vessel and require a feed pump to force the water through the media. A gravity filter operates on the basis of differential pressure of a static head of water above the media, which causes flow through the filter.

All fixed media filters have influent and effluent distribution systems consisting of pipes and fittings. Strainers in the tank bottom are usually stainless steel screens. Layers of uniformly sized gravel also serve as bottom strainers and as a support for the sand. For both types of filters, the bed builds up headloss over time. When the headloss becomes unacceptable, the filter needs to be backwashed. Troughs are provided above the filter media to collect filtered particles during backwashing. Filters are backwashed by reversing the flow of water (upward) from below the media. Sometimes air is dispersed into the sand bed to scour the media.

Fixed bed filters (see Figure A-26) can be automatically backwashed when the differential pressure exceeds a preset limit or when a timer starts the backwash cycle. Powered valves and a backwash pump are activated and controlled by adjustable cam timers or electronic programmable logic controllers to perform the backwash function. A supply of clean backwash water is required. Backwash water and trapped particles are commonly discharged to an equalization tank upstream of the water treatment system's primary clarifier or screen for removal. Backwash water may also be discharged to a sanitary sewer if discharge criteria are met.

Moving bed filters (shown in Figure A-27) use an air lift pump and draft tube to recirculate sand from the filter bottom to the top of the filter vessel, which is usually open at the top. Dirty water entering the filter at the bottom must travel upward, countercurrently, through the downward-moving fluidized sand bed. Particles are strained from the rising water and carried downward with the sand. Due to the difference in specific gravity, the lighter particles are removed from the filter when the sand is recycled through a separation box at the top of the filter or in a remote location. The heavier sand falls back into the filter, while the lighter particles flow over a weir to waste. Moving bed filters are continuously backwashed and have a constant rate of effluent flow.

For waters having less than 10 mg/L suspended solids, cartridge filters may be cost effective. Cartridge filters have very low capital cost and can remove particles of 1 μm or larger size. Using two-stage cartridge filters (coarse and fine) in series extends the life of the fine cartridge. Disposable or backwashable bag filters are also available and may be quite cost effective for certain applications. For applications with high concentrations of suspended solids or a long duration, reusable filter media should be investigated.

A.13.2 Applications

Filters are used to remove suspended solids from the effluent upstream of processes such as secondary clarifiers of biological systems or gravity separators of physical/chemical treatment systems. Examples of compounds that can be removed by filtration are listed in Tables 4-3 to 4-22. Generally, only those compounds that are associated with suspended solids or colloids are removed by filtration; dissolved compounds are not removed.

A.13.3 Pretreatment Requirements

Dissolved compounds should be pretreated by biological or chemical precipitation processes to convert the compound to a solid particle before filtration. Metal precipitates form at elevated pH; therefore, filters may contain water of high pH that has been treated with lime (CaO) or caustic soda (NaOH). Polymers may have to be injected into the filter feed piping downstream of feed pumps to enhance flocculation of "pin flocs" that may escape an upstream clarifier. Pretreatment for iron and calcium may be required to prevent fouling and scaling.

A.13.4 Parameters of Interest

The following parameters apply to filtration:

- Suspended solids concentration: 20 to 200 mg/L typical.
- Particle size, distribution: 10 to 30 μm typical.
- Particle characteristics: variable, from hard granular to gelatinous possible.
- Pretreatment: high or low pH, temperature, corrosiveness, fouling, scaling tendency.
- Flow rate: consider transportable diameter, number of units required.
- Type of feed water: oily, metal precipitate, biological, algae, mill scale, etc.

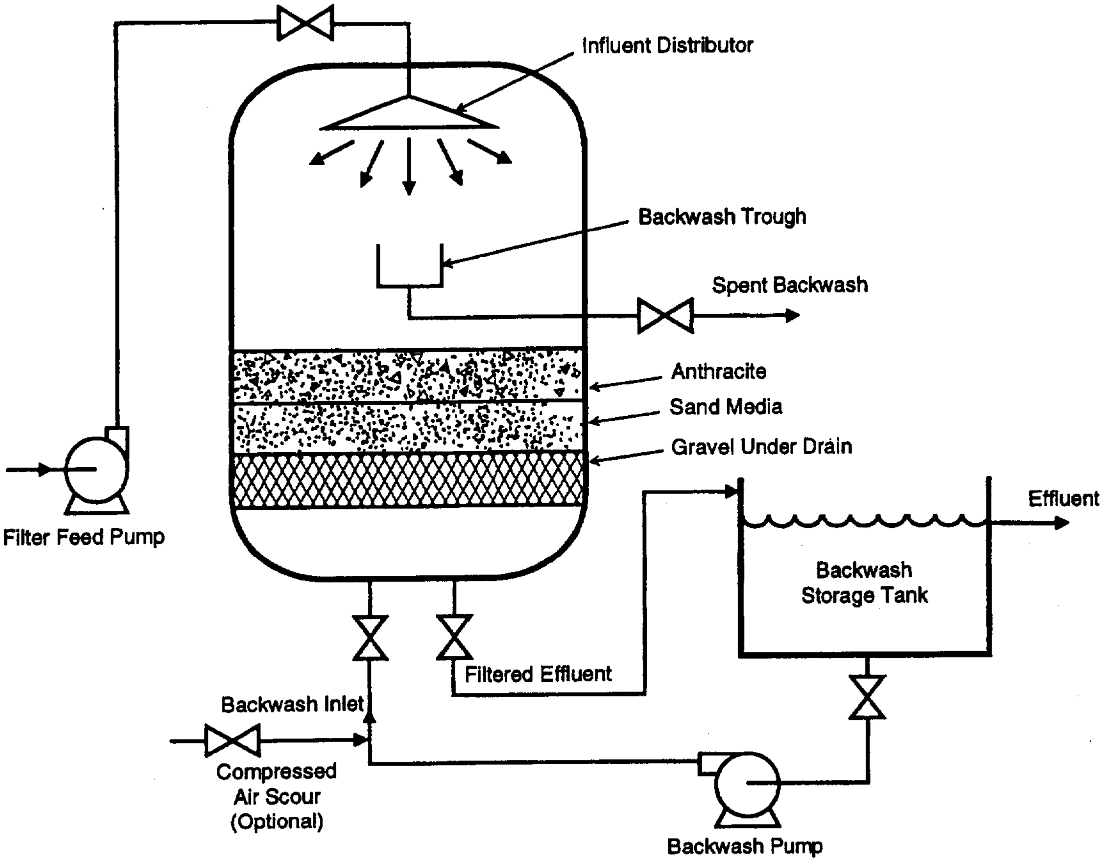

Figure A-26. Fixed bed filter.

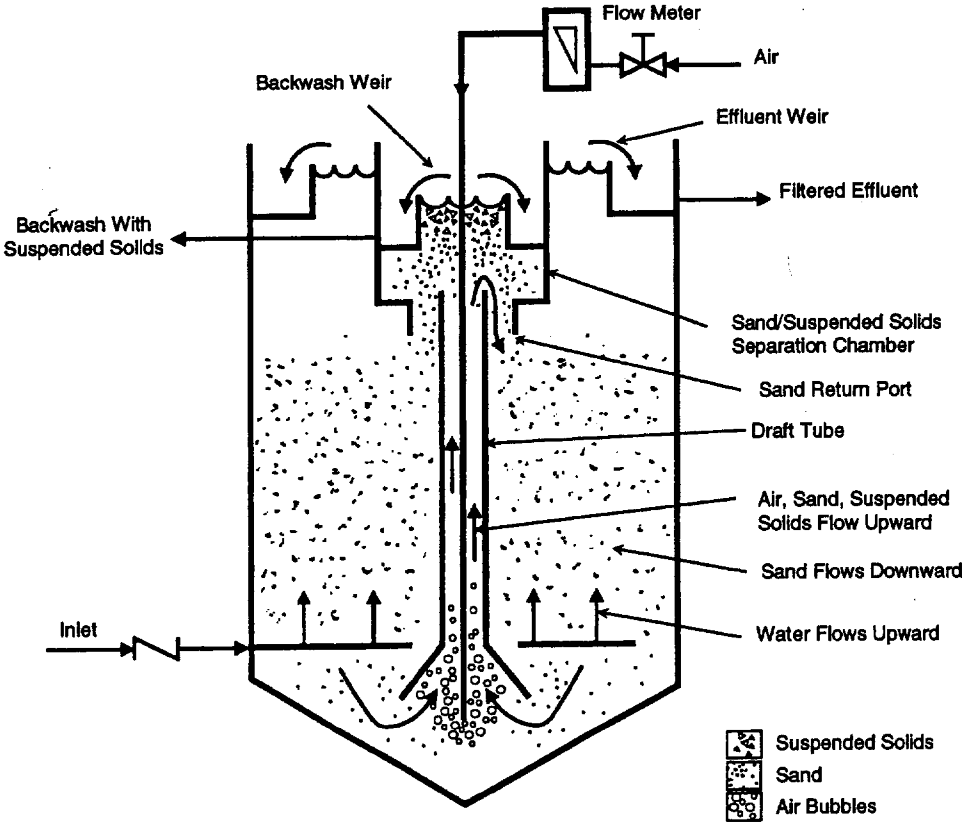

Figure A-27. Moving bed filter.

The above information is necessary to determine the hydraulic loading rate, type of filter, type of media, materials of construction, and need for air scour.

A.13.5 *Design Considerations and Criteria*

The following design information serves as a guide for evaluation and preliminary filtration design (1, 2):

Hydraulic loading rate	2 to 10 gal/min/ft^2 range; 4 to 6 gal/min/ft^2 typical.
Transportable size	Limit diameter to 8 ft.
Backwash requirement (fixed bed)	—Use multiple filters for continuous flow unless interruptable flow is acceptable. —Backwash at 10 to 15 gal/min/ft^2. —Provide effluent storage for 10 min at 15 gal/min/ft^2. —Allow equalization tank size or disposal capacity for backwash at 8- to 36-hour intervals. —Air scour, 5 ft^2/min/ft^2. —Backwash flow 2 to 5 percent of feed water typical. —Air requirement, 0.05 to 0.15 ft^2/min/ft^2.
Power	See Table 3-4 for typical power required. Add extra power for air compressors; gravity filters and moving bed filters need less power for feed pump.
Bed depth	Sand, 1 to 2 ft; anthracite, 1 to 2 ft; garnet, 4 to 6 in. Allow 25 to 50 percent for bed expansion.
Filter height	8 to 16 ft; allow for handrails and access above filter vessel. For large flows, pressure filters with horizontally mounted cylindrical tanks are common.
Pressure loss	Moving bed, 1 to 2 ft; gravity filter, 2 to 10 ft; pressure filter, 5 to 40 psi; cartridge filter, 5 to 50 psi.

A.13.6 *Treatment Ranges*

The removal efficiency of filters depends on particulate size, characteristics, loading rate, and media. Effluent quality deteriorates at high loading rates and long runs. See Tables 4-3 to 4-22 for removal efficiencies of filters for selected compounds.

A.13.7 *Major Cost Elements*

Estimated costs for filtration systems of various sizes are as follows:

Nominal Flow Rate

Gal/Min	Million Gal/Day	Capital Cost[a]	Annual O&M Cost[b]	Cost per 1,000 Gal
10	0.014	$5,000	$4,300	$0.85
50	0.072	$13,000	$7,300	$0.30
100	0.144	$20,000	$10,400	$0.20
300	0.432	$39,000	$21,200	$0.15

[a] Price based on completely assembled dual vessel, prewired, prepiped, skid-mounted system. Site work not included.

[b] Based on ½-hour operator per day at $10/hour, 5 percent of capital cost for maintenance, $0.08/kWh, capital recovery of 8 percent for 5-year life, and 360 days of operation annually.

A.13.8 *Residuals Generated*

Residuals consist of backwash waste with suspended solids:

Volume of backwash	2 to 5 percent for fixed bed filter; 4 to 8 percent for moving bed filter.
Cartridge filters	Spent cartridges.
Suspended solids	Calculate from removal efficiency.

A.13.9 *References*

1. U.S. EPA. 1975. Process design manual for suspended solids removal. Technology Transfer. EPA/625/1-75/003a.
2. U.S. EPA. 1974. Wastewater filtration: Design considerations. Technology Transfer. July.

A.14 Ultraviolet Radiation

A.14.1 Technology Description

Ultraviolet (UV) radiation technology can be used for oxidizing organic contaminants. Peroxide is sometimes used with UV radiation to catalyze the photolytic decomposition reaction. In this case, a reactive hydroxyl radical (OH°) is cleaved from the hydrogen peroxide molecule. The hydroxyl radical is highly reactive and facilitates oxidation. Ozone may also be used with UV.

Alkalinity is a key parameter in oxidation processes. Carbonate and, to a lesser extent, bicarbonate ions are excellent scavengers for free radicals (1, 2). Consequently, influent pH control may be necessary to shift the carbonate equilibrium toward carbonic acid (1, 3).

This system has four major components: the reactor module, the air compressor/ozone generator module, the hydrogen peroxide feed system, and the ozone decomposer unit (4). Each system requires that pretreatment steps be employed to maximize treatment efficiency.

Each major UV treatment application, i.e., UV/hydrogen peroxide, UV/ozone, and UV/hydrogen peroxide/ozone is described below.

A.14.2 Applications

A.14.2.1 UV/Hydrogen Peroxide/Ozone

UV/hydrogen peroxide technology has been used to treat landfill leachate, ground water, and industrial wastewater, all containing a variety of organic contaminants (3). The UV/hydrogen peroxide/ozone system was also reported effective for volatile organic compound oxidation, achieving removals of better than 90 percent.

A.14.2.2 UV/Hydrogen Peroxide

An evaluation of 70 full-scale UV/hydrogen peroxide systems revealed that 30 percent were treating wastewaters with organic concentrations between 10 ppm and about 10,000 ppm, and 70 percent were being used to treat ground water (5). These systems have the following components: a chemical oxidation unit, a hydrogen peroxide feed module, a UV lamp drive, and a control panel (3). This system is shown in Figure A-28. The UV/hydrogen peroxide system has been paired with carbon adsorption, air stripping, or biological treatment, depending on water quality and treatment objectives (3, 5).

The contaminated water is dosed with hydrogen peroxide before it enters the reactor. A splitter can be used, however, to add hydrogen peroxide before any of the six reactors within the oxidation unit. Acid may be added to lower the pH. Water then flows through the six UV reactors, which are separated by baffles to direct water flow. Each UV reactor contains one high-intensity, medium-pressure UV lamp mounted inside a quartz tube. The lamp and tube assembly are positioned perpendicular to the side walls of the chamber. The combined UV lamp power intensity for reactors ranges from 10 to 720 kW. Effluent pH adjustment, with sodium hydroxide, for instance, may be required to meet the permitted pH discharge criteria.

A.14.2.3 UV/Ozone

EPA (1) reported a typical contact time of 15 minutes for UV/ozone oxidation systems. The use of ozone is described in the technology summary on chemical oxidation.

A.14.3 Pretreatment Requirements

UV radiation works best when interferences, such as suspended solids or iron, are absent from the water to be treated. Typical pretreatment steps may include the following unit operations:

- Equalization, storage, recirculation to adjust for variable flow.
- Separate immiscible liquid (LNAPL, DNAPL) by gravity separation or flotation.
- Remove suspended solids by sedimentation and/or filtration.
- Remove iron by oxidation and precipitation (iron can interfere with UV transmission).
- Remove as much of other nontarget dissolved species as possible. Other oxidizable substances, such as naturally present humic material, have an associated demand that competes with contaminant degradation.
- With hydrogen peroxide, adjust solution pH to between 4 and 6 if the influent carbonate plus bicarbonate concentration is greater than about 400 mg/L as equivalent calcium carbonate. (Low and high pH rapidly decrease destruction efficiencies.)
- Disposal of total suspended solids, chemically precipitated sludges, and LNAPL or DNAPL.

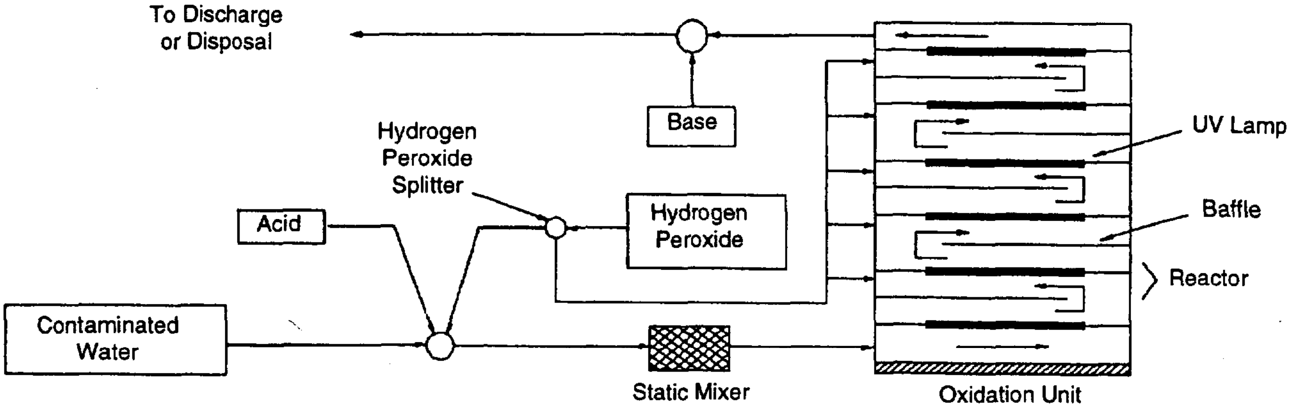

Figure A-28. perox-pure UV oxidation treatment system (6).

A.14.4 Design Considerations

The UV reactor varies from 300 gal to 3,900 gal (7). Ozone generators range from 10 to hundreds of pounds per day. Hydrogen peroxide is either used in place of or in combination with ozone. The optimal proportion of oxidants for maximum removals, however, cannot be predetermined, although the stoichiometry for hydroxyl radical formation is predictable (4). Pilot-scale or treatability tests, therefore, still need to be undertaken.

The performance of the Ultrox system is influenced by waste characteristics, operating parameters (e.g., hydraulic retention time, ozone and hydrogen peroxide dose, UV lamp intensity, influent pH level, and gas-to-liquid flow rate ratio), and maintenance requirements.

An alternative chemical oxidation system typically consists of a chemical oxidation unit (reactor chamber), a hydrogen peroxide feed module, a UV lamp drive, and a control panel unit. Systems capable of treating flow rates varying from 5 gal/min to thousands of gallons per minute have been built (3).

The principal operating parameters are hydrogen peroxide dose, influent pH, and flow rate. Although initial values of these parameters can be estimated, treatability studies are necessary to accurately establish their design values.

A.14.5 Major Cost Elements

Figures A-29 and A-30 present estimated capital and O&M costs associated with the UV/hydrogen peroxide/ozone system. Figures A-31 and A-32 present estimated capital costs and O&M costs for the UV/hydrogen peroxide system.

A.14.6 Residuals Generated

UV/oxidation is claimed to be able to destroy organic chemicals without creating a waste product. Oxidation products include carbon dioxide, water, various salts, or harmless organic acids. If the reactor off-gas contains volatile compounds along with unreacted ozone, a catalytic system can be employed to convert the organics to mainly carbon dioxide, water, and salts (7).

A.14.7 References

1. U.S. EPA. 1990. Technologies for upgrading existing or designing new drinking water treatment facilities. EPA/625/4-89/023. Cincinnati, OH.
2. Glaze, W.H., J.-W. Kang, and D.H. Chapin. 1987. The chemistry of water treatment processes involving ozone, hydrogen peroxide, and ultraviolet radiation. Ozone Sci. Engin. 9:335-352.
3. U.S. EPA. 1993. perox-pure chemical oxidation technology. Applications analysis report. EPA/540/AR-93/501. Washington, DC.
4. U.S. EPA. 1990. Ultrox international ultraviolet radiation/oxidation technology: Applications analysis report. EPA/540/A5-89/012. Cincinnati, OH.
5. Froelich, E.M. 1992. Advanced chemical oxidation of organics using the perox-pure oxidation system. Wat. Poll. Res. J. Canada 27:169-183.
6. U.S. EPA. 1993. perox-pure chemical oxidation treatment. EPA/540/MR-93/501. Washington, DC.
7. Ultrox. 1993. The Ultrox UV/oxidation process: On-site destruction of organics in water. Santa Ana, CA: Zimpro Environmental.
8. Schmidt, J.M. 1993. Pump and treat ground water. In: NATO/CCMS. Demonstration of remedial action technologies for contaminated land and ground water. Final Report. EPA/600/R-930/012c. pp. 65-75.

A.14.8 Additional Source

1. Kearney, P.C., M.T. Muldoon, and C.J. Somich. 1987. UV/ozonation of eleven major pesticides as a waste disposal pretreatment. Chemosphere 16:2,321-2,330.

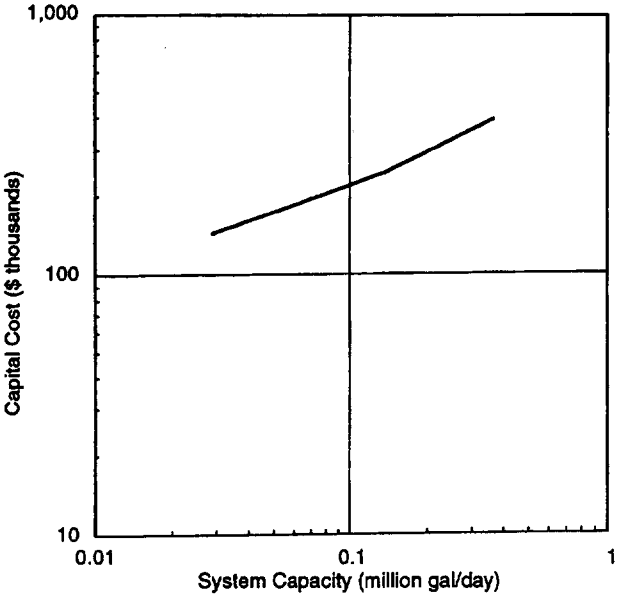

Figure A-29. Capital cost curve for UV/hydrogen peroxide/ozone technology, in 1990 dollars (8).

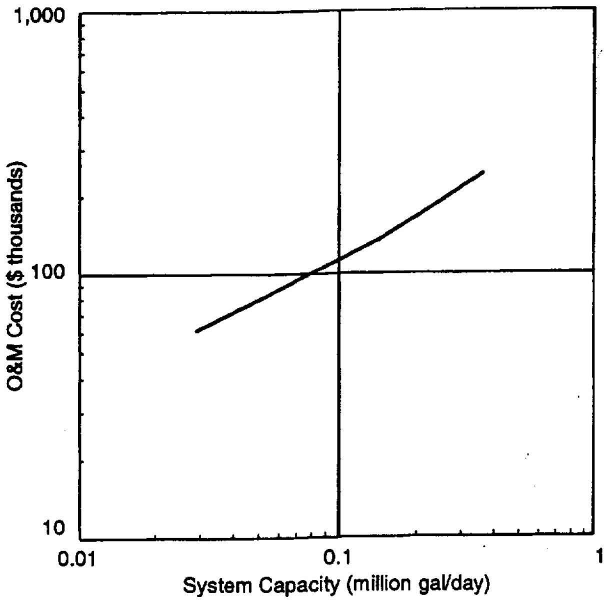

Figure A-30. O&M cost curve for UV/hydrogen peroxide/ozone technology, in 1990 dollars (8).

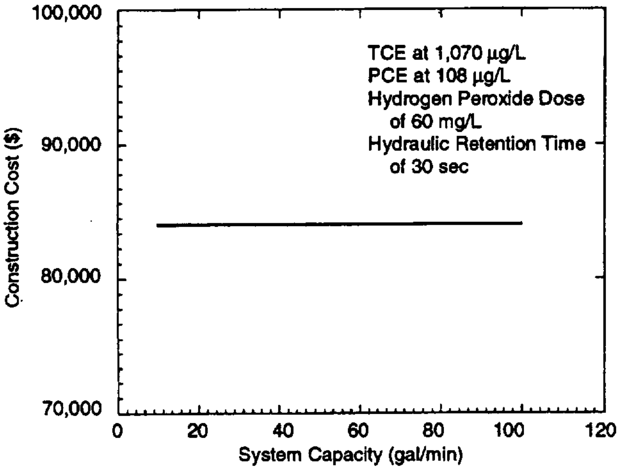

Figure A-31. Construction cost curve for perox-pure technology, in 1993 dollars (3).

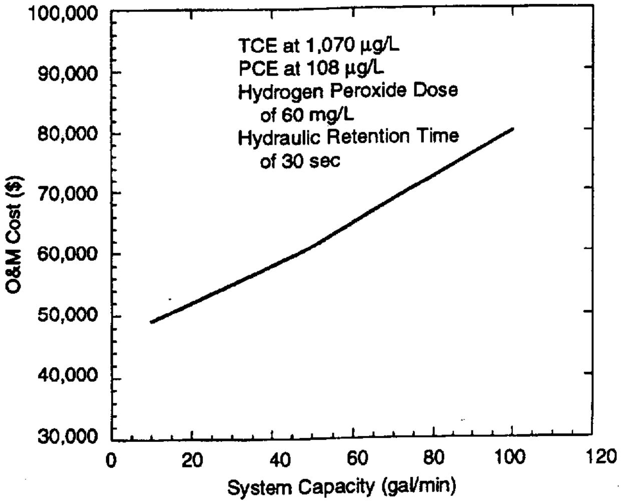

Figure A-32. O&M cost curve for perox-pure technology, in 1993 dollars (3).

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