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An Investigation Conducted by:
Raymond W. Regan
State College, PA 16801

TREATMENT OF NAVY LANDFILL LEACHATE CONTAMINATED WITH LOW LEVELS OF PRIORITY POLLUTANTS

ABSTRACT The goal was to assist NCEL in identifying available technical information concerning the remediation of landfill leachate and contaminated groundwater at selected Naval facilities. A conventional treatment train (air stripping, ion exhange, and carbon adsorption) was used to illustrate the treatment potential for a diluted leachate at Naval Weapons Station, Seal Beach. The treatment removed specified organics to below 29 ppb and specified metals to below California's drinking water standards. Available costs for conventional and innovative treatment trains were considered.

NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME CALIFORNIA 93043

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

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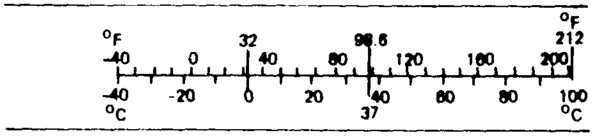
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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Chloe Jue
Raymond W. Regan, Sr.

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Dr. Raymond W. Regan
913 South Sparks Street
State College, PA 16801

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The goal was to assist NCEL in identifying available technical information concerning the remediation of landfill leachate and contaminated groundwater at selected Naval facilities. A conventional treatment train (air stripping, ion exhange, and carbon adsorption) was used to illustrate the treatment potential for a diluted leachate at Naval Weapons Station, Seal Beach. The treatment removed specified organics to below 29 ppb and specified metals to below California's drinking water standards. Available costs for conventional and innovative treatment trains were considered.

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Table of Contents

List of Tables

List of Figures

Figure

Capsular Summary

The goal of this project was to assist the Naval Civil Engineering Lab (NCEL) in identifying available information concerning the remediation of landfill leachate and contaminated groundwater at selected Naval facilities.

The results of chemical analyses obtained from contaminated water and soil at seven Navy facilities were obtained from the respective Engineering Field Divisions (EFD).

From the data gathered and grouped, individual unit processes were investigated. A process description, applicable predictive equations, and the advantages and disadvantages were given for each unit process. Treatment trains which were used for other related sites were identified. Combining the predictive equations described in the unit process section and the unit processes used in the selected treatment trains, an attempt was made to predict the treatability of a contaminated water source.

An example treatment train was selected for potential treatment of a dilute leachate at the Navy site: Seal Beach. This site was selected because the contaminants in the diluted leachate were judged to be similar to sources reported in the literature successfully found to be renovated by the treatment train (conventional approach) indicated. The treatment train used included the following unit operations, (1) air stripping, (2) ion exchange and (3) carbon adsorption.

Major targeted contaminants subjected to treatment were acetone, hexachlorobenzene, phenanthrene pyrene, silver, chromium, mercury, nickel and zinc. Contaminants in the treated effluent ranged from 0.6 to 28.5 ppb for organics and 0.1 to 400 ppb for metals. Metallic contaminants were projected to be removed to levels well below the California drinking water standards for silver, chromium, mercury and zinc. Based on 1986 dollars, the costs for operating this treatment train were $308,000 for capital and $144,000 annually for operating and maintenance, exclusive of operator labor.

The use of land treatment and a constructed wetland as innovative treatment approaches were considered in a preliminary fashion in the report. Information applicable to the Navy landfill remediation efforts was not found in the literature. However, these approaches represent emerging research areas that may provide technical improvements and cost savings to the Navy in the future.

The technical assistance and guidance provided by Theresa Smith-Rawecki and Nicholas Olah (NCEL) and Kitty Collins (Battelle, Triangle Park Office) is acknowledged.

I. INTRODUCTION

A. Problem Statement

Environmental regulations [including SARA and RCRA] require the Navy remediate groundwater which is contaminated from Navy sources. Landfills used for the disposal of solid wastes generated from personnel and industrial activities on selected bases have been identified as specific sources of concern. Due to the limitations of design and operation practices in the past, and the evolution of increasingly stringent Federal and State environmental regulations, leachates generated by these landfills may contain specific contaminants, known as priority pollutants, that are regulated for potential public health considerations. The goal of the project was to provide information to select unit operations suitable for treating both the leachate and contaminated groundwater at specific Navy landfills to meet appropriate regulatory standards.

B. Objectives

The general objectives were to investigate individual unit processes and to select series of unit processes (treatment trains) that met regulatory clean-up levels and were technically and economically feasible. The specific tasks were:

- to provide a literature search for technologies for the treatment of landfill leachate (and contaminated groundwater) as applicable to Navy landfills (and similar Department of Defense (DOD) facilities):
- to provide a review and assessment of applicable predictive equations for the treatment conditions reported in the literature. The assessment was based upon three main criteria:
  - achievement of the specified level of decontamination,
  - applicable as an in-situ or in-place treatment,
  - suitability for monitoring the degree of decontamination; and
- to recommend treatment train(s) or approach(es) based on the characteristics and concentration of contaminants present, as indicated by the chemical reports available from the Naval facilities along with an illustrated calculation(s) for the anticipated results.

C. Rationale

To meet the stated objectives several unusual features of Navy landfills were considered. Navy landfills may differ from other DOD and municipal landfills due to their location and age. First of all, since many Navy bases are located in low-lying coastal areas the effect of elevated salinity levels in the groundwater (due to salt water intrusion) on the treatability of the aqueous discharges from a landfill may be a consideration. Also, many of the Navy landfills studied in this document have been inactive for at least ten years. Assuming that the facilities have been actively leaching for an extended period of time, leachate contamination concentrations would have decreased in general over time and would contain lesser amounts of biodegradable materials due to in-situ physical, chemical and biological reactions in and below the landfill. Therefore, the treatability of the Navy's landfill may be significantly effected by these factors.

II. BACKGROUND

A. General

The Naval Facilities Engineering Command and Naval Energy and Environmental Support Activity have been conducting Remedial Investigations/Feasibility Studies (RI/FS) at Naval activities since the early 1980s. Naval activities have several industrial activities, therefore, there may be several RI/FS sites at each base, including sites that are either old or closed landfills.

Seven Navy activities were studied: Marine Corps Air Station, Cherry Point; Naval Air Station, Moffett Field; Naval Base, Norfolk; Naval Shipyard, Norfolk; Pacific Missile Testing Center, Point Mugu; Naval Construction Battalion Center, Port Hueneme; and Naval Weapons Station, Seal Beach. (Table II-1)

The available laboratory analyses which is used in this document were summarized in Appendix A. The laboratory analyses from the bases were gathered from the respective Engineering Field Division (EFD).

Because the landfills were unlined, there is the strong possibility that the leachate has migrated into the groundwater. The data therefore are taken mainly from groundwater analyses. Available information from potable water, surface water, soil and leachate were also included.

These analyses primarily characterize the samples in terms of the priority pollutants present. Other more traditional measurements of water quality, as would be expected from landfill operations, were reported less completely. These information gaps may contribute to some uncertainty in the treatability of the water present at the Navy sites.

From the information gathered, the data were placed into priority pollutant groupings. Table II-2 identifies the ten groupings and lists the compounds included within each group, after those used by Chapman et al., (1982).

B. Literature Review

A large volume and variety of literature is available for the treatment of groundwater and leachate. Most of the processes described were adopted from wastewater and water treatment processes. However, the effectiveness for their use with dilute mixtures of priority pollutants and for achieving desired decontamination levels has not been generally reported.

Unit processes most likely to be applicable were well documented in the literature. To establish an improved basis for information, contacts were made with people that either had designed a groundwater treatment train or better yet had a treatment train in place. Most of the sites were only in the design stage, but many had conducted treatability studies. Table II-3 lists the point-of-contact (POC) for the respective sites. Section V summarizes the treatment trains used at these sites and key elements of the discussions the authors had with the respective POC.

Table II-1

STATUS OF INFORMATION COLLECTED FROM SEVERAL NAVY LANDFILLS

ACTIVITY	GW	PW	SW	SOIL	LEACH	EST YEARS OF OPERATION
MCAS Cherry Point						
Site 10	X	X	X	X	X	1955-early 1980's
NAS Moffett Field						
Site 1	X			X		1962-1975
Site 2	X			X		1947-1960's
NAVBASE Norfolk						
Site 1	X		X			early 1940's-1974
NAVSHIP Norfolk						
Site 2 (draft)	X		X	X		1950's
Site 3-7 (draft)	X		X	X		1950's-60's&70's
PMTC Point Mugu						
Site 1	X			X		1952-1975
NCBC Port Hueneme						
Site 14 (draft)				X		1950-1980's
NWS Seal Beach						
Site 7	X			X		1955-1973

Notes:
PW = Potable water analyses
GW = Groundwater analyses
SW = Surface water analyses
SOIL = Soil analyses
LEACH = Leachate analyses
DRAFT = Information is from a draft report

TABLE II-2

LISTING OF COMPOUNDS FOUND IN SEVEN NAVAL LANDFILLS (SOIL AND WATER)

GROUP COMPOUNDS

1. METALS AND INORGANICS

Antimony
Arsenic
Beryllium
Cadmium
Chromium
Copper
Cyanide
Lead
Mercury
Nickel
Selenium
Silver
Thallium
Zinc
Aluminum
Barium
Chlorides
Cobalt
Fluoride
Iron

2. PESTICIDES

DDD
DDE

3. PCB'S AND RELATED COMPOUNDS

Polychlorinated biphenyls
AROCLOR-1254
AROCLOR-1242
AROCLOR-1260

4. HALOGENATED ALIPHATICS

Chloromethane (Methyl Chloride)
Dichloromethane (Methylene Chloride)
Trichloromethane (Chloroform)
Chloroethane (Ethyl Chloride)
1, 1 - Dichloroethane (Ethylyidine Chloride)
1, 2 - Dichloroethane (Ethylene Dichloride)
1, 1, 1 - Trichloroethane (Methyl Chloroform)
Chloroethene (Vinylidine Chloride)
1, 2 - Trans-dichloroethene
Trichloroethene
Tetrachloroethene (Perchloroethylene)
1, 3 - Dichloropropene
Trichlorofluoromethane

5. ETHERS

Bis (2-chloroisopropyl, 1) ether
4-Bromophenyl Phenyl Ether

6. MONOCYCLIC AROMATICS

Benzene
Chlorobenzene
1, 2 - Dichlorobenzene (o-dichlorobenzene)
1, 3 - Dichlorobenzene (m-dichlorobenzene)
1, 4 - Dichlorobenzene (p-dichlorobenzene)
Hexachlorobenzene
Ethylbenzene
Toluene

7. PHENOLS AND CRESOLS
   - Phenol
   - 2, 4 - Dichlorophenol
   - 2-Chlorophenol
   - Pentachlorophenol

8. PHTHALATE ESTERS
   - Diethyl Phthalate
   - Di-n-octyl phthalate
   - Di-n-butyl-phthalate
   - Bis (2-ethylhexyl) phthalate

9. POLYCYCLIC AROMATICS
   - Acenaphthene
   - Benzo(a)pyrene
   - Benzo(a)fluoranthene
   - Fluorene
   - Naphthalene
   - Pyrene
   - Anthracene
   - Benzo(a)anthracene
   - Chrysene
   - Flouranthene
   - Phenanthrene

10. ANIONS
   - Bicarbonate
   - Nitrate
   - Carbonate
   - Sulfate
   - Chloride
   - Borate

CATIONS
- Calcium
- Sodium
- Potassium
- Magnesium

MISCELLANEOUS
- Acetone
- 2-Butanone
- 4-Chloroaniline
- Dibenzofuran
- 2-Methylphenol
- 4-Methyl-2-Pentanone
- Styrene
- Benzoic Acid
- Xylenes
- Carbon Disulfide
- 2-Methylnaphthalene
- 4-Methylphenol
- 4-Chloro-3-Methylphenol

TABLE II-3

POC for Landfills Contacted

Site	Point-of-Contact/ Phone Number
Sylvester Site Nashua, NH	Chet Janowski (617)573-9623
Heleva Landfill North Whitehall Township, PA	Richard Watman (215)597-3155
Sand, Gravel,& Stone Site Elkton, MD	Peter Ludzia (215)597-0910
Marshall Landfill Boulder, CO	Ann Vigil (303)293-1648
Lipari Landfill Mantua Township, NJ	Fred Cataneo (212)264-1913
Helen Kramer Landfill Mantua Township, NJ	Ramona Pez~ella (212)264-8216
Fresh Kills Landfill New York City	Phil Gleason (212)566-8264
Stringfellow Acid Pits Glen Avon, CA	EPA, Region IX Superfund Section San Francisco, CA
Constucted Wetlands Tennesse Valley Authority	Dr. Donald Hammer (615)632-6433

III. LEACHATE GENERATION AND CONTROL

A. Introduction

This section discusses leachate generation and control. Leachate is generated from landfilling operations. Because leachate may contaminate the groundwater, it is important to control it by decreasing the quantity generated and/or decreasing the toxicity of the contaminants.

The types of wastes disposed of in the landfill determine the characteristics of the leachate generated, therefore, landfill characteristics are different from each other. Navy activities usually have various types of industry on base, so Navy landfills have municipal solid waste and some industrial waste.

A number of the past Navy landfills are closed and are unlined. Unlined landfills are common for most older landfills, since proper solid waste management regulations were not in place yet. Unlined landfills have a tendency to have leachate leak from the landfills, migrate out of the region, and contaminate the groundwater. Thus both the leachate and groundwater needs to be treated.

Initially, leachate generation is controlled by reducing infiltration, then the leachate is treated. Methods of leachate control and/or treatment are to cap the landfill to reduce the amount of leachate generated; to build a slurry wall to prevent lateral movement of leachate; and/or to pump the groundwater contaminated with leachate and treat it with a unit process or a series of unit processes.

Leachate generation and control will be discussed in this section and leachate/groundwater treatment will be discussed in sections IV and V.

B. Water Balance

The amount of leachate generated from a landfill can be estimated by the Water Balance Method (EPA, 1979). Leachate production is expressed in inches per month or per year.

$$\text{Percolation} = P - R - AET - S \qquad \text{(eq. 1)}$$

where:
P = precipitation (inches)
R = runoff (inches)
AET = actual evapotranspiration (inches)
S = gain in moisture storage within the soil (in)

The precipitation percolates into the landfill while the remainder is lost to evapotranspiration, runoff, or storage within the soil or refuse. If the percolation exceeds the evapotranspiration for a sufficient period of time, then the field capacities of the soil and refuse will be exceeded. When this occurs the leachate is released at the bottom of the refuse layer unless the landfill is lined and has a leachate collection system.

As precipitation percolates through the landfill, the liquid picks up pollutants. Subsequently the leachate migrates out of the landfill and into the surrounding surface water, soil and groundwater. The mechanisms by which the contaminants are leached out of the landfill are summarized in Figure III-1.

Primary leaching is the dissolution of soluble salts or soluble organic material which exist in the landfill. The dissolved organic material, humic acid, will give the leachate a brownish color. The organic material in the fill has low solubility but the biodegradation of this material tends to produce more soluble end products like simple organic acids and alcohols. These products undergo further biochemical reactions to release gaseous end products, but some of the soluble organic material is leached out of the landfill. The nitrogen present in the original organic material is converted into ammonium ions, NH_4, which are readily soluble and may give rise to significant quantities of ammonia in the leachate.

The landfill quickly uses its oxygen and becomes anaerobic, thus becoming a chemically reducing environment. This environment induces oxidized ions, such as those in ferric salts to be reduced to ferrous form. Ferrous salts are more soluble and therefore iron leaches from the landfill. Suspended solids and turbidity may be present in the leachate due to the washout of fine solid material from the landfill.

Groundwater contamination occurs due to seepage or vertical movement of the leachate towards the groundwater. The rate of seepage from the bottom of the landfill can be estimated by Darcy's law which can be expressed as:

$$Q = -KA(dh/dl) \qquad \text{(eq. 2)}$$

where: Q = leachate discharge per unit time
K = coefficient of permeability
A = cross-sectional area through which the leachate flows
dh/dl = the hydraulic gradient

Three key points to remember about Darcy's Law are:

- Darcy's velocity is not the actual velocity of the water particles, but the overall velocity of the groundwater;
- the driving force for flow is the difference in total head at the two points;
- the distance over which the head difference is taken is along the streamline; the streamline between points 1 and 2 is not the actual path taken by the water molecule, but rather the net average of the tortuous path taken by the molecules.

C. Hydrologic Evaluation Landfill Performance (HELP) Program

The Hydrologic Evaluation of Landfill Performance (HELP) program was developed by the U.S. Army Corps of Engineers Waterways Experiment Station (WES), Vicksburg, MS for the USEPA Municipal Environmental Research Laboratory, Cincinnati, OH in response to needs identified by the EPA Office of Solid Waste, Washington, DC. The HELP model is believed to be

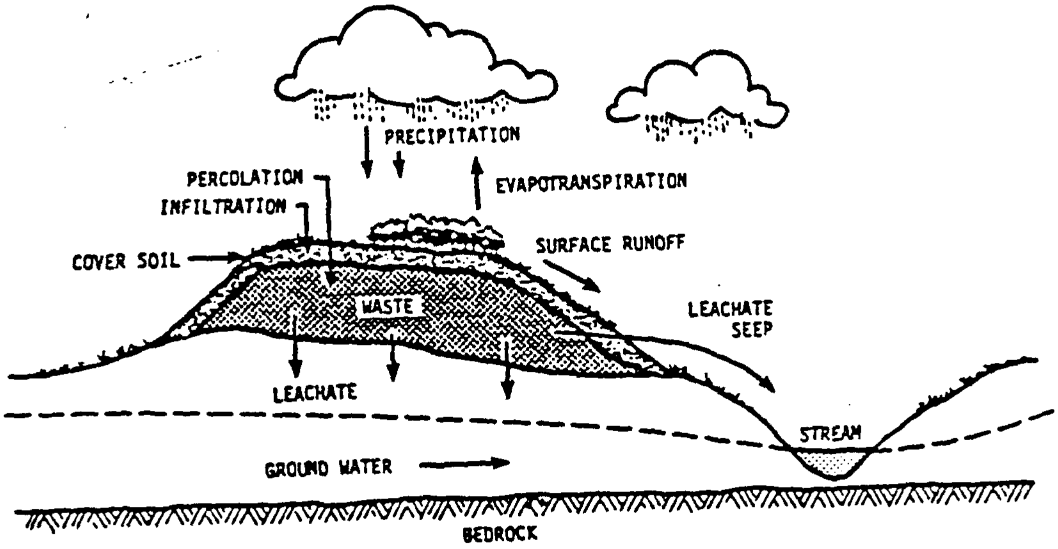

Figure III-1: Mechanism of leachate generation from McArdle, et al., 1988, Treatment of Hazardous Waste Leachate.

applicable for most landfill applications, but was developed specifically to perform hazardous waste disposal landfill evaluations as required by RCRA.

The HELP model was developed to estimate daily water movement on the surface and through the landfill. Precipitation is partitioned into runoff, evapotranspiration, percolation, and subsurface lateral drainage to maintain a continuous water balance. The HELP model computes runoff by the Soil Conservation Service (SCS) runoff curve number method and percolation by Darcy's Law for saturated flow with modifications for unsaturated conditions. Lateral drainage is computed analytically from a linearized Boussinesq equation, corrected to agree with numerical solutions from a non-linearized Boussinesq equation for the range of the design specifications used in hazardous waste landfills. Evapotranspiration is determined by a modified Penman method developed by Ritchie and adapted for limiting soil moisture conditions in the manner of Shanholtz et al. and Saxton et al, as cited by Schroeder et al (1948).

The HELP model is a mathematical model dealing with deterministic variables. A deterministic variable is one whose temporal and spatial properties are known, i.e., it is assumed that the behavior of such a variable is definite and its characteristics can be predicted. The HELP model is deterministic since the model treats all variables and their relationship as being definitely known, although often empirical relationships. However the results of 20 years of simulation should not be considered as simulation through a 20-year period since the effects of aging of the landfill are not modeled. The simulation results should be used to demonstrate the probabilities of various outcomes for the given characteristics of the landfill.

The HELP program requires climatologic, soil, and design data. This data can be obtained from each site or the model can default the climatologic and soil data. It would be better for the Navy to obtain the site specific information from the appropriate sources. Possible sources include local weather stations, libraries, universities, agricultural and climatologic research facilities, and the National Oceanic and Climatic Center, NOAA, Federal Building, Ashville, North Carolina, 28801. The U.S. Geological Survey (USGS) is also a good source of information, Table III-1 gives the addresses and numbers of the local USGS (Canter et al., 1987). Other federal agencies who publish material related directly or indirectly to groundwater are: U.S. Army Corps of Engineers, U.S. Bureau of Reclamation, U.S. Soil Conservation Service and the Environmental Protection Agency. Insolation data may be obtained from architectural publications, solar heating handbooks, and general reference works. Insolation values are more difficult to obtain.

The climatologic data include daily precipitation in inches, mean monthly temperature in ^{o}F, mean monthly insolation (solar radiation) in langleys, leaf area indices, and winter cover factors. This data may be entered in manually or be defaulted into the built-in files. The precipitation data base is limited to only five years of daily records which may not be representative since the period of record could have been unusually wet or dry.

Table III-1. Addresses of the District Offices of the U.S. Geological Survey Water Resources Division. From Canter, et al., 1987.

University of Alabama
Oil and Gas Bldg.-Room 202
P.O. Box V
Tuscaloosa, AL 35486
(205) 752-8104

218 E. Street
Anchorage, AK 99501
(907) 271-4138

Federal Building
301 W. Congress Street
Tucson, AZ 85701
(508) 378-6391

855 Oak Grove Avenue
Menlo Park, CA 94025
(405) 323-8111

Building 53
Denver Federal Center
Lakewood, CO 80225
(303) 234-5092

135 High Street-Room 235
Hartford, CT 06103
(203) 244-2528

Subdistrict-District Office/MD
Federal Building-Room 1201
Dover, DE 19901
(302) 734-2506

325 John Knox Road-Suite F-240
Tallahassee, FL 32303
(904) 386-1118

Suite B
6481 Peach Tree, Industrial Blvd.
Doraville, GA 30360
(404) 221-4858

Field Headquarters
4398D Loke St.
P.O. Box 1856
Lihue, Kauai, GUAM 96766

Subdistrict
U.S. Navy Public Works Center
FPO S.F. 96630-P.O. Box 186
Agana, GUAM 96910

P.O. Box 50166
300 Ala Moana Blvd.-Room 6110
Honolulu, HI 96850

P.O. Box 2230
Idaho Falls, ID 83401
(208) 526-2438

P.O. Box 1026
605 N. Nek Street
Champaign, IL 61820
(217) 398-5353

1819 North Meridian Street
Indianapolis, IN 46202
(317) 269-7101

Federal Building-Room 269
P.O. Box 1230
Iowa City, IA 52244
(319) 337-4191

University of Kansas
Campus West
1950 Avenue A
Lawrence, KS 66045
(913) 864-4321

In the default climatologic or soil data options, the user must specify one of seven types of vegetative cover. The user must also specify the evaporate zone depth as one of the climatologic variables. The evaporative zone depth may be thought of simply as the maximum depth from which water may be removed from the landfill by evapotranspiration.

The HELP program can model landfills with up to nine distinct layers. The layers must be properly identified. The program assumes that each layer is homogeneous with respect to hydraulic conductivity, transmissivity, wilting point, porosity, and field capacity. Vertical percolation layers are assumed to have great enough hydraulic conductivity that vertical flow in the downward direction is not significantly restricted. Lateral drainage layers are assumed to have hydraulic conductivity high enough that little resistance to flow is offered. Barrier soil layers restrict vertical flow. These layers have hydraulic conductivity substantially lower than vertical percolation, lateral drainage, or waste layers. The program only allows downward flow in barrier soil layers. Water movement through a waste layer is modelled in the same manner as it is for a vertical percolation layer.

Of the nine layers, as many as three layers can be identified as barrier soil layers. The following basic rules should be followed relative to the order of the layers in the profile. The rules are:

1. a vertical percolation layer or a waste layer may not be placed directly below a lateral drainage layer;
2. a barrier soil layer may not be placed directly below another barrier soil layer;
3. when a barrier soil is not placed directly below the lowest drainage layer all drainage layers in the lowest subprofile are treated as vertical percolation layers, therefore no lateral drainage is allowed in the profile;
4. the top layer may not be a barrier soil layer.

The type of soil in each layer must be specified by the user. This can be done manually or by the default. Characteristics for twenty-one default soil types are presented in Table III-2.

The user may enter soil characteristics manually. In this instance, the program requires the following numerical values to be entered: porosity, field capacity, wilting point, hydraulic conductivity (i.e., saturated hydraulic conductivity) in inches per hour, and evaporation coefficient in millimeters per square root of day. Table III-3 defines some terms used in the model.

The HELP program is beneficial to the Navy because it estimates the volume of leachate produced. Unfortunately the model does not consider the effects of aging of the landfill. But these results may be used to select and size appropriate drainage and collection systems, and size leachate treatment facilities. The HELP documentation and user's guide are available from the EPA publication office at (202)475-9327. The titles and EPA document numbers are: The Hydrologic Evaluation of Landfill Performance (HELP) Model, Volume I. User's Guide for Version I (EPA/530-SW-84-009) and Volume II. Documentation for Version I (EPA/530-SW-84-010).

Table III-2. DEFAULT SOIL CHARACTERISTICS (Schroeder A. C. et al, 1984).

Soil Texture Class			MIR[d]	Porosity	Field Capacity	Wilting Point	Hydraulic Conductivity	CON[e]
HELP[a]	USDA[b]	USCS[c]	In/hr	Vol/Vol	Vol/Vol	Vol/Vol	in/hr	mm/day$^{0.5}$
1	CoS	GS	0.500	0.351	0.174	0.107	11.95	3.3
2	CoSL	GP	0.450	0.376	0.218	0.131	7.090	3.3
3	S	SW	0.400	0.389	0.199	0.066	6.620	3.3
4	FS	SM	0.390	0.371	0.172	0.050	5.400	3.3
5	LS	SM	0.380	0.430	0.16	0.060	2.780	3.4
6	LFS	SM	0.340	0.401	0.129	0.075	1.000	3.3
7	LVFS	SM	0.320	0.421	0.176	0.090	0.910	3.4
8	SL	SM	0.300	0.442	0.256	0.133	0.670	3.8
9	FSL	SM	0.250	0.458	0.223	0.092	0.550	4.5
10	VFSL	MH	0.250	0.511	0.301	0.184	0.330	5.0
11	L	ML	0.200	0.521	0.377	0.221	0.210	4.5
12	SIL	ML	0.170	0.535	0.421	0.222	0.110	5.0
13	SCL	SC	0.110	0.453	0.319	0.200	0.084	4.7
14	CL	CL	0.090	0.582	0.452	0.325	0.065	3.9
15	SICL	CL	0.070	0.588	0.504	0.355	0.041	4.2
16	SC	CH	0.060	0.572	0.456	0.378	0.065	3.6
17	SIC	CH	0.020	0.592	0.501	0.378	0.033	3.8
18	C	CH	0.010	0.680	0.607	0.492	0.022	3.5
19	Waste		0.230	0.520	0.320	0.190	0.283	3.3
20	Barrier Soil		0.002	0.520	0.450	0.360	0.000142	3.1
21	Barrier Soil		0.001	0.520	0.480	0.400	0.0000142	3.1

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[a] Soil classification system used in the HELP model (see discussion in text).

[b] Soil classification system used by the U.S. Department of Agriculture.

[c] The Unified Soil Classification System.

[d] MIR - Minimum Infiltration Rate.

[e] CON - Evaporation Coefficient (Transmissivity).

TABLE III-3

DEFINITIONS OF SOME TERMS IN THE HELP MODEL

Porosity - the ratio of the volume of water to the total volume occupied by a soil.

Field capacity - the ratio of the volume of water that a soil retains after gravity drainage ceases to the total volume occupied by a soil.

Wilting Point - the ratio of the volume of water that a soil retains after plants can no longer extract water (thus, the plants remain wilted) to the total volume occupied by a soil.

Available (or plant available) water capacity - the difference between the soil water content at field capacity and at the wilting point.

Hydraulic Conductivity - the rate at which water moves through soil in response to gravitational forces.

Evaporation coefficient - (also called transmissivity) an indicator of the relative ease by which water is transmitted through soil in response to capillary suction.

*Adapted from the HELP manual.

Version II is the updated version of the HELP model and is available from WES. These documents are free to the Navy.

The software and information concerning the program are available from the WES at (601)634-3710, Anthony Gibson or (601)634-3709, Dr. Paul Schroeder.

D. Characterization of Landfill Stabilization

Through most of an activated landfill life it exists as an anaerobic, microbial process. Landfills experience an initial lag or adjustment phase which lasts until sufficient moisture has accumulated to encourage the development of a viable microbial community. Stabilization of a landfill refers to the process by which the biodegradable organic material within the landfill is microbially decomposed to methane, carbon dioxide, water and refractory and other organic materials. The first evidence that sufficient moisture has accumulated is first observed when field capacity has been reached. Further manifestations of refuse conversion and stabilization may be reflected by changes in leachate and gas quality as stabilization proceeds through several, more or less discrete and sequential phases, each varying in intensity and longevity according to prevailing operational circumstances.

Pohland (1987) discusses the phases stabilized landfills go through. The phases are not clearly delineated, there may be overlap in the phases or one portion of the landfill is in one phase and another portion of the landfill is in another phase. The following stabilization stages are:

1. In the first phase, sufficient moisture accumulates in the voids in the waste to develop a viable microbial community. The stabilization process begins in this phase.
2. In the second phase, the field capacity is exceeded and leachate is formed. The refuse components go through a transition to become soluble in the liquid. The system goes from an oxic to an anoxic system. Volatile organic acids are found in this phase.
3. Volatile organics acids are formed during the third phase and the waste goes through hydrolysis and fermentation. The pH of the leachate decreases, which may lead to increased mobility of some heavy metals. The formation of metal-organic complexes may be enhanced during this phase. Microorganisms use the released organisms.
4. In the fourth phase there is fermentation-methane production. In this phase, the microbes convert the volatile organic fatty acids to methane and carbon dioxide. A bicarbonate buffering system develops that minimizes further lowering of the pH. The redox potential is low and both gas production and leachate pH increases.
5. Landfill maturation is the final phase of landfill stabilization. The rest of the degradable organic matter is used up, the microbial processes become dormant and gas production decreases to a minimum. Refractory organics (humic materials) may complex with heavy metals in the leachate which decreases the heavy metal concentration.

Since most of the Navy landfills are older, they are probably in the later phases of stabilization. Table III-4 compares the leachate characteristics of a young landfill to an older landfill.

E. Leachate Control

There are four major natural controls involved in shallow groundwater contamination. The first natural control includes the physical and chemical characteristics of the earth materials which the liquid and wastes flow through. Many compounds are attenuated in the unsaturated zone.

The second major control includes the natural processes that tend to remove or degrade a contaminant as it flows through the subsurface from areas or points of recharge to zones or points of discharge. These processes include filtration, sorption, ion-exchange, dispersion, oxidation and microbial degradation and dilution.

The third natural control relates to the hydraulics of the flow system through which the waste migrates. The system begins with infiltration and ends in discharge. The contaminant may enter directly, by flowing through the unsaturated zone, by interaquifer leakage, by migration in the zone of saturation, or by flow through open holes.

The fourth control in the nature of the contaminant includes physical, chemical and biological characteristics. Particularly the contaminant's stability under varying conditions.

The most common strategy for leachate control is to minimize the amount of water infiltrating into the site. Permeability is the greatest factor in determining the movement of water through the soil, therefore a landfill covered with clay would allow only a fraction of the water to infiltrate into the solid waste compared to a sand or gravel cover.

The surface slope of the landfill is also important. Water collects and infiltrates on flat slopes, while water tends to run off steeper slopes, therefore, reducing the amount of water reaching the wastes contained in the landfill. Table III-5 gives the approximate runoff coefficient for the cover type and slope.

An effective method of reducing the infiltration of surface water is to have a combination of low permeability and sufficient surface slope. If the slope of the landfill surface is greater than about 8%, there is the possibility of surface runoff eroding the top cover and exposing the landfill. So a domed, clay cap with a less than 8% grade surface on a completed landfill would fulfill both criteria. The use of vegetative cover over the cap also helps reduce the leachate quantity. The vegetation intercepts the precipitation which allows for more time for percolation and evaporation. The vegetation increases the roughness of the surface, which tends to reduce velocities of surface runoff and, hence, reduce erosion. The roots of the vegetation may increase the permeability of the liner. But more importantly, the vegetation draws up the soil water from the top cover and upper layers of the landfill and moves it up through the plant. This water is lost by evapotranspiration from the plant surface and

Table III-4. Typical analyses of leachate from domestic landfill prior to dilution by sulfate runoff, Crawford and Smith (1985)

	Age of refuse	
	<2 years old	>10 years old
pH	5.0-6.5	6.5-7.5
BOD_5	4000-30000	<100
COD	10000-60000	50-500
TOC	1000-20000	<100
Total solids	8000-50000	1000-3000
TSS	200-2000	100-500
Total N (mainly NH_3-N or Org-N)	100-1000	<100
Phosphate	5-100	<5
Chloride	500-2000	100-500
Sulphate	50-1000	<10
Iron	100-1500	10-400
Sodium	500-3000	<200
Potassium	200-1000	50-400
Calcium	500-2500	100-400

Notes:

(1) All units expressed as milligrams per litre, except pH.

(2) Dilution by surface runoff from the tip may substantially reduce these concentrations.

Table III-5. Effect of slope of top cover on runoff coefficients, Crawford and Smith (1985).

Type of cover	Slope (%)	Approximate runoff coefficient
Sandy with grass cover	2	0.05-0.10
	3-6	0.10-0.15
	7	0.15-0.20
Clayey with grass cover	2	0.12-0.17
	3-6	0.17-0.25
	7	0.25-0.36

therefore reduces the quantity of water percolating down into the lower areas of the landfill.

Surrounding the solid waste with impermeable materials also helps reduce the migration of leachate out into the soil and clean groundwater. This reduces the groundwater from entering into the landfill and reduces the amount of leachate from contaminating clean groundwater and soil.

Surface drainage in the area near the landfill is also important to reducing leachate production. Surface water from areas outside the landfill site should be diverted away from the landfill.

A drainage ditch is combined with a layer of free-draining material overlaying a low permeability base of the landfill. The granular material is graded down to the outer edge of the landfill where the leachate can flow into the drainage ditch. The landfill water level is controlled by the water level in the drainage ditch. The leachate can be pumped or flow away from the ditches. Downward movement of the leachate is not prevented unless the base of the landfill has been lined with low- permeability material like clay. But even without the low- permeability base, this type of system can be used to prevent pollution of a nearby waterway.

The reduction of infiltration is the major method of leachate control. The less leachate that is generated, the less is treated. The one drawback to reducing the amount of infiltration into the landfill is that moisture is needed in order to microbially stabilize the landfill. If moisture is prevented from reaching the landfill it will take longer for the landfill to stabilize, but there is less leachate that has to be treated.

Navy landfills should be capped and covered to reduce the amount of leachate generated. Also, the installation of a slurry wall would help in the isolation of the leachate so that it would be easier to treat only contaminated groundwater and leachate. A slurry wall would also help keep the salt water from intruding into the landfill.

IV. TREATMENT TECHNOLOGIES

A. Introduction

This section discusses the candidate technologies which were reviewed. The nineteen technologies which were investigated fall into the following four categories: pretreatment, physical/ chemical, biological, and natural systems. The pretreatment, biological, physical/chemical and natural systems are conventional technologies which are used at Superfund sites and would possibly be beneficial to the Navy landfill sites. The natural systems are not conventional treatment processes but are innovative systems which may be applicable for leachate treatment at some of the activities. Table IV-1 lists the unit processes which are discussed in this section.

B. Applicability of Unit Processes to Leachate Treatment

The conventional technologies used to treat leachate were taken from wastewater and water treatment processes. A numerous amount of literature is available on these technologies since they are commercially available and known to work in the field of water treatment. These processes were adapted for leachate treatment by placing the unit processes in a specific series to treat specific contaminants in the leachate.

This section gives a brief description, the advantages and disadvantages, the design and operation considerations, and the applicable predictive equations of each process. Before a process is chosen for treatment train, the process should be researched in the literature for the removal of site specific contaminants. Also bench-scale studies should be conducted to make accurate predictions on the degradability of the contaminants in the leachate for a given process.

Table IV-2 is a matrix of the technologies and the applicability of the removal of the contaminants. This shows the unit processes which are applicable to the removal of specific contaminants. A (+) means the process is applicable for removal of the contaminant, a (o) means the process is not applicable for the removal of the contaminant, and a (-) means the process is not applicable unless the leachate is pretreated for the removal of the contaminant. [modified from McArdle, et al., (1988)].

Appendix B summarizes the predictive equations. Table IV-3 includes comparative costs for 25, 50 and 100 gallons per minute flows for various technologies. The capital and the operation and maintenance costs are given for the three different stream ranges. These costs are based on 1986 dollars, so adjustments would have to be made based on inflation and cost of the area. Costs for natural systems were not available in the literature.

C. Pretreatment

Pretreatment operations are needed to enhance or to ensure the subsequent unit processes work properly. Navy leachate is relatively dilute and may not need pretreatment.

TABLE IV-1

CANDIDATE TECHNOLOGIES

- PRETREATMENT
  - SEDIMENTATION
  - GRANULAR-MEDIA FILTRATION
  - OIL/WATER SEPARATOR
  - EQUALIZATION

- BIOLOGICAL
  - ACTIVATED SLUDGE
  - TRICKLING FILTER
  - POWDERED ACTIVATED CARBON
  - ROTATING BIOLOGICAL CONTACTOR
  - SEQUENCING BATCH REACTOR

- PHYSICAL/CHEMICAL
  - NEUTRALIZATION
  - OXIDATION/REDUCTION
  - CARBON ADSORPTION
  - PRECIPITATION/FLOCCULATION/SEDIMENTATION
  - AIR STRIPPING
  - ION EXCHANGE

- NATURAL
  - AQUATIC SYSTEMS
    - STABILIZATION PONDS
    - AQUACULTURE
  - WETLANDS (ENGINEERED)
  - LAND SYSTEMS
    - SLOW RATE SYSTEMS
    - OVERLAND FLOW
    - RAPID INFILTRATION

TABLE IV-2

TREATABILITY MATRIX

	CONTAMINANT CODE								
Technolgy	1	2	3	4	5	6	7	8	9
Sedimentation	+	+	o	o	o	o	o	o	o
Graular-media Fil.	+	-	o	o	o	o	o	o	o
Oil/Water Separ.	o	+	o	o	o	o	o	o	o
Neutralization	o	o	+	o	o	o	o	o	o
Precip/Flocc/Sed	+	+	o	+	+	o	o	o	o
Oxidation/Reduction	-	-	o	o	+	+	o	+	+
Carbon Adsorption	-	-	o	o	+	+	+	+	+
Air Stripping	-	-	o	o	o	o	+	o	o
Ion Exchange	-	-	o	+	+	+	o	o	-
Activated Sludge	-	-	-	o	-	o	+	+	o
Sequencing Batch Reactor	-	-	-	o	-	o	+	+	o
PACT	+	-	-	o	-	o	+	+	+
Rotating Biological Contactor	o	-	-	o	-	o	+	+	o
Trickling Filter	-	-	-	o	-	o	+	+	o

Key:
1 - Suspended Solids
2 - Oil, Grease, Immiscible Liquids
3 - pH (Acidic, Basic)
4 - Total Dissolved Solids
5 - Metals
6 - Cyanides
7 - Volatile Organics
8 - Semivolatile Organics
9 - Pesticides, PCB's

(+) process is applicable for removal of the contaminant;
(o) process is not applicable for removal of the contaminant;
(-) process is not appplicable unless the leachate is pretreated for removal of the contaminant.

Adapted from McArdle et al., 1988.

TABLE IV-3. COMPARATIVE COSTS OF LEACHATE TREATMENT TECHNOLOGIES (1986 dollars) (McArdle et al, 1988).

	25 gal/min		50 gal/min		100 gal/min	
Technology	Capital	Annual O&M	Capital	Annual O&M	Capital	Annual O&M
Equalization	86,000	6,300	126,000	9,400	178,000	11,400
Sedimentation	99,000	4,800	121,000	5,100	163,000	8,500
Granular-media filtration	17,000	4,900	25,000	6,200	38,000	7,400
Oil/water separation	57,000	1,700	63,000	1,900	75,000	2,300
Neutralization	28,000	3,100	49,000	3,500	53,000	4,000
Precipitation/ floculation/ sedimentation	171,000	16,000	229,000	30,000	312,000	58,000
Oxidation/reduction	96,000	3,500	121,000	4,300	162,000	5,600
Carbon adsorption	65,000	38,000	107,000	58,000	163,000	112,000
Air stripping	72,000	38,000	118,000	70,000	208,000	137,000
Ion exchange	59,000	10,000	83,000	16,000	118,000	26,000
Activated sludge	184,000	18,000	249,000	28,000	364,000	47,000
Sequencing batch reactor	109,000	10,000	158,000	16,000	224,000	26,000
Powdered activated carbon treatment (PACT)	249,000	39,000	340,000	73,000	492,000	138,000
Rotating biological contactor	103,000	13,000	183,000	20,000	383,000	36,000
Trickling filter	150,000	15,000	239,000	31,000	345,000	58,000

1. Sedimentation

Process Description

Sedimentation is the gravitational settling of suspended particles that are heavier than water in a large tank or basin under quiescent conditions. The settled solids are mechanically collected on the bottom of the clarifier and pumped out as sludge underflow. The clarifiers are either circular or rectangular and are equipped with surface-skimming equipment to remove floating scum. Chemical coagulants may be added to improve the settleability of fine particles and colloidal substances. Clarifiers are used to remove settleable solids and immiscible liquids, including oil and grease and some organics.

Advantages

This process prevents fouling and interference from suspended solids downstream from the process. It also separates solids generated by chemical and biological processes. Sedimentation is an integral part of precipitation/flocculation, activated sludge, and powdered activated carbon treatment processes.

Disadvantages

The wet sludge underflow produced by sedimentation may be hazardous and require further treatment and disposal. Another disadvantage is that if a nonaqueous organic liquid phase is generated in the process, then it may have to be recovered and disposed of.

Design and Operation Considerations

The design is based on the settling rate or rise rate of the smallest particles to be removed and is expressed as flow rate per unit area. Most applications fall within a range of 0.2 to 1.0 gallon per minute per square foot (300 to 1500 gallon per day per square foot) (Metcalf and Eddy, 1985). Horizontal velocities are limited to prevent scouring of settled solids from the sludge bed and their eventual escape in the effluent.

This is a reliable process when it is properly operated and maintained. If properly operated and designed, clarifiers can achieve removals of 50 to 65 % total suspended solids and will generate an underflow sludge solids concentration of 3 to 7 % (EPA, 1980).

Depending upon the suspended concentration of the leachate, this process may or may not be used.

Predictive Equation

In an ideal settling basin, discrete particles settle at a constant velocity (v_t) as defined by Stokes' Law which applies to laminar flow and spherical particles. The following equation represents Stokes' Law and defines v_t (Weber, 1972):

$$v_t = [g(p_s - p_l)d^2]/[(18)(u)] \quad \text{(eq. 3)}$$

where u = kinematic viscosity
g = gravity
p_l = density of water
p_s = density of the particle
d = diameter of the particle.

Hazen (1904) and Camp (1946) as cited by Peavy et *al* (1985) have developed relationships to describe the removal of discrete particles in an ideal settling tank assuming:

- particles and velocity vectors equally distributed over the tank cross section;
- the liquid moves as an ideal slug;
- any particle striking the bottom is effectively removed. Hazen and Camp have suggested that the terminal velocity of a particle which settles at a distance equal to the effective depth of a tank in a detention period can be thought of as an overflow rate, v_t:

v_t = tank depth/detention time
= depth/[tank volume/flow rate]
= depth/[(area x depth)/flow rate] = Q/A
where Q = rate of flow through the tank
A = surface area of the tank.

Ideal discrete particles which have settling velocities greater than v_t will be removed completely. But particles with a settling velocity, v_f, less than v_t will only have a portion of the particles removed. That portion removed can be defined by v_f/v_t. The overflow rate, v_t, is expressed as: $v_t = Q/A$.

2. Granular-Media Filtration

Process Summary

In filtration, suspended solids are removed from leachate by forcing the fluid through a porous media. The granular-media filter consists of a bed of granular material (usually sand or sand with anthracite or coal) contained within a vessel and supported by an underdrain system. Water containing suspended solids passes through the filter bed medium and the particles become trapped on top of and within the bed. This either reduces the filtration rate at a constant pressure or increases the amount of pressure needed to force the water through the filter. When the maximum pressure drop is reached or when breakthrough of the filter occurs, the filter is backwashed at high velocity with treated effluent to dislodge the particles. The backwash water contains high concentrations of solids and is typically recycled to the headworks of the treatment plant. Periodic backwashing of the filter media is essential for the continued operation of the treatment plant.

Advantages

Filtration is a useful pretreatment step for adsorption processes (activated carbon) and ion exchange processes which are rapidly plugged or fouled by high loadings of suspended solids. Filtration is most commonly used as pretreatment for carbon adsorption or it may be used as a polishing step after either precipitation/flocculation or biological processes for removal of residual suspended solids in the clarifier effluent. In these applications, filtration should be preceded by gravity sedimentation of suspended solids to minimize premature plugging and backwashing requirements (Metcalf and Eddy, 1985).

Design and Operation Considerations

Key design variables include the filter medium, bed porosity (solids storage capacity), filter bed depth, filtration rate, maximum head loss, and influent leachate characteristics (Metcalf and Eddy, 1979). Grain size of the medium will affect the head loss and suspended solids removal. If the grain size is too small, the driving force used to push the leachate through the filter is spent overcoming the frictional resistance of the grain. Filter bed porosity or solids storage capacity determines the amount of solids that can be retained in the filter and the filter bed depth affects the head loss and the length of the run. The filtration rate, which usually ranges from 2 to 15 gallons per minute per square foot, affects the size of the filter and the maximum head loss affects the length of the run. Influent leachate characteristics (i.e., suspended concentration, particle size and distribution, and floc strength) affect the effluent quality.

Filtration is widely used in leachate treatment because it is simple and reliable. Filters can produce an effluent with a suspended solids concentration as low as 1 to 10 mg/L (EPA, 1985h as cited by McArdle et al., 1988). This type of removal will improve the performance of downstream processes.

Predictive Equations

As noted originally by Iwasaki (1937) and as cited by Weber (1972), all macroscopic physical models are based on the fact that the rate of removal per unit depth of filter is proportional to the local concentration of suspended solids. The following is the mathematical model for deep granular filters:

$$-dC_{SS}/dL = aC_{SS} \qquad \text{(eq. 4)}$$

where C_{SS} = concentration of suspended solids at any time and depth in the filter
L = length (depth) of the filter
a = filter coefficient which varies with time and depth in the filter.

There is an accumulation of deposit in the filter pores which is due to the removal of suspended solids in the filter. The decrease in quantity of suspended matter in a filter lamina must equal the increase in deposited matter in that lamina. The following equation (Weber, 1972) describes the above situation:

$$v(dC_{ss}/dL) = d\Omega_d/dt + (e - \Omega_d)(dC_{ss}/dt) \qquad \text{(eq. 5)}$$

where v = superficial velocity (Q/A)

Ω_d = volume of specific deposit per unit filter volume (dimensionless)

e = porosity of the clear filter (dimensionless)

dC_{ss}/dt = the change in the amount of material in suspension within the pores and time, this value is generally insignificant and the term is therefore omitted.

3. Oil/Water Separator

Process Description

Oil/water separation technology is a good pretreatment which can be used to separate immiscible organics such as chlorinated solvents and PCB oils from leachate. When the leachate has not been diluted by groundwater, leachate may be composed of two immiscible phases that will require separation before further treatment of the aqueous waste stream.

Coalescing separators use baffles in the tank to promote oil droplet agglomeration. The agglomerated droplets form a continuous oil phase that more readily travels to the surface where it can be skimmed off via an oil-removal mechanism. Baffles provide more effective separation and can be used in situations where subsequent treatment processes cannot tolerate significant concentrations of immiscible organics. Gravity separators also offer an effective means for phase separation. Gravity separators consist of simple, readily available tends that provide space in which the oil/water mixture can reside in relative calmness and separate by natural gravity forces.

Disadvantages

This process is limited to waste streams that are composed of two immiscible phases that have significantly different specific gravities. If the oil is present as an emulsion, an emulsion-breaking chemical may be required.

Design and Operation Consideration

The size of the separator tank should be determined by tests that measure the settling time for a given volume based on the leachate flow rate. The maximum flow rate should be used for the design of the tank. Gravity feed provides the most effective delivery mechanism since pumping can cause emulsification. But demulsifying agents can be added to break emulsions and enhance separation. The efficiency of the system is a function of the oil concentration and droplet size, retention time, density difference between the two phases, and temperature. The baffle surface area also affects the efficiency of coalescing separators.

Bench-scale tests are required to determine the separability of the liquid phases of the leachate since the contaminants in the leachate may affect the immiscibility of the oil and water phases.

4. Equalization

Process Description

Equalization entails the mixing of incoming leachate in a large tank or basin and discharging it to the treatment plant at a constant rate. This process improves efficiency, reliability, and control of downstream processes by providing them with a more uniform feed. Leachate is subject to large fluctuations in volume and strength, and equalization helps to normalize the fluctuations. This system also helps in the automation of chemical additions, and helps maintain an active biomass for biological treatment processes.

Advantages

Equalization is required to achieve optimum performance of the treatment system since the composition and volume of the leachate varies greatly. When equalization is placed ahead of chemical operations in the process treatment train, the chemical feed control and process reliability improves. When equalization is placed ahead of biological treatment, shock loadings are minimized, inhibitory substances are diluted, pH is stabilized, and secondary settling is improved. Equalization tanks may act as influent storage tanks for plants which operate on intermittent schedules. Equalization is reliable and can improve the performance of operations like carbon adsorption, biological treatment, chemical precipitation, and ion-exchange.

Disadvantages

Solids, oil and grease present in the leachate tend to accumulate on the basin walls, but these materials may be removed by spraying the walls with water. Mixing the contents of the basin may strip the highly volatile components from the leachate, so the volatilized compounds will have to be controlled.

Design and Operation Considerations

The tanks can be constructed of steel, concrete, or lined earthen materials. Provisions should be made for mixing the leachate to prevent the deposition of solids. Discharge pumping and flow control are also required. The required volume can be determined from the average daily flow and the magnitude of inflow fluctuations. The mixing requirements for leachate containing 200 mg/L of suspended solids range from 0.02 to 0.04 hp per 1000 gallons of storage (EPA, 1977 as cited by McArdle et al., 1988). There are control devices for pumping and discharge flow rates. Pumping will normally be required and may precede or follow equalization. Discharge from the basin is regulated with a flow-control device and should be monitored with a flowmeter.

In-line and side-line equalization are two types of equalization. In-line equalization is when the entire daily flow passes through the basin and leachate is discharged to the treatment plant at essentially a constant rate. This is the preferred arrangement for leachate treatment applications because contaminant concentrations as well as flow rates are equalized. In side-line equalization, only the flow above the average daily flow rate is diverted into the basin. When the flow rate falls below the daily average, leachate from the equalization basin is discharged to the treatment plant to bring the flow rate up to the average. This system only provides flow-rate equalization.

D. Biological Treatment

In biological processes, the microorganisms can grow in either aerobic or anaerobic environments. An aerobic bacteria uses molecular oxygen as their terminal electron acceptor, while anaerobic bacteria use some other compound as their terminal electron. Anaerobic bacteria are best suited for degrading organics in the 4000 mg/L to 50,000 mg/L BOD range. Aerobic bacteria are usually used for organic concentration between 50 and 4000 mg/L BOD.

The bacteria uses the organics as a source of energy and building blocks for new bacterial cells. The bacteria can consume the organics and produce carbon dioxide, water and new bacteria. The bacteria also requires macronutrients, nitrogen, phosphorous, and micronutrients. The following environment is conducive to bacteria growth: pH = 6 to 9; temperature = 45 to 105 ^{O}F; and all toxic organics and metals are below the toxic levels.

There are two main types of biological reactors: suspended-growth reactors and fixed-film reactors. The bacteria are grown in the water and mixed with the organics in the water. Examples of suspended growth reactors are: activated sludge, sequencing batch reactors, and PACT. In fixed-film reactors, bacteria grow on an inert support media and the water with the organics passes over the film of bacteria. Examples of fixed-film reactors are: rotating biological contactor and trickling filter.

Certain compounds degrade quickly in biological systems, while other compounds require longer contact times with the bacteria in order to degrade. The easier a compound can be assimilated by bacteria, the faster and more efficiently the bacteria can turn that compound into new bacteria. The bacteria will first remove the easily degradable organics before they produce enzymes necessary to degrade the refractory compounds. In design, this is represented by the food-to-microorganism ratio, F/M. The following is the equation:

$$F/M = (Q)(S)/(V)(X) \qquad \text{(eq. 6)}$$

where Q = flow
S = organic concentration
V = volume of aeration basin
X = mixed liquor suspended solids (MLSS)

Table IV-4 lists the advantages and disadvantages of the two reactor systems. The restrictions of this system include: it must be run twenty-four hours per day, seven days a week since it is a living system.

- It must have sufficient amount of food
- The bacteria must have grown to a sufficient concentration in order to effectively remove the contaminants
- Standard biological reactors are designed for influent concentrations above 50 to 75 mg/L BOD_5.

Because leachate has several organic contaminants, bench-scale and pilot-scale tests should be run on the leachate to determine its treatability by biological technology. The Navy leachate is dilute and biological technologies may not be as effective as other processes.

1. Activated Sludge

Process Description

This suspended growth, biological treatment process uses aerobic microorganisms to biodegrade organic contaminants in the leachate. The leachate is aerated in an open tank with diffusers or mechanical aerators to provide the microorganisms with oxygen to oxidize biodegradable compounds present in the waste to NO_3, SO_4, CO_2, and H_2O. After aeration, the mixed liquor (mixture of leachate and microorganisms) is pumped to a gravity clarifier to settle out the microorganisms. A high percentage of the settled biomass is recycled to the aeration rank to maintain the design mixed liquor suspended level. The excess sludge is wasted. Process modifications include complete mixing, step aeration, modified aeration, extended aeration, contact stabilization and use of pure oxygen.

Advantage

Biologically, this is the most cost-effective means for reducing the organic content of the leachate, especially if on-site treatment is required. Activated-sludge process can readily degrade simple organic species such as alkanes, alkenes, and aromatics. Halogenated organics, including chlorobenzene, carbon tetrachloride, chlorodibromoethane, methyl chloride, and 2,4,6- trichlorophenol have been successfully treated by the activated-sludge process.

Disadvantage

Upper limits for this process for BOD_5 is 10,000 mg/L. Equalization should precede activated sludge process to buffer hydraulic and organic load variations. Precipitation/flocculation/sedimentation remove metals, while neutralization is used to adjust the pH. The addition of phosphorous, nitrogen or carbon may be required for microbial growth. Post-treatment by carbon adsorption is required if there is a high fraction of nonbiodegradable (refractory) organics. Filtration may be provided to remove any residual suspended solids.

TABLE IV-4

Comparison of Biological Treatment Reactors

Disadvantages of suspended growth system

- Cost of manpower to keep system adjusted to influent conditions
- Relative cost of oxygen transfer compared to fixed-film systems
- Critical need to keep the bacteria in a growth stage in which their settling characteristics are at a maximum

Advantages of suspended growth system

- Process produces low effluent concentrations
- Can treat many organics at the same time
- Same equipment can be used for a variety of influent conditions

Disadvantages of fixed-film system

- This is a plug-flow reactor, so the influent portion of the reactor receives a high influent concentration of the contaminant
- It will not remove a high percentage of the influent contaminant as suspended growth systems (i.e., activated sludge). 70 to 85 % BOD removal and 85 to 95 % removal of a specific organic can be expected. The lower the influent concentration, the less percentage removal can be expected.
- System must be built on site and disassembled at the end of the project.

Advantages of fixed-film system

- Bacteria are maintained in high concentration without the need of a clarifier.
- Oxygen can be supplied at lower costs.
- General ease of operation.

Design and Operation Considerations

Design parameters for this process include organic loading (lbs BOD_5 per day per 1000 ft^3), hydraulic retention time (HRT, hours), mixed-liquor suspended solids concentration (MLSS, mg/L), food-to-microorganism ratio (F/M, lb BOD_5 per day per lb MLVSS), air requirement (ft^3 per minute per lb BOD_5 removed), and solids residence time (SRT, days). When influent waste and return sludge are introduced at several points in the aeration tank (completely mixed activated sludge process), the effect of shock loads of organics are reduced. When there is a long detention time and a low F/M ratio (extended-aeration process), a high degree of oxidation and a minimum of excess sludge is provided. Pure oxygen processes operate at higher organic loadings and lower aeration requirements (EPA, 1982a as cited by McArdle et al., 1988).

Predictive Equation

Activated-sludge systems can remove 85-90% of the biodegradable organics from the influent and 99+% of specific organic compounds. A BOD effluent concentration can be expected with a well-run system.

Kincarnon and Stover (as cited by Canter et al, 1987) developed a model which is ideal for waters containing priority pollutants:

$$V = \frac{(FS_i/X)}{\{(U_{max}S_i)/[(S_i - S_e) - K_B]\}} \qquad \text{(eq. 7)}$$

where V - volume of aeration tank (m^3)
F - flow rate (m^3/day)
X - mixed liquor volatile solids (mg/L)
S_i - influent BOD, COD, TOC or specific organics (mg/L)
S_e - effluent BOD, COD, TOC or specific organics (mg/L)
U_{max} and K_B - biokinetic constants (day^{-1})
A - surface area of biological tower or rotating biological contactor (m^2)

Some of the biokinetic constants may be found in literature, but it would probably be for only one contaminant and not for a mixture of contaminants. It would be more accurate to determine biokinetic constants by conducting lab or pilot plant studies.

2. Trickling Filter

Process Description

In this aerobic biological process, the reactor is randomly packed with granular media which provides a surface area for biofilm growth. The reactor does not act like a filter, but rather sorption and subsequent biological oxidation are the primary means of food removal.

The leachate is continuously distributed over a bed of rocks or plastic medium that supports the growth of microorganisms. Leachate trickles through the filter bed, contacts slime layer formed on the medium, and is collected by an underlain system. Microorganisms assimilate and oxidize substances in the leachate. As the microorganisms grow, the slime layer increases. Periodic sloughing of the slime layer into the underdrain system results from organic and hydraulic loadings on the filter and a new slime layer begins to grow. Sloughed solids are separated from the treated effluent by settling. Since trickling filters operate under a short retention time and biodegradation of organics is not complete, effluent recirculation is required to increase the net contact time of the leachate with the biomass and to achieve a high organic removal efficiency. Recirculation also provides a constant hydraulic loading and dilutes high-strength leachate (EPA, 1982a as cited by McArdle et al., 1988). Effluent recirculation is essential for trickling filters constructed with plastic medium which has a high percentage of void space to ensure that the medium is thoroughly wetted and will sustain microbial growth and promote effective sloughing.

Advantage

Trickling filters may be used to biodegrade nonhalogenated and certain halogenated organics in leachate. This process is more resilient to variations in hydraulic and organic loadings. This process is best suited as a pretreatment unit that precedes more sensitive processes such as activated sludge (Metcalf and Eddy, 1985). When designed as a pretreatment unit, the process reduces the organic load to subsequent operations and provides a more uniform feed. Process reliability is generally good.

Disadvantage

This process is not as efficient as suspended-growth biological treatment processes. Applicability of trickling filters to the full-scale treatment of hazardous waste leachate has not yet been demonstrated. Pretreatment processes to remove metals and adjust the pH should be provided. If this process is disrupted, it is slow to recover (EPA, 1982a as cited by McArdle et al., 1988).

Design and Operation Consideration

Design parameters include hydraulic loading, organic loading, bed depth, and recirculation ratio. Plastic-medium filters are able to handle higher hydraulic and organic loadings are less susceptible to clogging, and can be built higher than rock-medium filters. Recirculation rates typically do not exceed four times the influent rate (EPA, 1982a as cited by McArdle et al., 1988).

Predictive Equations

Eckenfelder (1980 as cited by Canter and Knox, 1987) developed the following formula for trickling filters:

$$S_e/S_o = \exp\ [-kD/Q^{\,n}] \qquad \text{(eq. 8)}$$

where S_e = effluent substrate concentration, BOD_5 (mg/L)
S_o = influent substrate concentration, BOD_5 (mg/L)
D = depth of the medium (m)

k - treatability constant relating to the wastewater and the medium characteristics (min^{-1})
n - coefficient relating to the medium characteristics

The formula is commonly used and is applicable at 20°C. The values of the treatability constant, k, ranges from 0.01 to 0.1. A correction for temperatures other than 20°C can be made by adjusting the treatability factor:

$$k_T = k_{20C}\ (1.035)^{T-20} \qquad \text{(eq. 9)}$$

where k_{20C} - reaction rate coefficient, $days^{-1}$ values usually range from 0.2 to 1.0
k_T - reaction coefficient at the system temperature
T - temperature of the system

3. Powered Activated Carbon (PACT)

Process Description

The powdered activated carbon treatment (PACT) process (Zimpro, Inc.) involves the controlled addition of powdered activated carbon to the aeration tank of a conventional activated-sludge system. Removal of organics is achieved through a combination of biological oxidation/assimilation and physical adsorption. Leachate is mixed with powdered activated carbon, nutrients, and biological solids. The mixed liquor is aerated for several hours to affect biological oxidation and is then discharged to a clarifier. In the clarifier, the powdered carbon and biological solids are settled and separated from the treated waste stream. The clarifier overflow is discharged from the PACT process for additional treatment. Clarifier underflow solids are continuously returned to the aeration tank, along with make-up carbon to maintain the desired concentration of powdered carbon and microorganisms in the mixed liquor.

Advantage

The process is applicable to nearly all wastewaters with a COD between 50 to 50,000 mg/L (Meidl and Wilhelmi, 1986 as cited by McArdle et al., 1988). This process is effective for treatment of wastes such as leachate that are variable in composition and concentration, that are highly colored and contain refractive materials. Priority pollutants amenable to PACT include: volatile organics (benzene, carbon tetrachloride, chlorobenzene, chloroethane, chloroform, ethylbenzene, methyl chloride, tetrachloroethylene, toluene, 1,1,1-trichloroethane, trichloroethylene,trichlorofluoromethane), acid-extractable organics (2-Chlorophenol, 2,4-Dinitrophenol, 4-Nitrophenol, Phenol), and base/neutral-extractable organics (1,2-Dichlorobenzene, 2,3-Dinitrotoluene, 2,6-Dinitrotoluene, Nitrobenzene, 1,2,4-Trichlorobenzene). Some of the advantages the PACT have over conventional activated-sludge system include:

- higher BOD and COD removal
- stability of operation with variability in influent concentration and composition

- enhanced removal of refractive substances and priority pollutants
- effective color removal
- improved solids settling
- suppression of volatilization of organics (Copa et al., 1985 as cited by McArdle et al., 1988).

The process is buffered against variations in organic loadings, so pretreatment requirements are generally limited to neutralization. Equalization has not been shown to improve performance significantly (Heath, 1986 as cited by McArdle et al., 1988). PACT process limits volatilization of organics from the aeration tank, air emission controls are generally not required (Meidl and Wilhelmi, 1986 as cited by McArdle et al., 1988).

Disadvantage

Granular-media filtration of the clarified effluent for removal of residual suspended solids may be required to meet discharge limitations. Lab studies show that the PACT process is capable of better organic removal efficiencies than either activated sludge or carbon adsorption alone. The reasons for these good results are because of the high-mixed liquor carbon concentration and the long solids residence times (Heath, 1986; Meidl and Wilhelmi, 1986 as cited by McArdle et al., 1988).

Design and Operation Consideration

Treatability of a particular leachate stream by the PACT process can be approximated from a biophysical adsorption isotherm. This isotherm expresses the quantity of material that can be assimilated/adsorbed per unit weight of carbon as a function of the effluent strength (Copa et al, 1985 as cited by McArdle et al., 1988). The solids residence times are typically measured in days or weeks as opposed to hours for conventional activated-sludge system. Mixed liquor from a municipal wastewater treatment plant can be used to establish the PACT mixed liquor. Several runs with increasing concentration of leachate will be required to acclimate the biomass (Copa, et al., 1985 as cited by McArdle et al., 1988). Skid-mounted package treatment systems are available for low-flow application (20,000 to 55,000 gal/day).

Navy leachate concentrations are lower than typical wastewater concentrations, so this process may not be suitable as a treatment process without specialized design considerations.

Predictive Equation

Refer to the carbon adsorption process in the physical/chemical technologies section. IV-E.

4. Rotating Biological Contactor

Process Description

The rotating biological contactor (RBC) is an attached-growth, aerobic biological treatment process. It consists of a series of closely spaced plastic (polystyrene, polyvinyl chloride, or polyethylene) disks on a horizontal shaft. The series of disks are mounted in a contoured-bottom tank containing leachate so that the disks are partially (about 40%) immersed in leachate. The disks slowly rotate through the leachate and alternately contact the biomass with the organic matter in the leachate and then with the atmosphere for adsorption of oxygen. The disks eventually develop a microbial slime layer 2 to 4 mm thick over the entire wetted surface. Excess biomass on the media is stripped off by rotational shear forces and the stripped solids are held in suspension with the leachate by the mixing action of the disks. The sloughed solids are carried with the effluent to a clarifier where they are separated from the treated water.

Advantage

RBC is used for the treatment of leachate containing readily biodegradable organics. It is better able to withstand fluctuating organic loadings because the large amount of biomass they support (EPA, 1982a). It also provides a greater degree of flexibility for meeting the changing needs of a leachate treatment plant than do other attached-growth biological process, i.e., tricking filter. From treatability studies of the Stringfellow leachate, biodegradable organics completely disappeared within four days, removal of the refractory organics were from the treated effluent by adsorption onto powdered activated carbon was required to meet the discharge limits for DOC and COD (Opatken, Howard, and Bond, 1986 as cited by McArdle et al., 1988).

Disadvantage

This process is inhibited or ineffective at high concentrations of metals, refractory organics, or other toxic conditions. Equalization, metals precipitation, and neutralization should be considered minimum pretreatment requirements. Post treatment involves clarification for removal of biological solids and carbon adsorption for removal of residual organics.

Design and Operation Consideration

Hydraulic retention time of the waste and the rotational speed of the disks can be controlled to effect the desired degree of the system performance (EPA, 1982a as cited by McArdle et al., 1988). Primary effluent from a municipal wastewater treatment plant can be used to develop a biomass on the disks, but several preliminary runs with increasing proportions of leachate will be required to acclimate the microorganisms (Opatken, Howard, and Bond, 1986 as cited by McArdle et al., 1988). For winter operations, units should be housed or covered, treatment systems that can be operated in a batch mode are available for low-flow applications.

Predictive Equation

FIG IV-1 (Peavy, Rowe, and Tchobanoglous, 1985), shows and efficiency and loading rate relationship for Bio-Surf medium treating municipal wastewater for RBC systems. If the influent and effluent BOD and the hydraulic loading rate are known, then the disk area can be determined.

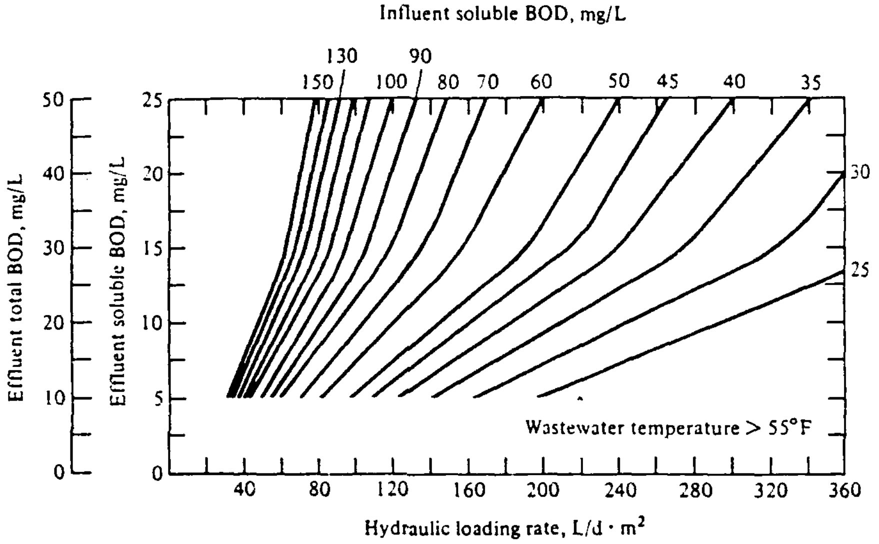

Figure IV-1. Efficiency and Loading Relationship for a RBC Treating Wastewater. (Peavy et al, 1985)

Kincannon and Stover (as cited in Canter and Knox, 1987) developed models that are reliable for waters containing priority pollutants. The following model is for a biological tower and RBC:

$$A = FS_i/([(U_{max})/(S_i - S_e)] - K_B) \qquad \text{(eq. 10)}$$

where V = volume of aeration tank (m^3)
F = flow rate (m^3/day)
X = mixed liquor volatile solids (mg/L)
S_i = influent BOD, COD, TOC or specific organics (mg/L)
S_e = effluent BOD, COD, TOC or specific organics (mg/L)
U_{max} and K_B = biokinetic constants (day^{-1})
A = surface area of RBC (m^2)

5. Sequencing Batch Reactor

Process Description

The sequencing batch reactor (SBR) is a fill-and-draw activated-sludge system. The SBR performs all operations in a single tank instead of having single tanks for equalization, aeration, and clarification. Each cycle of the batch operation involves five phases of treatment in timed sequence. The five phases are:

- Fill: Leachate is fed to the SBR which contains an acclimated biomass from the previous cycle. Aeration may or may not be provided during the fill phase.
- React: The reactor contents are actively mixed and aerated to allow the microorganisms to aerobically degrade the organic matter present in the leachate.
- Settle: Mixing and aeration are stopped and the suspended sediments are allowed to settle under quiescent conditions.
- Draw: The clarified supernatant is withdrawn from the reactor for further treatment and discharge.
- Idle: Settled solids are retained in the reactor for the next cycle. A portion of the settled sludge may be wasted during the idle phase.

Advantage

The SBR can be used to biodegrade organic contaminants in the leachate. The process is particularly applicable to the treatment of leachate that is not generated in sufficient volume to justify a continuous-flow process. In this process, the leachate can be accumulated in a holding tank for intermittent treatment. This process has greater operational flexibility to accommodate changing feed characteristics (flow and/or organic loading) and can achieve more complete treatment through adjustment of reaction parameters than the conventional activated-sludge system (McCoy & Associates, 1986; Ying et al., 1986 as cited by McArdle et al., 1988).

Disadvantage

SBR can be upset by the rapid introduction of biotoxic substances, therefore chemical equalization of the reactor feed should be provided (Staszak et al., undated as cited by McArdle et al., 1988). Post treatment like filtration is usually required since the nature of the SBR effluent is turbid.

Design and Operation Consideration

The operating and cycle schedules of the SBR can be adjusted to meet specific treatment objectives at variable influent flow rates and organic loadings. In a typical 24 hour treatment cycle, the fill phase may last 6 hours; the react phase, 8 hours; the settle phase, 5 hours; the draw phase, 4 hours; and the idle phase, 1 hour (Staszak et al., undated as cited by McArdle et al., 1988). Process control is achieved through the use of automatic valves, sensors, flow meters, timers, and microprocessors. The system is sensitive to rapid temperature drops, therefore tank insulation and a supplemental heat source are required for winter operations.

E. Physical/Chemical

Physical/chemical operations are more likely candidate technologies for treatment of leachate from stabilized landfills. Navy landfills are stabilized and the leachate is at dilute concentrations, therefore physical/chemical treatment processes are more effective than biological treatment processes.

1. Neutralization

Process Description

When a leachate exhibits an extreme pH, it is neutralized by the addition of a base or an acid. This adjusts its pH upward or downward as required to an acceptable level (usually between 6 and 9). Bases commonly used for neutralization include lime (CaO), calcium hydroxide ($Ca(OH)_2$), caustic ($NaOH$), soda ash (Na_2CO_3), and ammonium hydroxide (NH_4OH). Acids commonly used include sulfuric acid (H_2SO_4), hydrochloric acid (HCl), and nitric acid (HNO_3). Salts (soluble and insoluble) are formed as reaction byproducts of neutralization. Neutralization is carried out by complete mixing of the aqueous leachate with the neutralizing agent in a corrosion-resistant tank. Tanks may be operated in a batch or continuous mode. Continuous flow neutralization is generally suitable only for flow rates greater than about 70 gallon per minute which may be automatically controlled by using feedback, feed-forward, or multimode controllers.

Advantage

This process is one of the simplest and most common technologies available for the treatment of leachate. It serves as pretreatment for optimization of the performance of pH-sensitive processes (particularly biological treatment processes) or for minimization of corrosion in more sophisticated physical/chemical processes (especially stripping processes). This process may be applied as a post-treatment operation down-stream of certain chemical processes that yield acidic or caustic effluents. Post-treatment effluent may be used to meet final discharge criteria. This is particularly applicable where treated effluent is discharged to surface or groundwater.

Design and Operation Consideration

The performance of this system is highly dependent upon the reliability of automated control systems. The major process design considerations include reagent selection and dosage, mixing, contact time, and process control. Consideration should be given to the selection of vessels, piping, and instrumentation.

2. Oxidation/Reduction

Process Description

Oxidation/reduction reactions are those where the valence state of one reactant is raised while that of another is lowered. Oxidation/reduction of certain leachate constituents may render them non-hazardous or more amenable to removal by subsequent processes (i.e., precipitation, ion exchange, or biological treatment). Oxidation/reduction involves the addition of a chemical oxidizing or reducing agent to leachate under a controlled pH. Common oxidizing agents include chlorine gas (plus caustic), calcium and sodium permanganate, hydrogen peroxide, and ozone (alone or in combination with ultraviolet radiation). Common reducing agents include sulfur dioxide, sodium sulfite salts (sodium bisulfite, metabisulfite, and hydrosulfite), sodium borohydrite, and the base metals (iron, aluminum, and zinc). Oxidation/reduction reactions (batch or continuous) are usually carried out in an enclosed, cylindrical vessel equipped with rapid-mix agitators. The reaction progress is monitored with an oxidation/reduction potential probe. Chemical oxidation of refractory organic compounds can be used as an alternative to the adsorption process.

Advantage

This is a well-developed technology and has many applications in industrial wastewater treatment. Oxidizable leachate constituents include organics (acids, aldehydes, mercaptans, polynuclear aromatic hydrocarbons, pesticides, PCB's, and other halogenated organics), cyanides, ammonia, and some metals (iron, manganese, and selenium). Reducible leachate constituents include a variety of metals (chromium, mercury, lead, silver, nickel, copper, and zinc). Metal-cyanide complexes can be treated by first oxidizing the cyanide and then reducing the metal (Metcalf and Eddy, 1985 as cited by McArdle et al., 1988). The most common application of oxidation/reduction to hazardous waste leachate include cyanide reduction of hexavalent chromium to the less hazardous trivalent form.

Large, complex organic molecules, ring-structured detergents, and phenolic and humic compounds can be broken into simpler compounds by the action of strong oxidants like ozone or chlorine. This process may include ammonia removal, oxidation of inorganic substances such as iron and manganese, and disinfection.

Disadvantage

To use this process, the minimal pretreatment requirements include equalization and sedimentation. Oxidation/reduction of metals is usually followed by chemical precipitation/sedimentation which produces a wet sludge which has to be disposed of. Partial oxidation with chlorine may result in formation of toxic and/or odorous chlorinated organic species (Metcalf and Eddy, 1985 as cited by McArdle et al., 1988). Residual chlorine, ozone, or sulfites in the effluent should be neutralized since they may be damaging to downstream processes.

Design and Operation Consideration

Design considerations include determination of the appropriate type and dosage of chemical reagent, the minimum contact time required to assure complete reaction and the optimum solution pH (Patterson, 1985 as cited by McArdle et al., 1988). These parameters can be determined from lab bench studies. Selection of the appropriate oxidation/reduction agent is influenced by chemical and equipment costs, ease of handling, and safety. These reactions are typically exothermic and can be violent, therefore, they are normally conducted at dilute processes. Chemical oxidizing and reducing agents are nonselective, thus leachate containing multiple oxidizable/reducible constituents will exert a higher chemical demand than will a less complex waste stream. Effectiveness of oxidation/reduction for a given constituent is directly related to the time of reaction and the degree of which interfering or competing constituents are present. Oxidation with ozone is much more rapid than oxidation with chlorine. For example, oxidation of cyanide to cyanate requires 10 to 15 minutes with ozone, compared to 0.5 to 2 hours with chlorine (Patterson, 1985 as cited by McArdle et al., 1988). Reduction of chromium and other metals is more than 90% complete within 1 or 2 hours (Metcalf and Eddy, 1985 as cited by McArdle et al., 1988).

3. Carbon Adsorption

Process Description

Carbon adsorption is a separation technique for removing dissolved organics from leachate. Adsorption mechanism consists of three steps: 1) diffusion of the molecules through the liquid phase to the carbon particle; 2) diffusion of the molecules through the macropore to the adsorption site; 3) adsorption of the molecule to the surface.

The carbon is specially processed to develop internal porosity and is characterized by a large specific surface area (300 to 2500 m^2/g). The leachate passes through beds of granular activated carbon and the contaminants are adsorbed from the leachate onto the carbon surface and held there by physical and chemical forces. Since the adsorption forces are relatively weak, the carbon surface can be regenerated.

Various methods of contacting leachate with granular carbon include fixed-bed, expanded bed, and moving-bed columns. In the fixed-bed adsorber, leachate is distributed at the top of the column, flows downward through the carbon bed which is supported by an underdrain system, and is withdrawn at the bottom. When the pressure drop through the column becomes excessive (from the accumulation of suspended solids), the column is taken off line and backwashed with the treated effluent. The backwash water is then returned to the headworks of the plant for treatment. In the expanded-bed adsorber, a countercurrent flow of carbon and leachate is created. Leachate is introduced at the bottom of the column and flows upward through the carbon bed. The spent carbon is withdrawn intermittently from the bottom of the column and replaced with fresh carbon at the top. Activated carbon has a fixed adsorptive capacity. Breakthrough occurs when this fixed adsorptive capacity is approached and is indicated by elevated concentrations of organics in the effluent. Because of the breakthrough phenomena, two columns are usually operated in series and a third is ready to come on line when one of the columns is exhausted. The spent carbon may be regenerated on site, returned to the supplier for regeneration or disposed of offsite.

Advantage

Granular activated carbon adsorption is a well-developed process that has become a recognized standard technology for the treatment of most hazardous waste leachates. This process is well suited for the removal of mixed organic contaminants, including volatile organics, phenols, pesticides, PCB's and foaming agents (EPA, 1982a; Soffel, 1978 as cited by McArdle, 1988). This process is economically competitive with air stripping for the removal of relatively low concentrations of volatile organics when the volatile organic carbon (VOC) air emissions must be controlled. This process is typically used for effluent polishing of nonvolatile organics following air stripping for higher contaminant loadings. Activated carbon effectively removes some inorganics (including arsenic, cyanide, and chromium), but hazardous waste leachate treatment facilities typically remove these contaminants through precipitation and/or oxidation/ reduction units upstream of the adsorber. These systems can be designed to effect greater than 99% removal of most organic contaminants.

Carbon adsorption is a relatively expensive process. But it is particularly suited for low concentrations of nonvolatile components, high concentrations of nondegradable compounds and short-term projects (Nyer, 1985).

Disadvantage

Influent concentrations should be limited to 50 mg/L suspended solids and 10 mg/L oil and grease (EPA, 1982a; Metry and Cross, 1976 as cited by McArdle et al., 1988). Suspended solids, oil and grease must be removed in the pretreatment processes or they will accumulate on the surface and on the first few inches of carbon. The surface accumulation blinds the adsorber and greatly increases the pressure drop across the filter bed. Granular-media filtration is usually provided upstream to minimize suspended loadings and to reduce the frequency backwashing operations. Activated carbon is expensive so regeneration of the carbon is preferred. Thermal regeneration will completely destroy compounds that decompose at temperatures of 600 to 1200 °F. But the presence of certain contaminants (i.e., PCB's) that are not destroyed at these temperatures may render regeneration impractical and mandate incineration or disposal of the carbon instead. Backwashing is normally provided for downflow, fixed-bed adsorbers which are susceptible to blinding. Use of low-pressure systems that limit compaction of the carbon beds and through effective treatment, backwashing requirements can be minimized. Effluent concentrations of target contaminants in the parts-per-billion range are difficult to achieve because of the complex nature of hazardous waste leachate and the nonselectivity of carbon for specific hazardous constituents. System reliability is largely a function of the pretreatment provided. Carbon filters that are provided with a low-turbidity, nonscaling feed can be expected to be highly reliable and require only infrequent backwashing.

Design and Operation Consideration

Factors which affect the dynamics of this process include characteristics of the adsorbent (surface area, pore structure and size distribution, particle size, surface polarity), characteristics of the solute (solubility, molecular structure, molecular size, ionization, polarity) and characteristics of the aqueous system (temperature, pH, competing solutes, dissolved solids) (Patterson, 1985 as cited by McArdle et al., 1988). Adsorption isotherms approximate the capacity of carbon for removing a particular compound from leachate. The isotherm expresses the quantity of material that can be adsorbed per unit weight of carbon as a function of the equilibrium solute concentration at a constant temperature of the carbon dosage required (EPA, 1982 as cited by McArdle et al., 1988). Pilot tests should be performed to include the determination of the design hydraulic load, bed depth, and contact time, pretreatment requirements, carbon dosage in pounds of pollutants removed per pound of carbon, and breakthrough characteristics.

This is a suitable process for Navy leachate since it treats low concentration of non-volatile components.

Predictive Equations

When an organic molecule is brought to the activated carbon surface and held there by physical and/or chemical forces, it is adsorption. The quantity of a substance or a group of substances that can be adsorbed by activated carbon is determined by a balance between the forces that keep the compound in solution and the forces that attract the compound to the carbon surface.

When the activated carbon particles are placed in the water containing organic chemicals and mixed to give adequate contact, the adsorption of the organic chemicals occurs. The organic chemical concentration will decrease from an initial concentration, C_o, to an equilibrium concentration, C_e. It is possible to obtain a relationship between the equilibrium concentration and the amount of organics adsorbed per unit mass of activated carbon by conducting a series of adsorption tests.

An isotherm test will determine whether or not a particular organic can be removed effectively, it will show the approximate capacity of the carbon for the application, and provide a rough estimate of the carbon dosage required.

According to Rich (1973), adsorption of organic materials from solution by activated carbon can be expressed by the following empirical relationship:

$$(C_o - C)/m = kC^{1/n} \qquad \text{(eq. 11)}$$

where C_o, C = concentration of organic materials in solution, initially and after contact with activated carbon [g/m^3]
m = concentration of activated carbon [g/m^3]
k, n = constants, values of which vary with organic solute and temperature

Design of an activated carbon adsorption column can be accomplished by using the following kinetic equation developed by Thomas (1987, as cited by Canter et al 1987):

$$\ln [(C_o/C)-1] = [(K_1 A_o M)/Q] - [(K_1 C_o V)/Q] \qquad \text{(eq. 12)}$$

where C = effluent pollutant concentration (g/m^3)
C_o = influent pollutant concentration (g/m^3)
K_1 = rate constant (m^3/day/g)
Q = flow rate (m^3/day)
A_o = adsorption capacity (g/g)
M = mass of carbon (g)
V = throughput volume (m^3)

Typical breakthrough curves are determined by pilot studies.

4. Precipitation/Flocculation/Sedimentation

Process Description

This is the most common method of removing soluble metals from leachate. In precipitation, chemicals are added to the leachate to transform dissolved contaminants into insoluble precipitates. Flocculation promotes the agglomeration of the precipitated particles which helps in their subsequent removal from the liquid phase by sedimentation (gravity settling) and/or filtration. Metals can be precipitated from leachate as hydroxides, sulfides, or carbonates by adding an appropriate chemical precipitant and adjusting the pH to favor solubility. Better efficiencies are possible with precipitation with lime or caustic as the precipitant is practiced more widely because of its materials-handling and cost advantages (Canter and Knox, 1986).

Precipitation, flocculation, and sedimentation can be carried out in separate basins or in a single basin (i.e., an upward flow, solids-contact reactor-clarifier) with separate zones for each process. Precipitation requires rapid mixing in order to have complete dispersion of the chemical precipitant. But flocculation requires slow, gentle, mixing to promote particle contact. Frequently, flocculants such as alum, lime, ferric chloride or polyelectrolytes are added along with the precipitant to reduce repulsive forces between particles and bring about particle agglomeration and settling.

In chemical precipitation, a chemical is added to remove inorganics. The chemical addition chosen depends upon the low solubility of inorganics at a specific pH. The three common basic chemical addition systems are: (1) the carbonate system, (2) the hydroxide system, and (3) the sulfide system. Based upon the solubility products for these systems, the sulfide removes most inorganics, with the exception of arsenic since sulfide compounds have low solubility. Since the sulfide system has a better removal efficiency, it would be more effective than the hydroxide system. But one disadvantage of the sulfide system is that the chemicals are difficult to handle and sulfide sludges are susceptible to oxidation to sulfate when exposed to air resulting in the resolubilization of the metals. The carbonate system uses soda ash and has a pH adjustment between 8.2 and 8.5. The carbonate system is workable in theory, but difficult to control. The hydroxide system is the most widely used method in metals/inorganic removal. The system directly responds to pH adjustment. This system uses either lime (CaOH) or sodium hydroxide (NaOH) as the chemical to adjust the pH upward. The advantage to using sodium hydroxide is the ease of chemical handling and low volume of sludge. But the hydroxide is often gelatinous and difficult to dewater.

Two types of flocculation processes are perikinetic and orthokinetic. Perikinetic flocculation is a transport process where interparticle contacts are produced by Brownian motion (Overbeek, 1952 as cited by Weber, 1972). The random motion of the colloidal particles results from the rapid and random bombardment of the colloidal particles by molecules of the fluid. Orthokinetic flocculation is the process where contacts between particles is caused by fluid motion (Overbeek, 1952 as cited by Weber, 1972).

Advantage

This process is applicable for the removal of most metals (arsenic, cadmium, chromium (III), copper, iron, lead, mercury, nickel, and zinc) as well as suspended solids and some anionic species (phosphates, sulfates, and fluorides) from the aqueous phase of leachate (Shuckrow, Pajak and Touhill, 1982 as cited by McArdle, et al., 1988). Effluent metal concentrations of less than 1 mg/l are theoretically achievable. In practice, theoretical values are seldom attained because of the influence of complexing agents like, fluctuations in pH, slow reaction rates, and poor separation of colloidal precipitates (Metcalf and Eddy, 1985; Patterson, 1985)

Disadvantage

Equalization should be provided prior to precipitation because fluctuating influent flow rate and metals content of leachate make chemical dosages difficult to control. Nonaqueous liquids, including oil and miscible organics should be removed during pretreatment. Metals-complexing agents, including cyanide and ammonia will inhibit chemical precipitation by forming soluble metal complexes. Metals-complexing agents may be removed by either oxidation/reduction or other processes prior to precipitation which would greatly improve treatment system performance. Such process interferences should be evaluated during treatability studies. Since precipitation of most metals is usually conducted at a high pH, neutralization of the effluents may be required. Neutralization may be needed especially if a pH-sensitive biological treatment unit is downstream.

Design and Operation Consideration

Design involves determination of required chemical dosages, optimum operating pH, degree of precipitation, reaction times, and sludge production and settling rates (Canter and Knox, 1987). These parameters can be determined from simple bench-scale treatability studies (jar tests) for the chemicals of choice. Hydroxide or carbonate precipitation is preferred over sulfide precipitation for hazardous waste leachate applications because of the potential for the latter to generate toxic hydrogen sulfide gas. Depending upon the nature of the leachate, chemical dosages can be high.

Predictive Equations

For perikinetic flocculation, the time to halve the concentration, $t_{1/2}$, of particles for water at 25^{o} C is represented in the following equation:

$$t_{1/2} = (3n)/(4a_{p}kTN_{o}) \qquad \text{(eq. 13a)}$$

where N_o = total concentration of particles in suspension at time 0
n = collision efficiency factor representing the fraction of the total number of collision which are successful in producing aggregate
k = Boltzmann's constant = 1.36×10^{-16} ergs/ ^{o}K
k_p = rate coefficient (cm^3/sec)
T = ^{o}K
a_p = collision efficiency factor
erg = dyne-cm = $(g\text{-}cm^2)/sec^2$

Type 2 settling involves flocculating particles in dilute suspension. The flocculating particle size is continually changing so it is difficult to develop a general formula for determining settling velocities. Treatability studies should be conducted to determine the percentage of contamination removed by sedimentation.

Samples should be taken at several places in the settling column. Samples should be drawn off at several time intervals and analyzed for suspended-solids concentration. These concentrations are used to compute mass fraction removed at each depth and for each time.

The mass fraction in the percentage that is removed at the ith depth at jth time interval is:

$$x_{ij} = (1 - C_{ij} / C_o) \times 100 \qquad \text{(eq. 13b)}$$

5. Air Stripping

Process Description

Air stripping is a mass transfer process where a substance in water is transferred to a solution in gas. Air stripping effectively treats leachate containing organics that are volatile and are only slightly water-soluble. This technology is widely used at Superfund sites.

Vapor/liquid equilibria data can help predict the applicability of air stripping for removal of a particular contaminant. The vapor/liquid equilibrium behavior of a compound varies with temperature and the presence of other constituents, so air-stripping efficiency should be determined experimentally in laboratory evaluations with actual leachate (Warner, Cohen, and Ireland, 1980 as cited by McArdle et al., 1988). Removal of suspended solids and separation nonaqueous phases are pretreatment requirements for air stripping. If chemical neutralization or precipitation/sedimentation, is a chosen pretreatment process, sodium-based reactants should be used over calcium-based reactants. Calcium-based reactants can lead to scale formation.

Disadvantage

Air stripping transfers volatile contaminants from the aqueous leachate to the air stream, so air emission limitations for volatile organic compounds (VOC's) limit direct discharge into the atmosphere. Not appropriate for low volatility compounds, highly soluble compounds, metals or inorganics (Glynn, et al., 1987).

Predictive Equations

Air stripping is governed by the rate of mass transfer which depends upon several factors and is described in the following equation (Kincannon and Stover, 1985):

$$M = K_L a(C_L - C_g) \qquad \text{(eq. 14)}$$

where M = mass of substance transferred per unit time and volume ($g/hr/m^3$)
K_L = coefficient of mass transfer (m/hr)
a = effective area (m^2/m^3)
$(C_L - C_g)$ = driving force (concentration difference between liquid phase and gas phase (g/m^3)

The Henry's law constant may be used to predict the strippability of a chemical. A compound with a high Henry's law constant is usually easier to strip from water than one with a lower Henry's law constant. One form of Henry's law constant (Mills, et al., 1985) is:

$$H = P/C \qquad \text{(eq. 15)}$$

where H = Henry's law constant ($atm\text{-}m^3/mole$)
P = equilibrium partial pressure of pollutant in the atmosphere above the water (atm)
C = equilibrium concentration of pollutant in the water at ($mole/m^3$)

Air stripping may be used to remove volatile organic compounds with Henry's constant greater than 3.0×10^{-3} $atm\text{-}m^3/mole$ from aqueous wastes. In general, organic concentrations less than 1.0 percent are treatable by air stripping.

6. Ion Exchange

Process Description

In this process, there is an exchange of an ion with a high ion selectivity for an ion with a lower one. The leachate passes through a resin and the lower selectivity ions in the solution will exchange with the higher selectivity ions on the resin. The ion exchange resin can exchange either positive (cations) or negative (anions) ions. The exchangeable ions (i.e., H^+, Na^+, OH^-, Cl^-) are held to the resin by relatively weak electrostatic forces and can be readily displaced by ions in leachate with a greater affinity for the resin.

When the resin has exhausted its exchange capacity it can be regenerated by washing it with a solution containing an excess of the ion initially adsorbed on the solid. Essentially, regeneration reverses the exchange process.

Ion-exchange can be carried out in separate fixed-bed columns in series or in a single column that contains both resin types. It is more common to operate ion-exchange in series.

Advantage

This process is used to remove dissolved ionic species when a high-quality effluent is required. This technology is widely used for domestic-water softening, boiler-water deionization, and treatment of metal plating wastes. Its use is probably limited as a polishing stage. This process removes a wide range of inorganics, including metals, halides, and cyanides.

Disadvantage

This process has not been applied to the full-scale treatment of hazardous waste leachate. If the leachate has a high concentration of dissolved solids, it would not be suitable for ion-exchange, since it would quickly exhaust the resin. A practical upper concentration limit for exchangeable ions for efficient operations is about 2500 mg/L as $CaCO_3$ or 0.05 equivalents/L (EPA, 1982a as cited by McArdle, et al., 1988). This would not be a cost effective method. Suspended solids and nonaqueous liquids (i.e., oil and grease) should be removed beforehand to prevent fouling and plugging of the resin beds. Strong oxidizing agents and some organic compounds which can irreversibly bind to the resin should be removed prior to ion exchange.

Design and Operation Consideration

The primary consideration in the design of this system is to select an appropriate resin which exhibits selectivity or affinity for ions. Table IV-5 summarizes the ion exchange resin selectivity. Ions with a high selectivity are preferred by the resin over ions with low selectivity. Studies show that total dissolved solids and metals have removal efficiencies of 90 to 99 percent.

F. Natural Systems

This section discusses three types of natural treatment systems: aquatic systems, wetlands, and land treatment systems. Aquatic systems can be either ponds and lagoons or aquaculture. Ponds and lagoons depend on microbial life and lower plants and animals, while an aquaculture uses higher plants and animals. In wetlands, the water table is at or above the ground and keeps the soil saturated and has enough vegetation growth. Only constructed wetlands are discussed in this paper. Regulatory agencies strictly control natural wetlands, while constructed wetlands may avoid these regulations. Constructed wetlands hydraulics regime is more reliable, making the system more reliable. The third system is land treatment. This system depends on physical, chemical, and biological reactions on and within the soil matrix and produces a high quality effluent.

Principal methods of removing trace organics in natural treatment systems are volatilization, adsorption, and biodegradation (Reed et al., 1988). Loss of volatile organics can be described by first order kinetics. The following is the mathematical expression:

$$C_t / C_o = \exp(-k_{vol}\ t/y) \qquad \text{(eq. 16)}$$

where C_t = concentration at time t, mg/L (or ug/L)
C_o = initial concentration at t = 0, mg/L (or ug/L)
k_{vol} = volatilization mass transfer coefficient, cm/hr
k = overall rate coefficient, hr^{-1}
y = depth of liquid, cm

$t_{1/2}$, expressed in hour, is the time at which the final concentration is half the initial concentration. $t_{1/2} = 0.693y/k_{vol}$.

Sorption of organics in the natural treatment system is primarily a physicochemical removal mechanism. The partition coefficient, K_p, defines the concentration of the organic which is sorped relative to that in solution and is related to the solubility of the chemical. The octanol-water partition coefficient, K_{ow}, and the percentage of the organic carbon in the system estimates the K_p.

$$\log K_{oc} = 1.00 \log K_{ow} - 0.21 \qquad \text{(eq. 17)}$$

where K_{oc} = sorption coefficient expressed on an organic carbon basis = K_{sorb} /(OC), cm/hr

Table IV-5

ION EXCHANGE RESIN SELECTIVITY
(Adopted from Patterson, 1978 as cited by Nyer, 1985).

Resin	Selectivity
Strong Acid	Li^+, H^+, Na^+, NH_4^+, K^+, Rb^+, Cs^+, Mg^{2+}, Zn^{2+}, Cu^{2+}, Ca^{2+}, Pb^{2+}
Weak Acid	Na^+, K^+, Mg^{2+}, Ca^{2+}, Cu^{2+}, H^+
Strong Base	F^-, OH^-, $H_2PO_4^-$, HCO_3^-, Cl^-, NO_2^-, HSO_3^-, CN^-, Br^-, NO_3^-, HSO_4^-, I^-
Weak Base	F^-, Cl^-, Br^-, I^-, PO_3^-, NO_3^-, CrO_4^{2-}, SO_4^-, OH^-

K_{sorb} = sorption mass transfer coefficient, cm/hr
OC = percentage of organic carbon present in the system
K_{ow} = octanol/water partition coefficient

The K_p can be determined by the following expression:

$$K_p = K_{oc} x_{oc} \qquad \text{(eq. 18)}$$

where x_{oc} = mass fraction of organic carbon in sediment

In many cases removal of trace organics is a combination of sorption and volatilization. The combined removal is described by the following:

$$C_t/C_o = \exp(-k_{sv}\, t) \qquad \text{(eq. 19)}$$

where k_{sv} = overall rate constant

Microorganisms are capable of catalyzing reactions which either transform or degrade organic pollutants. Often, microbial degradation or biodegradation is the most important, if not only process that decomposes an organic pollutant in aquatic environment.

The rate at which a compound degrades is dependent upon how the microorganisms metabolize it. The microorganisms either metabolize or cometabolize the compound. In growth metabolism, the organic pollutant is a food source which provides energy and carbon for growth and cell maintenance. In cometabolism, the pollutant is transformed but is not used for microbial growth.

In growth metabolism the organic pollutant is used as a carbon source. There must be sufficient microbial population which have acclimated to the environment and are able to use the pollutant as a growth substrate. If more easily degraded carbon sources are available in the environment, it would delay the adaptation of the microbial community to the metabolism of a pollutant. Also the concentration of the pollutant in the environment should be at a level which is not toxic to the microbes.

Once the microbial population adapts to the environment, including the organic pollutant, the biodegradation rate can be described by the Monod equation. The Monod equation assumes that the compound is the sole carbon source. The Monod equation is:

$$-dC/dt = (1/Y)(dB/dt) = (u_{max}/Y)[(BC)/(K_s + C)] \qquad \text{(eq. 20)}$$

where C = pollutant concentration
B = bacterial concentration
Y = biomass produced per unit C assumed
u_{max} = maximum specific growth rate
K_s = half-saturation constant

Often the Monod equation is reduced to a second-order biodegradation expression by assuming $C \ll K_s$. Therefore, the expression becomes:

$$-dC/dt = K_{B2}\ BC \qquad \text{(eq. 21)}$$

where K_{B2} = second-order biodegradation rate constant
= $u_{max} / (Y\ K_s)$

Since the environment has other carbon sources besides the pollutant, first order kinetics is a frequently used alternative:

$$-dC/dt = K_B C \qquad \text{(eq. 22)}$$

where K_B = first order biodegradation rate constant

Through cometabolism, microorganisms degrade compounds which cannot be used as a nutrient or growth substrate. Cometabolism has no effect on microbial population size since it does not provide growth or energy.

The following expresses the biodegradation in cometabolism:

$$-dC/dt = K_B C \qquad \text{(eq. 23)}$$

where C = pollutant concentration
K_B = first order biodegradation rate constant

The bacterial population, B, is independent of the cometabolism rate. To use the above equation, the size of the bacterial population should be estimated.

Some other environmental influences on biodegradation rates include: temperature, nutrient limitation, sorption substrate, solubility of the compound, pH and anoxic conditions.

Equation 9 represents the temperature dependence of biodegradation.

Microbes require nutrients like nitrogen and phosphorous to metabolize organic substrates. The limitation on inorganic nutrients is a significant factor influencing biodegradation on rates in the aquatic environment. There is a correlation between hydrocarbon degradation rates and phosphorous concentration which natural waters fit. This data fits a saturation relationship of the Michaelis-Menten type:

$$K_B(C_p) = K_B\ (C_p^*)\ [(0.0277)(C_p)/(1 + (0.0277)(C_p))] \qquad \text{(eq. 24a)}$$

where $K_B(C_p)$ = specific biodegradation rate constant at dissolved inorganic phosphorous concentration, ug/L
C_p = dissolved inorganic phosphorous concentration, ug/L
$K_B(C_p^*)$ = non-nutrient limited biodegradation rate constant

This relationship has been used as an indicator of possible phosphorous limitation of biodegradation in the environment.

Many organic pollutants adsorb onto the sediment. The compounds must be dissolved for it to be degraded. If the compound is sorbed onto the sediment, it is not available for biodegradation. The following equation represents the sorption of the compound onto the soil:

$$dC_T /dt = K_B C_W = a_W K_B C_T \qquad \text{(eq. 24b)}$$

where C_W = pollutant concentration in the aqueous phase
a_W = decimal fraction of the total analytical pollutant concentration which is in the aqueous phase ($a_W = 1$ - fraction sorbed)
K_B = biodegradation rate constant

The compounds must be dissolved for it to be degraded. If the pH range is 5 to 9 the biodegradation rates are independent of pH. If the pH is outside this range, the biodegradation rates decrease.

The log octanol/water partition coefficient, log K_{OW}, is the distribution of a compound between two immiscible solvents, n-octanol and water. Log K_{OW} oil and water phases. This is a useful parameter for predicting the bioconcentration potential of compounds and sorption of compounds by organic soils. This value also determines the applicability of solvent extraction as a treatment alternative. An increasing log K_{OW} value favors strong bioaccumulation, adsorption, and solvent extraction potentials.

1. Aquatic

a. Stabilization Pond

Process Description

Other names for a stabilization pond are facultative pond, oxidation pond, sewage lagoon, and photosynthetic pond. The key mechanism of this system is that oxygen production is by photosynthetic algae and surface reaeration. The oxygen is used by the aerobic bacteria in stabilizing the organic material in the upper layer. The algae is needed for oxygen production, but its presence in the effluent is a negative performance criteria. The ponds are usually 1.2 to 2.5 meters deep. The aerobic layer is over the anaerobic layer. Aerobic stabilization occurs in the upper layer. The anaerobic layer contains sludge and anaerobic fermentation occurs in the lower layer.

In an aerated pond, oxygen is supplied through mechanical or diffused aeration. The depth is usually 2 to 6 meters and the detention time is 3 to 10 days. The aerated pond can be designed as a complete mix reactors or as partial reactors. Design of complete mix reactors is similar to activated sludge system without sludge recycle. For complete mix reactors, sufficient energy must be used to keep the pond contents in suspension at all times.

In high-rate aerobic ponds the depth is usually 30 to 45 centimeters and the dissolved oxygen (DO) is maintained throughout the entire depth. Since the depth is shallow, this process allows light to penetrate the full depth. Mixing is provided to expose algae to sunlight and to prevent deposition and subsequent anaerobic conditions. Photosynthesis and surface aeration provides oxygen and aerobic bacteria stabilizes the waste. Aerobic ponds have a detention time of 3 to 5 days and are limited to warm, sunny climates.

Anaerobic ponds are ponds which receive a heavy organic loading so that there is no aerobic zone. The usual depth is 2.5 to 5 meters and a 20 to 50 days detention time. The principal biological reactions are acid formation and methane fermentation. Anaerobic ponds are usually used for treatment of strong industrial and agricultural wastes.

Unless the leachate has high concentrations, this system is probably not applicable to Navy leachate.

Predictive Equation

Thirumurthi (1974) as cited by Reed et al., 1988 found that the flow pattern in facultative ponds is somewhere between ideal plug and complete mix. The following equation developed by Wehner and Wilhelm (1956) as cited by Reed et al., 1988 is recommended for chemical reactor design:

$$C_e/C_o = [4a \exp(1/2D)]/[(1+a)^2 (\exp(a/2D) - (1-a)^2 \exp(-a/2D)] \quad \text{(eq. 25)}$$

where C_o = influent BOD concentration, mg/L
C_e = effluent BOD concentration, mg/L
$a = (1+4ktD)^2$
k = first order reaction rate constant, days^{-1}
t = hydraulic residence time, days
D = dimensionless dispersion number
$= H/vL = Ht/L^2$
H = axial dispersion coefficient, area per unit time
v = fluid velocity, length per unit time
L = length of travel path of a typical particle

FIG. IV-2 is the Wehner and Wilhelm equation chart of the term kt versus BOD remaining. If the chart is not used, the equation can be solved on a trial and error basis.

b. Aquaculture

Process Description

This system uses aquatic plants or animals as a component in the treatment system. The treatment responses in this system are due to either one major type of plant or animal or a variety of plants and animals. There is a direct uptake of material by the plants or animals by the presence of these biota altering the physical environment of the system which provides a significant degree of treatment or the plant roots acting as the host substrate for attached microbial organisms which provide a significant degree of treatment.

The water hyacinth or floating plant may be used in this system. Water hyacinths (eichhornia crassipes) are perennial, freshwater aquatic

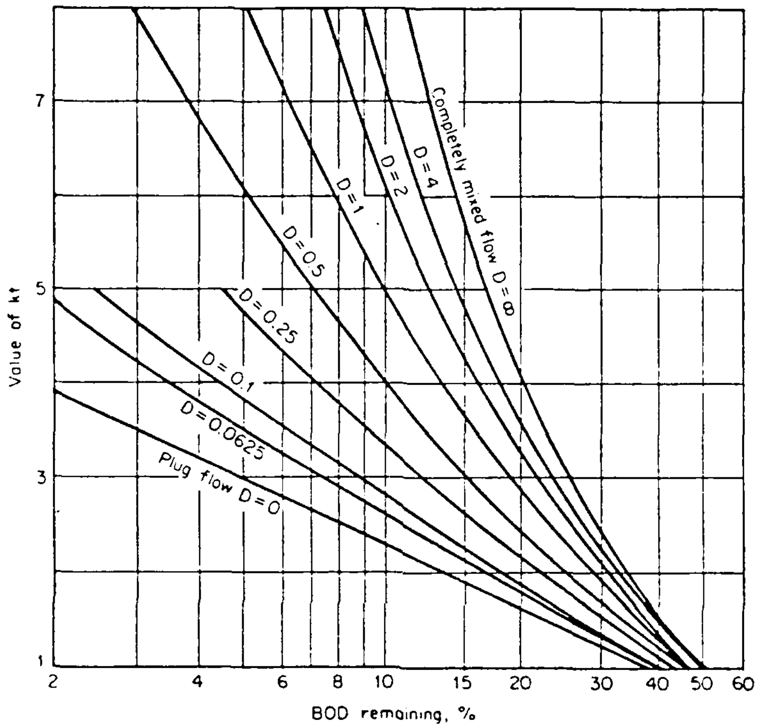

Figure IV-2. Wehner and Wilhelm Chart for Estimating the Degree of Mixing (from Reed, et al., 1988).

macrophyte (water tolerant vascular plant) with rounded, upright, shiny green leaves and spikes of lavender flowers. It is one of the most photosynthetic plants in the world. Rapid growth of the plant is an advantage in the use of wastewater treatment.

Advantage

This system removes various pollutants. It is capable of removing high levels of BOD, suspended solids, metals, nitrogen, and significant levels of trace organics. Suspended solids removal occurs through entrapment in the plant root zone and by gravity sedimentation in the quiescent water beneath the surface mat of hyacinth plants. Solids control also contributed to suppression of algae growth. The plant shades the water surface and prevents the passage of sunlight to the water column. It is believed that the main mechanism of metal removal is chemical precipitation and adsorption on substrate and on the plant surfaces. The nitrogen removal is contributed by plant uptake, ammonia volatilization, and nitrification/denitrification. It is believed that nitrification/denitrification is the major factor responsible for nitrogen removal. Nitrifier organisms can flourish attached to the hyacinth root, which provide oxygen, while adjacent microsites and the benthic layer provides the anaerobic conditions and the carbon sources needed for denitrification. Nitrification/denitrification is more likely to occur at a relatively shallow depth because the bulk wastewater has the opportunity for contact with the hyacinth root zone.

In San Diego, a pilot scale hyacinth basin system measured the removal of some priority pollutants from wastewater in Table IV-6. It is believed that the removal of priority pollutants is primarily due to the decomposition of the compounds by bacterial action. But plant uptake can account for the decrease of a significant quantity of these materials. This system may be feasible for the Navy since it has a low influent concentration of priority pollutants and is capable of reducing the concentration.

Design and Operation Consideration

The critical design parameter is the organic loading on the system. The major operational concerns are control of mosquitos and odors, vegetation management, sludge removal, plant harvest, and the disposal or utilization of the harvested materials and sludge.

Predictive Equation

Overall nitrogen removal rate is a first-order reaction rate. The nitrogen removal was a function of plant density an temperature. The following estimates the nitrogen removal in pond systems:

$$Ne/No = \exp(-kt) \qquad \text{(eq. 26)}$$

where Ne = total nitrogen in the system effluent, mg/L
No = total nitrogen applied to the wastewater, mg/L

Table IV-6. Trace Organic Removal in Hyacinth Basins (Reed et al, 1988).

Parameter	Concentration, μg/L	
	Untreated wastewater	Hyacinth effluent*
Benzene	2.0	ND†
Toulene	6.3	ND
Ethylbenzene	3.3	ND
Chlorobenzene	1.1	ND
Chloroform	4.7	0.3
Chlorodibromomethane	5.7	ND
1,1,1 Trichloroethane	4.4	ND
Tetrachloroethylene	4.7	0.4
Phenol	6.2	1.2
Butylbenzyl phthalate	2.1	0.4
Diethyl phthalate	0.8	0.2
Isophorone	0.3	0.1
Naphthalane	0.7	0.1
1,4 Dichlorobenzene	1.1	ND

* Pilot scale system, 4.5 day detention time, 76 m^3/day flow, three sets of two basins each, in parallel, plant density 10–25 kg/m^2 (wet weight).

† ND = not detected.

k = rate constant dependent upon the temperature and plant density
t = detention time in the system, days.

The typical phosphorous removal from wastewater is 30 to 50 %. This system also removes significant levels of trace organics.

A correlation exists between nitrogen removal and the hydraulic loading on the basin surface. The following relationship is valid for a moderately dense (80 percent or more of basin covered with hyacinths) stand of plants with regular harvests to maintain optimum growth.

$$L_N = 760/(1-N_e/N_o)^{1.72} \qquad \text{(eq. 27)}$$

where L_N = hydraulic loading, limited by nitrogen removal, $m^3/(ha\text{-}day)$
N_e = nitrogen concentration required in system effluent, mg/L
N_o = nitrogen concentration in influent to hyacinth basins, mg/L

The following equation was derived to estimate the potential for phosphorous removal in hyacinth basins. The following equation is valid when basins surfaces are at least 80 percent covered with plants and there is a regular harvest.

$$L_P = (9353)[(P_e - 0.778P_o)/(P_o - P_e) \qquad \text{(eq. 28)}$$

where L_P = hydraulic loading, limited by phosphorous removal, $m^3/(ha\text{-}day)$
P_e = phosphorous concentration required in system effluent, mg/L
P_o = phosphorous concentration in influent to hyacinth basins, mg/L

2. Engineered Wetland

Process Description

In this system, the land is located where the water surface is near the ground surface long enough each year to maintain saturated soil conditions along with the related vegetation.

The two types of constructed wetlands are conventional wetland and vegetated submerged bed (VSB). The conventional wetland has an exposed free surface and the VSB has a subsurface flow through a permeable medium. Both concepts use emergent aquatic vegetation and all depend on the same basic microbiological reactions for treatment.

Wetlands consist of plants, soils, organisms, and bacteria. A variety of plants can be used in the wetland system for wastewater treatment. The water level in the system and the duration of flooding may be important factors in selecting and maintaining wetland vegetation. Water losses due to evapotranspiration (ET) losses can effect the feasibility of the various wetland designs in arid climates and their performance during the summer months. Evaporative water losses decrease the water volume in the system, therefore, the concentration of remaining pollutants tend to increase even though treatment is very effective on a mass removal basis.

Decreased water volume leads to increased detention time and may increase the potential for anoxic and anaerobic conditions. This may affect performance and may increase the risk of mosquito development in wetlands with exposed areas.

Oxygen transfer is also important in this system. Wetlands submerged for long periods are most likely anaerobic. Certain emergent plants are capable of absorbing oxygen and other needed gases from the atmosphere through their leaves and above-water stems and can conduct those gases to the roots through large gas vessels. Some of this oxygen will support aerobic microbes in and around the root system. It is not necessary to have plant diversity in a constructed, free-water-surface wetland. The function of the plant is to transfer oxygen to the root zone. Their physical presence allow more effective fluid movement and contact opportunities in the benthic layer.

Stalks and leaves provide shade, therefore, limits sunlight penetration and controls algae growth. Submerged leaves, stalks, and litter serve as a substrate for attached microbial growth. This microbial growth is responsible for much of the treatment which occurs. Plants contribute to treatment through uptake of nutrients and other wastewater constituents. Emergent aquatic plants obtain nutrients for plant growth from the soil, except for carbon. Void space in the soil or other media serve as the flow channels for the VSB wetlands. Treatment provided by microbial organisms attached soil surfaces. Attached microbial growth is believed to be the major contributor to wastewater treatment.

Advantage

The use of constructed wetlands offers a cost-effective treatment alternative. A constructed wetlands perform better than a natural wetland of equal area since the bottom is usually graded and the hydraulic regimes in the system is controlled. Process reliability is improved because the vegetation and the other system components can be managed as required.

This system reduces high levels of BOD. There is very rapid movement of settleable organics due to the quiescent conditions in the free-water-surface types and to deposition and filtration in the VSB systems. Soluble BOD is removed due to the attached microbial growth. Suspended solids removal is effective in the free-water-surface and the submerged flow constructed wetlands. Most of the suspended solids is removed in the first few meters beyond the outlet. Nitrogen removal is effective in the freewater-surface and submerged-flow constructed wetlands. It is believed that the major contribution to nitrogen removal is nitrification/denitrification. Phosphorous removal in natural systems occurs as a result of adsorption, complexation, and precipitation and is very effective in the soil-based land treatment systems. Significant clay content and the presence of iron and aluminum will enhance the potential for phosphorous removal. Removal mechanisms for metals is similar to what is described in phosphorous removal. In subsurface flow wetlands, there is greater opportunity for contact and adsorption and metals removal can be effective. Removal in gravel beds can be effective owing to adsorption on the media and contained organics.

Wetland systems are simple to control and maintain. These systems can withstand a wide range of operating conditions and have relatively low energy and manpower requirements.

Disadvantage

Leachate treatment must be demonstrated and the treatment level of individual constituents should be quantified before a full-scale wetland treatment system can be implemented.

Design and Operation Consideration

Constructed wetland systems are considered to be attached- growth biological reactors and their performance can be described by first-order plug-flow kinetics. Wetland performance is dependent upon water depth, temperature, pH, dissolved oxygen concentration. Pilot tests are recommended for large-scale projects.

Predictive Equation

The following general model applies to wetlands:

$$C_e/C_o = 0.52 \exp\,[(-0.7K_T(A_V)^{1.75}LWdn)/Q] \qquad \text{(eq. 29a)}$$

where C_e = effluent BOD, mg/L
C_o = influent BOD, mg/L
A = fraction of BOD not removed as settleable solids near headworks of the system (as a decimal fraction)
K_T = rate constant in days^{-1} at water temperature T (in ^{o}C), given by
KT = $0.005(1.1)^{(T-20)}$
A_V = specific surface area for microbial activity, m^2/m^3
L = length of system, m
W = width of system, m
d = design depth of system, m
n = porosity of system (as a decimal fraction)
Q = average flow in the system, m^3/day
= $(Q_{influent} + Q_{effluent})/2$

When the bed slope or hydraulic gradient is equal to 1 percent or greater, the model should be adjusted accordingly:

$$C_e/C_o = 0.52 \exp\,[(-0.7K_T(A_V)^{1.75}LWdn)/(4.63S^{1/3}Q)] \qquad \text{(eq. 29b)}$$

S = slope or hydraulic gradient of flow system, (as a decimal fraction)

The hydraulic residence time and design surface area for wetlands are:

$$t = [(\ln C_o - \ln C_e) - 0.6539]/(65K_T) \text{ and } \qquad \text{(eq. 30a)}$$

$$A = [Q(\ln C_o - \ln C_e - 0.6539)]/(65K_T d) \qquad \text{(eq. 31a)}$$

If the bed slope or hydraulic gradient is greater than 1 percent then:

$$t = [(\ln C_o - \ln C_e) - 0.6539]/(301K_T S^{1/3}) \text{ and } \qquad \text{(eq. 30b)}$$

$$A = [Q(\ln C_o - \ln C_e - 0.6539)]/(301KTd) \qquad \text{(eq. 31b)}$$

where t = hydraulic residence time in the system, days
C_o = influent BOD concentration, mg/L
C_e = effluent BOD concentration, mg/L
K_T = reaction rate constant, days^{-1}
= $K_{20}(1.1)^{(T-20)}$
d = design water depth in the system

These equations are valid for constructed wetland with a free water surface and meeting the design criteria below.

- organic loading < 112 kg BOD/(ha-day)
- specific surface area (A_V) for attached microbial growth = 15.7 m^2/m^3
- porosity (n) of wetland flow path = 0.75
- aspect ratio (L/W) > 10:1
- water depth, warm months < 10 cm, cool months < 45 cm

3. Land

Land treatment is the controlled application of wastewater to the soil to achieve treatment of constituents in the wastewater. Land treatment systems use the natural physical, chemical, and biological processes within the soil-plant-water matrix.

The three principal processes of land treatment are: slow rate (irrigation), rapid infiltration, and overland flow. Slow rate systems involve the application of effluent to the land for treatment and for meeting growth needs of plants. In rapid-infiltration systems, the effluent is applied to the soil at high rates (10 to 210 cm/week) by spreading in basins or by sprinkling. Overland flow is a biological process where wastewater is applied over the upper reaches of sloped terraced and allowed to flow across the vegetated surface to runoff collection ditches.

a. Slow rate systems

Process Description

The wastewater can be distributed over the land by either a sprinkler system or surface application system. This treatment is a predominant form of land treatment of municipal and industrial waste. There are two slow rate systems: Type 1 systems and Type 2 systems. Type 1 is designed on the basis of limiting design factor (LDF). In Type 1, the maximum possible amount of wastewater is applied to the minimum possible land area. The limiting design factor may be the hydraulic capacity, nitrogen, BOD, metals, or toxic wastes.

In Type 2, the system is designed to optimize the water reuse potential. In Type 2, just enough water is applied to satisfy the total irrigation requirements for the crop being grown.

Predictive Equation

Relating the water balance equation and the applied nitrogen to the nitrogen-limited hydraulic loading rate, $L_{w,n}$, for the Type 1 SR system the following equation applies:

$$L_{w,n} = [C_p (P_r - ET) + 10U]/[(1 - f)C_n - C_p] \qquad \text{(eq. 32)}$$

where $L_{w,n}$ = wastewater hydraulic loading rate controlled by nitrogen as the LDF, cm/year
C_p = percolate nitrogen concentration, mg/L, usually set at 10 mg/L
C_n = nitrogen concentration in applied wastewater, mg/L
ET = evapotranspiration rate
P_r = precipitation rate
P_w = percolation rate
U = crop uptake, kg/(ha-year)
f = fraction of applied nitrogen lost to denitrification, volatilization, and soil storage

For Type 2 systems, the following equation incorporates the leaching factor and irrigation efficiency:

$$L_w = (ET - P_r)(1 + LR)(100/E) \qquad \text{(eq. 33)}$$

where ET = crop evapotranspiration
P_r = precipitation
LR = leaching requirement
E = efficiency of the irrigation system

The leaching requirement may range from 0.05 to 0.30, depending on the crop, the amount of precipitation, and the total dissolved solids (TDS) in the wastewater (Fig. IV-3)

The land area requirement can be calculated by the following equation:

$$A = (Q + V_s)/(CL_w) \qquad \text{(eq. 34)}$$

where A = field area, ha
Q = annual flow, m^3/year
V_s = net loss or gain in stored wastewater volume due to precipitation on and evaporation and seepage from the storage pond, m^3/year

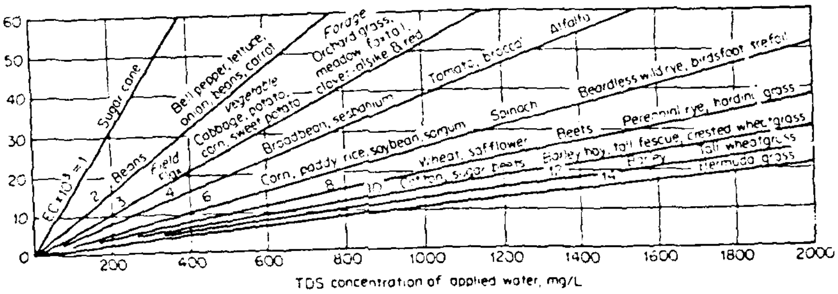

Fig. IV-3. Percent leaching requirements versus salinity for various crops. (Reed et al, 1988)

C = constant = 100 (metric)
L_w = design hydraulic loading rate based on the LDF, cm/year

Parker and Jenkins (as cited by Reed, et al., 1988) developed an equation for the volatilization of volatile organics by sprinkling. The following equation is:

$$\ln C_t/C_o = 4.535\,(k_{vol}' + 11.02 \times 10^{-4}) \qquad \text{(eq. 35)}$$

where C_t = concentration at time t, ppb
C_o = initial concentration at time o, ppb
k_{vol}' = volatilization coefficient, hr^{-1}

b. Overland flow

Process Description

In overland flow land treatment, wastewater is applied over the upper reaches of sloped terraces and allowed to flow across the vegetated surface to runoff collection ditches. The wastewater is renovated by physical, chemical, and biological means as it flows in a thin film down the relatively impermeable slope. Relatively little percolation is involved because of an impermeable soil. Sites which have surface soil permeabilities of 0.5 cm/hr or less is best suited for overland flow.

Advantage

Suspended solids are effectively removed on the slopes by sedimentation and filtration because of the low velocity and the shallow depth of flow. Most of the suspended solids (SS) will be removed within the first few meters of the application point.

Disadvantage

The accumulation of SS can create a sludge problem, the use of sprinklers is recommended. Winter conditions will cause some problems with the system.

Predictive Equation

The relationship between the hydraulic loading rate and the application rate is shown in the following equation:

$$L_w = [qP(100\text{ cm/m})]/[Z] \qquad \text{(eq. 36)}$$

where L_w = hydraulic loading rate, cm/day
q = application rate per unit width of the slope, m^3/(hr-min)
P = application period, h/day
Z = slope length, m

The relationship between the application rate, slope length, and BOD removal for municipal wastewater is the equation below:

$$[(C_z - c)/C_o] = A \exp(-KZ/q^{n}) \qquad \text{(eq. 37)}$$

where C_z = effluent BOD concentration at point Z, mg/L
c = residual BOD at end of slope = 5 mg/L
C_o = BOD of applied wastewater, mg/L
Z = slope length, m
q = application rate, m^3 /(h-m)
K,n = empirical constants

The organic loading rate can be calculated by the following equation:

$$L_{BOD} = 0.1 L_w C_o \qquad \text{(eq. 38)}$$

where L_{BOD} = BOD loading rate, kg/(ha-day)
0.1 = conversion factor (metric)
L_w = hydraulic loading, cm/day
= $qPWm/Z$
q = application rate, m^3 /(hr-m)
P = application period, hr
W = width of application slope, m
Z = length of application slope, m
m = conversion factor = 100 cm/m
C_o = BOD of applied wastewater, mg/L

When the BOD of the wastewater exceeds about 800 mg/L, the oxygen transfer capacity of the overflow system becomes limiting. This limitation can be overcome by recycling.

The field area required for OF depends on the flow, the application rate, the slope length, and the period of application. The following equation assumes no seasonal wastewater storage:

$$A_s = (QZ)/(qPC) \qquad \text{(eq. 39)}$$

where A_s = field (surface) area required, ha
Q = wastewater flow rate, m^3/day
Z = slope length, m
q = application rate, m^3 (hr-m)
P = period of application
C = conversion factor
= 10,000 m^2 /ha

If wastewater storage is a project requirement, the field area is determined by the following equation:

$$A_s = [365Q + V_s]/[DL_w C'] \qquad \text{(eq. 40)}$$

where V_s = net loss or gain in storage volume due to precipitation, evaporation, and seepage, m^3/year
D = number of operating days per year
L_w = design hydraulic loading, cm/day
C' = conversion factor = 100 (metric)

If the organic loading rate is limiting, the field area can be calculated by the following equation:

$$A_s = [C_o C'' Q_a]/L_{LBOD} \quad \text{(eq. 41)}$$

where A_s = field area, ha
C_o = BOD of applied wastewater, mg/L
C'' = conversion factor = 0.1 (metric units)
Q_a = design flow rate to the OF site, m^3 /day
L_{LBOD} = limiting BOD loading rate = 100 kg/(ha-day)

c. Rapid Infiltration

Process Description

In this system, the applied wastewater percolates through the soil and the treated effluent eventually reaches the groundwater. The wastewater is applied to rapidly permeable soils such as sands and loamy sands, by spreading in basins or by sprinkling, and is treated as it travels through the soil matrix.

Predictive Equation

The application area can be calculated by the following equation:

$$A = [CQ(365 \text{ days/year})]/L_w \quad \text{(eq. 42)}$$

where A = application area, ha
C = conversion factor = 10^{-4} ha/m^3,
Q = average wastewater flow, m^3/day
L_w = annual loading rate, m/year

4. Leachate Recirculation

Process Description

The leachate is collected and recirculated through the landfill.

Leachate recirculation accelerates the decomposition of solid waste material by maintaining optimal anaerobic conditions. The optimal anaerobic conditions stabilize the landfill more rapidly than conventional sanitary landfilling processes. Leachate recirculation through a landfill promotes a more rapid development of an active anaerobic population of methane formers, increases the rate and predictability of biological stabilization of the readily available organic pollutants in the refuse and leachate, dramatically decreases the time required for stabilization and reduces the potential for environmental impairment.

Advantage

Leachate recirculation with pH control and initial sludge seeding may further enhance treatment efficiency. Because of this enhanced treatment, time required for biological stabilization of the readily available organic pollutants in the leachate can be reduced to a matter of months rather than years with the opportunity for controlled final discharge and/or treatment of residuals as may be required. This is a good process for currently operating or young landfills.

Disadvantage

There should be a proper collection system in place to prevent the contamination of the groundwater. There must be post-recycle treatment of leachate. Post-recycle can be done by aerated lagoon or activated sludge treatment. This may not be a good treatment process for Navy sites, since these landfills are in the latter stabilization phases.

V. TREATABILITY

A. Introduction

The treatment of the leachate is dependent upon the characteristics of the leachate, including the contents disposed of in the landfill and the age of the landfill. The strength of the leachate in young landfills is stronger than leachate in older landfills. Most of the Navy landfills are either ten years old or older and the leachate strength is not as strong as younger landfills. Each landfill at each base is different because each base varies in type of industry(ies). Table V-1 gives the minimum and maximum concentrations of the analytical results for the compounds in the groundwater only. It is assumed that only the groundwater will be treated and these results show the concentrations at which the treatment train must treat. The TOC and TOX were calculated at each base (Table V-2). Each base is listed an the calculated TOC and TOX are given for the respective wells. General organic parameters (i.e., BOD, COD, TOC) were generally not analyzed for. This information may be helpful in determining the treatability of the leachate and indicates much of the measured organics concentrations (TOX, TOX) exceed that predicted from the priority pollutant alone. Therefore, as a possibility for future research identification of the chemical nature of these unidentified organics may aid in the selection of treatability options.

Young landfills generate leachate in which the organic matter mainly consists of free volatile fatty acids and can be readily degraded by *biological processes*. While old landfills contain organics corresponding to the refractory material excreted by microorganisms is more amenable to physical chemical treatment (Chian and DeWalle, 1976). Organic and inorganic contaminants follow a decreasing trend in strength with the increasing age of the landfill. There is a decrease in the COD/TOC ratio in the leachate samples which represents a more oxidized state of the organic carbon which becomes less readily available as an energy source for microbial growth. These organics are generally degradation products of microbial activities and increase as the age of the landfill increases. The resulting leachate thus becomes less amenable to biological treatment. Due to its initially biodegradable nature, the organic compounds decrease more rapidly than the inorganics is due to anaerobic methane fermentation and washout. The inorganics only decrease due washout by infiltrating rain water.

The treatability of leachate is related to chemical composition, especially to the nature of organic matter (Chian and DeWalle, 1976). Organic matter in addition to the inorganic constituents by analyzing the leachate for COD, BOD, free volatile fatty acids, organic nitrogen, and in another study lignins and tannins. Sulfate to chloride ratio, oxidation reduction potential (ORP), and pH reflect the degree of stabilization of the landfill and, thus, the leachate generated from the fill. The goal of relating parameters to the composition of organic matter and the age of the landfill is to establish useful criteria for the choice of specific treatment processes best suited for the removal of organic contaminants from leachate.

TABLE V-1

Minimum and Maximum Concentration of Contaminants Measured at Selected Naval Facilities

MARINE CORPS AIR STATION, CHERRY POINT (GROUNDWATER, SITE 10)

Waste Compound	Minimum (ppb)	Maximum (ppb)
Organics		
2-Butanone	730	730
4-Methyl-2-Pentanone	170	170
Benzene	5	160
Toluene	8	1100
Ethylbenzene	35	37
Total Xylenes	17	110
Chlorobenzene	5	200
1,1,1-Trichloroethane	12	160
1,1-Dichloroethane	8	1000
Chloroethane	9	2500
Tetrachloroethene	5	280
Trichloroethene	8	410
Trans-1,2-Dichloroethene	12	1900
1,1-Dichloroethene	14	70
Vinyl Chloride	14	2600
Methylene Chloride	5	560
Chloromethane	56	56
Acid/Base		
Phenol	20	150
Diethyl Phthalate	13	33
Naphthalene	11	131
1,2-Dichlorobenzene	12	12
1,4-Dichlorobenzene	15	26
Pesticides		
Beta-BHC	.34	.34
Inorganics		
Arsenic	1	68
Cadmium	8	8
Chromium	10	20
Mercury	.4	.7
Nickel	30	80
Zinc	10	20
Cyanide	5	13
Geochemical Parameters		
pH	4.93	8.63
specific conductance (umhos/cm)	100	1500
temp (^{o}C)	6.8	20.9
Phenolics	20	1700

NAVAL AIR STATION, MOFFETT FIELD (GROUNDWATER, SITE 1)

Waste Compound	Minimum (ppb)	Maximum (ppb)
Organics		
1,2-Dichloroethenes	2	2
1,4-Dichlorobenzene	12	35
2,4-Dimethylphenol	64	370
2-Butanone	46	49000
2-Chlorophenol	36	36
2-Methylphenol	13	2000
4-Chloro-3-methylphenol	22	22
4-Methyl-2-pentanone	16	8300
2-Methylnaphthalene	5	5
4-Methylphenol	37	7900
Acetone	3	2700
Benzene	3	9
Benzoic Acid	6	11000
Bis(2-Ethylhexyl)phthalate	2	31
Di-n-butylphthalate	3	3
Diethylphthalate	22	22
Ethyl Benzene	6	18
Methylene Chloride	2	1300
Naphthalene	14	14
N-nitroso-dipropylamine	54	54
N-nitrosodiphenylamine	14	25
Pentachlorophenol	24	24
Phenol	28	98
Toluene	2	660
Total Xylenes	6	56
Inorganics		
Aluminum	11.9	2110
Antimony	30.0	1670
Arsenic	6.0	29.2
Barium	16.8	4480
Beryllium	.7	5
Bicarbonate	500	2600
Cadmium	5.2	43
Calcium	11600	570000
Carbonate	2000	2000
Chloride	4900	94000
Chromium	10	173
Cobalt	6.1	69.6
Copper	5.6	41.1
Fluoride	12	160
Iron	8.3	108000
Lead	91	139
Magnesium	39700	1820000
Manganese	8.9	7060
Mercury	.4	.4
Nickel	9.2	121
Nitrate	4	378000
Potassium	4050	498000

NAVAL AIR STATION, MOFFETT FIELD (WATER, SITE 1)

Waste Compound	Minimum (ppb)	Maximum (ppb)
Selenium	5.9	5.9
Silver	3	276
Sodium	153000	16400000
Sulfate	6.9	4300
TDS	10000	>20000
Thallium	90	140
Vanadium	43	520
Zinc	3.2	296

NAVAL AIR STATION, MOFFETT FIELD (GROUNDWATER, SITE 2)

Waste Compound	Minimum (ppb)	Maximum (ppb)
Organics		
1,2-Dichloroethenes (Total)	16	22
2-Methylnaphthalene	3	5
Acetone	2	16
Benzene	6	38
Benzoic Acid	11	11
Bis(2-Ethylhexyl)phthalate	2	9
Bromodichloromethane	1	1
Butyl benzyl phthalate	2	2
Chlorobenzene	5	5
Chloroform	59	59
Chloromethane	3	3
Di-n-butylphthalate	3	3
Ethyl Benzene	2	20
Methylene Chloride	3	20
N-nitrosodiphenylamine	3	3
Naphthalene	42	50
Toluene	1	2
Total Xylenes	14	15
Trichloroethene	8	8
Vinyl Chloride	1	42
Inorganics		
Aluminum	18.6	24500
Antimony	78.4	1560
Arsenic	1150	6200
Barium	21.2	2550
Beryllium	.93	.93
Bicarbonate	6	570
Calcium	197	1460000
Carbonate	8	97
Chloride	3.1	22000
Cobalt	6.2	6.2
Copper	46.4	46.4
Fluoride	6.1	59
Iron	26.8	91700
Lead	3	462
Magnesium	436	1620000
Manganese	19.6	4950
Mercury	3	.5
Nickel	9	9
Nitrate	12	5.3
Potassium	1600	452000
Silver	6	74.6
Sodium	86.3	11500000
Sulfate	1.2	14000
TDS	40	20000
Thallium	2	35
Vanadium	4.4	94.3
Zinc	7.2	978

NAVAL BASE, NORFOLK (GROUNDWATER, SITE 1, DRAFT REPORT)

Waste Compound	Minimum (ppb)	Maximum (ppb)
Volatile Organics		
Vinyl Chloride	18	5400
Methylene Chloride	17	24000
Trichlorofluoromethane	1700	2300
1,1-Dichloroethane	17	170
Trans-1,2-Dichloroethylene	16	46000
1,2-Dichloroethane	11	74
1,1,1-Trichloroethane	24	95
Trichloroethylene	34	5600
Benzene	29	1200
Toluene	18	34000
Ethylbenzene	12	430
Acid Extractable Organics		
Phenol	44	67
2,4-Dimethylphenol	170	11000
Pentachlorophenol	110	110
Base Neutral Extractables		
Naphthalene	36	1200
Bis(2-Ethylhexyl)phthalate	15	97
Inorganics		
Antimony	1.8	1.8
Arsenic	04	.36
Cadmium	01	.54
Chromium	01	117
Copper	10	.62
Lead	05	5.8
Mercury	0002	.0014
Nickel	10	.30
Sellenium	034	.034
Thallium	06	.42
Zinc	02	7.7
Cyanide	014	.92
Phenols	001	60

NAVAL SHIPYARD, NORFOLK (GROUNDWATER, SITE 2, DRAFT REPORT)

Waste Compound	Minimum (ppb)	Maximum (ppb)
Volatile Organics		
Acetone	32	32
Methylene chloride	6.8	8.9
Semi-Volatile Organics		
Bis (2-ethylhexyl) phthalate	260	260
Di-n-butyl phthalate	12	12
Di-n-octyl phthalate	33	33
Pesticides & PCBs		
Aroclor-1254	1.3	1.3
General Chemistry		
pH (in pH units)	5.44	8.44
Metals		
Antimony	9	180
Arsenic	1	220
Beryllium	6	11
Cadmium	7	11
Chromium	10	210
Copper	10	17000
Lead	6	4100
Mercury	0.2	2.1
Nickel	50	2200
Silver	10	20
Zinc	80	12000

NAVAL SHIPYARD, NORFOLK (GROUNDWATER, SITES 3 - 7, DRAFT REPORT)

Waste compound	Minimum (ppb)	Maximum (ppb)
Volatile Organics		
Acetone	11	900
Benzene	5.4	21
2-Butanone	21	6800
Carbon disulfide	20	20
Chlorobenzene	5	17
Chloroethane	10	15
1,1 Dichloroethane	6.1	6.7
Ethylbenzene	5.1	190
Methylene Chloride	5.9	12
Tetrachloroethylene	5.7	12
Toluene	11	110
Trans-1,2-Dichloroethylene	6.4	6.4
Trans-1,3-Dichloropropene	5.6	5.6
Total xylenes	5.8	2100
Semi-Volatile Organics		
Acetanapthene	10	61
Acetanaphylene	14	14
Anthracene	13	13
Bis (2-chloroisopropyl) ether	17	17
Bis (2-ethylhexyl) phthalate	11	270
4-Chloroaniline	10	34
Dibenzofuran	11	56
1,2-Dichlorobenzene	23	23
1,4-Dichlorobenzene	16	22
2,4-Dichlorophenol	25	25
Diethyl Phthalate	12	12
2,4-Dimethylphenol	150	510
Di-n-butyl phthalate	14	320
Di-n-octyl phthalate	13	13
Fluorene	13	25
2-Methylnapthalene	14	76
4-Methylphenol	11	140
Napthalene	19	69
Phenanthrene	10	93
Phenol	17	18
Pesticides & PCBs		
Aroclor-1242	3.3	3.3
Aroclor-1254	5.2	36
General Chemistry		
Cyanide	0.09	0.09
Hexavalent Chromium	0.01	0.10
Oil and Grease	0.30	94
pH (in pH units)	6.25	12.08

NAVAL SHIPYARD, NORFOLK (GROUNDWATER, SITE 3 - 7, DRAFT REPORT)
(CONTINUTED)

Waste Compound	Minimum (ppb)	Maximum (ppb)
Metals		
Antimony	1	1400
Arsenic	2	300
Beryllium	5	8
Cadmium	5	51
Chromium	10	1700
Copper	10	12000
Lead	8	8800
Mercury	0.2	16
Nickel	30	4100
Selenium	10	20
Silver	10	40
Thallium	6	11
Zinc	10	22000

PACIFIC MISSILE TESTING CENTER, POINT MUGU (GROUNDWATER, SITE 1)

Waste Compound	Minimum (ppb)	Maximum (ppb)
Volatile Organics		
Acetone	4	11
Semi-Volatile Organics		
Bis(2-Ethyl)phthalate	2	110
Phenanthrene	2	2
Base-Neutral Extractable Organics		
1,4-Dichlorobenzene	8	8
Acid Extractable Organics		
Phenol	48	48
Pesticides & PCBs		
4,4-DDE	0.13	0.13
4,4-DDD	0.11	0.16
Aroclor-1016	2.70	2.70
Metals		
Barium	1270	2340
Cadmium	11	164
Chromium	59	728
Selenium	12	48
Copper	1550	1550
Lead	990	990
Zinc	5100	5100
Silver	140	140
Arsenic	906	1370

NAVAL WEAPONS STATION, SEAL BEACH (GROUNDWATER, SITE 7, DRAFT REPORT)

Waste Compound	Minimum (ppb)	Maximum (ppb)
Volatile Organic		
Acetone	99	130
Semi-Volatile Organic		
Di-n-butyl phthalate	11	11
Phenanthrene	15	15
Pyrene	11	11
Metals		
Silver	252	252
Chromium	47.8	402
Mercury	8.1	8.1
Nickel	63.3	270
Zinc	23	932
pH	5.9	6.9
Specific Conductance (umhos/cm)	22800	>50000
Salinity (parts/thousand)	15.7	40.0

TABLE V-2

SUMMARY OF THE CALCULATED TOC AND TOX OF CONTAMINANTS MEASURED AT SELECTED NAVAL FACILITIES

	CALCULATED TOC		CALCULATED TOX	
ACTIVITY	MIN	MAX	MIN	MAX
MCAS, Cherry Point	1.4	194	13	1800
NAS Moffett Field				
Site 1	3	41,268	2	1086
Site 2	5	113	2	68
NAVBASE Norfolk	(Draft Report)			
Site 1	11	6175	14	22,801
NAVSHIP Norfolk	(Draft Report)			
Site 2	245	246	6	7
Sites 3 - 7	364	8699	69	96
PMTC Point Mugu	46	130	4	4
NCBC Port Hueneme	4	6	--	--
NWS Seal Beach	(Draft Report)			
Site 7	27	88	8	8

* All of the values are in ppb.

B. Selection of Possible Parameters

Several investigators have studied the treatment of sanitary landfill leachate and promising results have been obtained with a number of treatment processes. Review of their studies indicate that specific process suitable for the treatment of a given leachate is related to its chemical composition which is in turn related to the degree of stabilization of the refuse or the age of the landfill. The second phase was conducted to relate the performance of each treatment method to the organic matter composition in the leachate.

Determining the value of the leachate parameters and knowing the age of the landfill will enable the design engineer to select suitable treatment processes for the removal of organic matter in leachate. For example, biological processes are not effective in removing organics from stabilized landfill leachate that have been generating leachate for substantial time period. Physical/chemical treatment processes are most effective in treating leachate from stabilized landfills or in further removing organic matter in the effluent of biological units treating leachate.

Since leachate characteristics vary widely for each landfill it is beneficial to concentrate at specific parameters. The solubility, volatility, adsorption potential, and degradation potential of the leachate is a good initial screening of the parameters to help determine which candidate technologies are suited for treatment (Gere & O'Brien Engineers, 1988).

The goal in leachate treatment is to reduce the constituents from groundwater. This objective can be accomplished by separating the compound or compounds of concern from the water. If the contaminant is an organic compound, it can be stripped with either air or water or biological treatment. If the contaminant is inorganic, it can be precipitated with physical/chemical processes. If the contaminants are organic and inorganic, ion exchange is a workable treatment process.

A paramount factor in choosing a treatment technology is the waste itself, its physical and chemical characteristics. The compounds are regulated by government standards and the chosen unit processes are affected by the treatability of the waste characteristics. Groundwater properties which affect the efficiency of the treatment process:

pH: The measurement of the hydrogen ion activity. Also an indicator of the corrosiveness of the groundwater. If the pH is extremely high or low, the groundwater is corrosive and would require special construction materials.

Alkalinity and acidity: An indicator of the consumption of chemicals in treatment systems, including the addition of chemicals to precipitate metals or to neutralize the water.

Total organic carbon, biological oxygen demand after 5 days, chemical oxygen demand: Indicators of whether excessive loading or fouling of adsorption filters might occur, and whether biological growth might occur within the treatment unit, such as in the packed column air stripper where conditions are favorable for growth of microorganisms when degradable compounds are present.

Total suspended solids (TSS): Matter that has the potential to plug carbon filters and ion exchange columns.

Odor: The smell of the treatment system is a concern because odorous volatile compounds can cause a public nuisance when released from the treatment system.

The contaminants are identified in the groundwater through laboratory analysis. The design goal is to use the properties of the compounds to advantage in the selection of a treatment technology and to make the treatment economical. The treatability of the contaminants depends upon the following properties: volatility, solubility, adsorption potential, and degradation potential.

Volatility

Volatility is the potential for a compound to evaporate--to pass from the liquid to the gas phase. Henry's law constant or the equilibrium constant quantifies the volatility of a compound (eq. 15). Henry's law states that the ratio of the concentration of a compound in water to its concentration in air is at equilibrium and a constant.

The amounts of solute, water and air must be constant an the water and air must be in contact for an extended time for equilibrium to take place. If a compound is not in equilibrium, it will either diffuse from water into air (stripping) or diffuse from air into water (scrubbing). The possibility that mass transfer will occur depends upon the driving force.

When the Henry's law constant for a compound is greater than 1000 atmospheres (1.03 x 10^7 kg/m2) the compound is considered highly volatile. When the constant is between 1 and 1000 atmospheres (1.03 x 10^4 and 1.03 x 10^7 kg/m2), the compound is moderately to highly volatile. Compounds with a Henry's law constant greater than 1 atmosphere (1.03 x 10^4 kg/m2) are amenable to treatment through stripping.

Solubility

The solubility of a compound gives an indication of the potential mobility of the compound within the ground water. Compounds which are water-soluble dissolve in the ground until either the water becomes saturated with the solute or the compound is completely dissolved. Water solubility defines the concentration at which water becomes saturated.

If the compound dissolves in water, it will flow with the ground water. But liquid compounds with slight solubility will form a separate phase. A compound with a density less than that of water, like gasoline, will migrate to the top of the water. But if a compound has a density less than that of water, like metal degreasing solvents trichloroethylene and perchloroethylene, it will sink through the ground water to the first confining layer.

Certain metallic elements like lead, chromium, copper, iron, cadmium, arsenic, barium, and silver become charged ionic species when dissolved in water. A change in the valence or charge can alter the solubility of the compound. For example, hexavalent chromium (Cr^{+6}) is converted to trivalent chromium (Cr^{+3}) by the addition of a reducing agent. The addition of this reducing agent diminishes the water solubility of the metal because the two ions have different properties. Usually metal ions are precipitated in the form of a metal hydroxide by increasing the pH of the solution with sodium hydroxide or lime. The chromium can be removed from solution by adjusting the pH.

Precipitation occurs when the reaction proceeds to the right and this can be initiated by the addition of either ionic species. The following solubility product expression describes the balance of the equilibrium between the anions and cations:

$$Ksp = [M+]^n[A-]^m \qquad \text{(eq. 43)}$$

where $[M+]$ = cation concentration
$[A-]$ = anion concentration
Ksp = solubility product constant

A precipitation system is designed to remove specific compounds. Inorganic compounds can be precipitated out by the addition of polymers, ferric hydroxide, or caustics. Precipitation is an effective treatment when the addition of the precipitating agent matches the concentration of the influent. Since the influent can vary daily, sophisticated controls should be used to operate this system. Suitable precipitation depends upon dissolved species present, intensity of the mixing, and availability of suspended solids for flocculation and settling. The control of the precipitating agent, intensity of mixing, storage and handling of the agent, and handling a disposal of sludge should be considered in the design of a precipitation treatment system.

Adsorption Potential

Compounds may have an affinity to adhere physically or chemically to the surfaces of certain solid substances called adsorbents. In the adsorption process, a solute can partition itself between the water and sorbent phases and an equilibrium is established for the partitioning of the solute. The preference of a solute for the sorbent phase (surface of the solid) depends generally on its solubility. Compounds with low solubility tend to partition to the sorbent phase. This equilibrium is expressed as (Metcalf and Eddy, 1979):

$$\log_{10} X/M = \log_{10} K + (1/n)\log_{10} C_s \quad \text{(eq. 44)}$$

where X/M = mass solute adsorbed/mass adsorbent
C_s = equilibrium concentration of solute in water
$1/n$ = measured constant
K = partition coefficient

The partition coefficient K and the constant 1/n are evaluated from a double-log plot of test data for X/M versus C_s, using a specific adsorbent and a specific solute or solute mixture.

Degradation Potential

Enzymes of organisms can break large contaminant molecules into fragments or organisms can modify the chemical nature of these molecules to obtain energy for cell growth. The resulting by-products usually have lower toxicity than the original substances. Many compounds are susceptible to degradation by biological action. The relative biodegradability of compounds can be determined by evaluating the ratio: BOD_5: COD: TOC. If the ratio is 1:2 to 3:1, the organic compounds are degradable. A low BOD_5 value indicates that part of the organic material resists degradation. A low TOC indicates that inorganic compounds making oxygen demands may be present.

C. Treatability Studies

Treatability studies are used to evaluate potential treatment processes of leachate (Henry and Heinke, 1989). Each site has different waste characteristics and it is the discretion of the engineering staff to determine the applicable treatability studies which should be conducted. After the field studies have been conducted and the wastes are identified, treatability studies can be conducted.

Treatability studies provide guidance in the identification of the candidate processes. Treatability studies examine the effectiveness of alternative methods as well as define design and operating standards. Treatability studies can also identify process modifications that may be required because of the strength and variable nature of landfill leachate.

Treatability studies can be divided into two groups: bench-scale and pilot-scale studies. Bench-scale studies are generally used to evaluate the most promising technologies for either selection or rejection. These studies are used to determine the impact of process variables on treatment performance over the range of expected and operating conditions. Pilot-scale studies are used to develop and optimize the design and operating parameters for a selected alternative and to demonstrate the long-term stability of the process.

Small scale, low cost bench tests enable the evaluation of many variables. Parameters which can be determined through bench-scale tests include chemical dosages, reaction rates, optimum temperature, pressure, and pH. Bench scale tests may require a few days to a few months to run.

Pilot-scale studies are used to define design and operating criteria for a selected alternative and to demonstrate the long- term stability of the process. Parameters which are easily tested at pilot-scale include mixing, separation, gas transfer, corrosion, and weather effects (EPA, 1985a as cited by McArdle et al., 1988). Stability of the process under fluctuation influent conditions (flow rate and composition) should be investigated to ensure that effluent limitations can be met. Pilot-scale test may require several months to a year or more to run.

Factors which influence selection are:

- effluent discharge alternative/limitations
- treatment process residuals
- permit requirements
- cost-effectiveness of treatment

Navy landfills contain inorganic and organic contaminants. The best overall treatment efficiencies generally can be achieved by removing the inorganic constituents first and then removing the organic constituents. This protects the biological, adsorption, and stripping processes from problems caused by metals toxicity, corrosion, and scaling.

Nyer (1985) suggests steps which should be taken before deciding on a biological treatment for the clean-up of a particular organic compound. The steps are:

- Search the literature for degradability of the compound.
- Run general organic concentration tests - BOD, COD, TOC.
- Run treatability studies.
- Select biological process to be applied.
- Set up on-site biological treatment system.

If the leachate has organics, biological processes may be used for treatment. If there are volatiles, air stripping may be used and if there are inorganics, chemical/physical processes may be used.

D. Treatment Trains

Treatability studies should be conducted to determine the unit processes which would be applicable to treat the leachate. But to narrow down the processes, the literature and treatment processes can help. Literature showed a number of landfills which had selected a treatment train.

After the treatment trains were reviewed, it was determined to choose sites which may be similar to Navy sites. Only two of the nine sites had a treatment train in place at the time this report was in preparation. The other sites had conducted treatability studies and were in either the design or construction phase. Discussions with the project managers concerning the treatability studies and operability of the selected sites would be beneficial to the Navy.

The project manager (PM) of each site was contacted in order to find more information about the treatment process (Table II-3). Table V-3 lists the sites, the respective contaminants, and the respective treatment process. These points of contact are available to answer questions concerning the site, including the reliability of the chosen treatment train. The following is a summary of the discussions which took place.

Sylvester Site (Gilson Road Site), Nashua, NH

This site was used as an illegal hazardous waste disposal site. The site was in operation in the 1970's and was stopped in the early 1980's. Remediation has been on-going for three years. The main problem is volatile organics, and metals are of a lesser concern. This process removes up to 99% of the volatiles. This may be a good process for the Navy to investigate further on concerning the removal of volatile organics, but Navy leachate will usually have a mixture of organics and metals.

Sand, Gravel, and Stone Site, Elkton, MD

This was a former sand and gravel quarry and hazardous waste was dumped into the pits. There was dumping in the mid-1970's. There is no design for the treatment system yet, but treatability studies are being conducted in January 1990. This site may help the Navy in the treatability studies.

Heleva Landfill, North Whitehall Township, PA

This is an unlined landfill, with mostly municipal solid waste and some industrial waste. A large amount of solvents was disposed of at this site. The landfill operated from the 1960's to the early 1980's. In the early 1980's, the landfill was shut down. The landfill cap has been completed and the treatment plant is being designed. The treatment process in the literature could not be confirmed, but the project manager thought that there would probably be a sedimentation tank and air stripper. Because this is an old landfill and there is municipal solid waste and industrial waste in the landfill, the leachate characteristics may be similar to the Navy's leachate. A follow- up call to the PM concerning the treatment train would help the Navy.

Marshall Landfill, Boulder, Colorado

This LF is unlined and is located by a water body, therefore the leachate is diluted with water. This LF was operating from the 1950's to the 1980's. A portion of the landfill is closed and another portion is active. MSW and industrial waste was disposed of in the LF. There are high concentrations of iron, magnesium, and ammonium, in addition to volatiles, semi- volatiles, oil and grease. Sedimentation and air stripping have been proposed in the conceptual design of the treatment train. The leachate is in dilute concentrations due to water intrusion, which is similar to Navy landfills.

Lipari Landfill, Mantua Township, N.J.

The landfill operated from the late 1950's to 1971. The contaminants include volatile organics, heavy metals, pesticides. Treatability studies

TABLE V-3

TREATMENT TRAINS IN USE OR TESTED AT SELECTED LANDFILLS

Site: Sylvester Site (Gilson Road Site)
Contaminants: Heavy Metals, Volatile Organics, Alcohols, Ketones
- Precipitation
- Neutralization
- Filtration
- High-Temperature Air Stripping/Fume Incineration
- Activated Sludge (Extended Aeration)

Site: Sand, Gravel, and Stone Site
Contaminants: Heavy Metals, Volatile Organics, Semivolatile Organics (Acid Extractables, Base/Neutral Extractables)
- Equalization
- Reduction
- Precipitation/Flocculation/Sedimentation/Sludge Dewatering
- Neutralization
- Filtration
- Carbon Adsorption

Site: Heleva Landfill
Contaminants: Heavy Metal Volatile Organics, Dissolved Organics
- Precipitation/Flocculation/Sedimentation
- Neutralization
- Activated Sludge
- Air Stripping
- Carbon Adsorption

Site: Marshall Landfill
Contaminants: Metals, Volatiles, Semi-volatiles, Oil and Grease
- Proposed Treatment:
- Sedimentation
- Air Stripping

Site: Lipari Landfill
Contaminants: Heavy Metals, Volatile Organics, Phenols
- Equalization
- Precipitation/Flocculation/Sedimentation
- Air Stripping/Vapor-Phase Carbon Adsorption
- Granular-Media Filtration
- Carbon Adsorption

Site: Helen Kramer Landfill
Contaminants: Heavy Metals, Volatile Organics, Phenols
- Equalization
- Precipitation/Flocculation/Sedimentation
- Air Stripping/Vapor-Phase Carbon Adsorption
- Activated Sludge
- Granular-Media Filtration
- Carbon Adsorption
- Chlorination

Site: Stringfellow Acid Pits
Contaminants: Heavy Metals, Organics
- Equalization
- Precipitation/Flocculation/Sedimentation/Sludge Dewatering
- Granular-Media Filtration
- Carbon Adsorption

have been conducted on the leachate. Construction has just started and it is anticipated that it will be completed in fifteen months. After treatment the effluent is discharged to the POTW. The landfill is surrounded by a slurry wall and has a natural clay lining. The leachate is extracted by extraction wells and clean water is injected into the landfill.

Helen Kramer Landfill, Mantua Township, N.J.

This is an unlined landfill that accepted municipal solid waste and light industrial waste. The landfill operated from the 1960's and 1970's and closed in 1981. Treatability studies were conducted on a bench-scale. After treatment the effluent is further treated by a POTW, and discharge to the Delaware River. The landfill is located by a stream and the leachate is leaching into the stream. A trench was located between the landfill and stream which is where the leachate is collected from. This site may be a helpful future reference because the waste characteristics are similar to Navy landfills and it is located by a waterway.

Fresh Kills Landfill, New York City, N.Y.

This is the largest landfill in the world and is located on Staten Island. Portions of the landfill are twenty to forty years old and other portions are still operating. Wetlands are located around portions of the perimeter of the landfill. Because the landfill is located by the ocean, there is also a tidal effect. The leachate is collected by perforated pipes and french drains which surround the perimeter of the landfill. Since portions of the landfill has a bottom clay layer or a layer with a low permeability, the leachate is recirculated through the landfill. The priority pollutants were below the detection limit but the BOD, COD and ammonia were at relatively high concentrations and are of concern. Treatability studies are being conducted and should be completed by mid 1990 summer. Treatability studies showed that sequencing batch reactor, rotating biological reactor, and activated sludge work on the ammonia problem. Chemical precipitation is not effective for COD, but carbon adsorption removes approximately 85% of the COD. This may help the Navy in conducting treatability studies since the landfill is located by an ocean. In this discussion, the New York State Energy, Research, and Developmental Commission was mentioned. This commission is currently doing work on treatability studies. A point of contact at the Commission is John Morelli at (518)465-6251.

Stringfellow Acid Pits, CA

This treatment plant has been in operation since 1985. The leachate has high concentrations of TCE, volatile, heavy metals, and organics, to name a few. The leachate is treated and the effluent is discharged to a POTW. This treatment process has no problems meeting the permit standards. The groundwater is naturally salty which would be of interest to the Navy. In order to fellow up on the site, the EPA, Region IX in San Francisco, Superfund Section should be contacted. Due to the earthquake, project managers were difficult to contact and phone numbers and offices are in the process of transition.

Engineered Wetlands To Treat Leachate

Dr. Donald Hammer of the Tennessee Valley Authority (TVA) studies the applicability of constructed wetlands for the treatment of municipal wastewater, acid mine drainage, industrial wastewaters, agricultural wastewaters, metal plating wastewaters and landfill leachate, to name a few. Studies show that various metals can be treated by the wetland, but not enough studies have been conducted on the removal of other pollutants. Volatile organics can probably be removed by wetlands. A constructed wetland is sealed at the bottom to isolate the water in the system from the groundwater. Dr. Hammer is currently working on an operating-scale constructed wetland to treat leachate landfill in Alabama. The landfill is approximately thirty to forty years old and contains some toxic wastes (i.e., PCB's). The estimated construction completion date is March 1990. The Navy may be interested in using constructed wetlands to treat landfill leachate. The Navy has land area and the pollutants are at relatively low concentrations, therefore constructed wetlands may be a economical and feasible treatment process. Two applicable books concerning constructed wetlands are: Ecological Consideration in Wetland Treatment of Municipal Wastewater, Godfrey, P.J. et al, Van Reinhold Company, N.Y., 1985 and Constructed Wetlands for Wastewater Treatment, Hammer, D., Lewis Publishers, 1989.

E. Illustrated Example

NWS, Seal Beach was selected as the subject of an illustrated example. to determine the percentage of contaminant removed based upon the selected treatment train. After reviewing the treatment trains in the literature, the summary table on the contaminants which are removed, and the contaminants at Seal Beach, the following treatment was selected:

equalization
precipitation/flocculation/sedimentation
air stripping/vapor-phase carbon adsorption
granular media filtration
carbon adsorption

These treatment steps are used at the Helen Kramer landfill.

The removal ranges for the compounds were taken from the Treatability Manual (U.S. EPA, 1980) except for acetone. Studies were conducted on various treatment technologies and the results list the removal ranges and the average achievable concentrations. These values are used to estimate the removal of a contaminant after a unit process. The conservative value was chosen from either the removal range or the average achievable concentration, whichever value was higher.

Treatability studies should be conducted to properly test the treatability of the leachate.

After precipitation/flocculation/sedimentation (chemical addition with lime)

Contaminant	Infl, ppb	Removal Range,%	Average Achiev,ppb	Effl, ppb
Acetone	130	---	---	130
Hexachlorobenzene	11	---	---	11
Phenanthrene	15	0	---	15
Pyrene	11	0	---	11
Silver	252	24	4	191.5
Chromium	402	49	340	340
Mercury	8.1	35	1.4	5.3
Nickel	270	40	540	270
Zinc	932	77	640	640

After air stripping (using aerated lagoon values).

Contaminant	Infl, ppb	Removal Range,%	Average Achiev,ppb	Effl, ppb
Acetone	130	72	---	36.4
Hexachlorobenzene	11	0	---	11
Phenanthrene	15	0	---	15
Pyrene	11	67	1	3.6
Silver	191.5	---	---	191.5
Chromium	340	63	380	340
Mercury	5.3	99	0.1	0.1
Nickel	270	17	34	224.1
Zinc	640	55	180	228

Note: The stripability of acetone (aeration by compresed air) is 72%.
After granular filtration (used values under filtration).

Contaminant	Infl, ppb	Removal Range,%	Average Achiev,ppb	Effl, ppb
Acetone	36.4	---	---	34.6
Hexachlorobenzene	11	---	---	11
Phenanthrene	15	40	40	15
Pyrene	3.6	0	---	3.6
Silver	191.5	11	22	170.4
Chromium	340	67	67	112.2
Mercury	0.1	45	340	0.1
Nickel	224.1	31	64	154.6
Zinc	288	39	940	288

After carbon adsorption (used values for granular activated carbon).

Contaminant	Infl, ppb	Removal Range,%	Average Achiev,ppb	Effl, ppb
Acetone	36.4	78	---	28.5
Hexachlorobenzene	11	---	0.4	11
Phenanthrene	15	63	2.5	5.6
Pyrene	3.6	82	2.0	2.0
Silver	170.4	7	32	158.5
Chromium	112.2	33	910	112.2
Mercury	0.1	33	0.8	0.1
Nickel	154.6	17	78	128.3
Zinc	288	40	200	200

Based on the above removal rates.
California

Contaminant	Infl, ppb	Percent Removed,%	Effl, ppb	Drinking Water Standard,ppb
Acetone	130	72	28.5	---
Hexachlorobenzene	11	0	11	---
Phenanthrene		15	45	5.6
Pyrene	11	82	2.0	
Silver	252	37	158.5	50
Chromium	402	47	112.2	50
Mercury	8.1	56	0.1	2
Nickel	270	43	128.3	---
Zinc	932	59	200	500

Based on the Treatability Manual and the removal rates of wastewater for each of the processes, the contaminants were removed. Standards for zinc and mercury were also met. Chromium and silver were still above the state standards. Air stripping process removal ranges were not included in the Treatability Manual but the aerated lagoon values were used and the value for air stripping for acetone was used from the Handbook of Environmental Data on Organic Chemicals (Verschueren, 1983). It was assumed that the removal values for aerated lagoons are more conservative than removal values for air stripping.

This selected process does not appear to be effective for the given leachate for achieving the mandated drinking water standards. The leachate is dilute so it was decided to try a train which removes more dilute concentrations. Technologies which are usually used for "polishing" were selected in series. The table of technologies and the wastes that they remove (Table IV-2) were compared with the wastes in the leachate. The following treatment train was selected:

air stripping
ion exchange
carbon adsorption

The Treatability Manual (U.S. EPA, 1980) did not give removal ranges for air stripping, so removal ranges for aerated lagoons were used. Aerated lagoons give more conservative removal range values than air stripping.

After air stripping (using aerated lagoon values).

Contaminant	Infl, ppb	Removal Range,%	Average Achiev. ppb	Effl, ppb
Acetone	130	72	---	36.4
Hexachlorobenzene	11	0	---	11
Phenanthrene	15	0	---	15
Pyrene	11	67	1	3.6
Silver	252	---	---	252
Chromium	402	63	380	380
Mercury	8.1	99	0.1	0.1
Nickel	270	17	34	224.1
Zinc	932	55	180	419.4

Note: The stripability of acetone (aeration by compressed air) is by 72%.

After ion exchange (values used for ion exchange).

Contaminant	Infl, ppb	Removal Range,%	Average Achiev. ppb	Effl, ppb
Acetone	36.4	---	---	36.4
Hexachlorobenzene	11	---	---	11
Phenanthrene	15	---	---	15
Pyrene	3.6	---	---	3.6
Silver	252	99	10	10
Chromium	380	99	10	10
Mercury	0.1	---	---	0.1
Nickel	224.1	99	10	10
Zinc	419.4	97	400	400

After carbon adsorption (values used for granular activated carbon).

Contaminant	Infl, ppb	Removal Range,%	Average Achiev. ppb	Effl, ppb
Acetone	36.4	21.8	---	28.5
Hexachlorobenzene	11	---	---	11
Phenanthrene	15	63	0.12	5.6
Pyrene	3.6	83	0.01	0.6
Silver	10	7	21	10
Chromium	10	33	20	10
Mercury	0.1	33	1.6	0.1
Nickel	10	17	110	10
Zinc	400	40	440	400

Based on the above treatment train.

Contaminant	Infl, ppb	Percent Removed,%	Effl, ppb	California Drinking Water Standard,ppb
Acetone	130	78	28.5	---
Hexachlorobenzene	11	0	11	
Phenanthrene	15	63	5.6	---
Pyrene	11	95	0.6	
Silver	252	96	10	50
Chromium	402	98	10	50
Mercury	8.1	99	0.1	2
Nickel	270	96	10	---
Zinc	932	57	400	500

In this treatment scheme, all of the drinking water standards were met.

F. Innovative Treatment

1. Land Treatment

In land treatment of the wastes, the decontamination mechanisms would include adsorption on clays and organic matter, chemical precipitation, uptake by plants and organisms, volatization, dilution and dispersion.

The leachate can be collected and go through air stripping or an aerated lagoon and then PACT. After PACT, the water can be applied to the land by irrigation. Air stripping removes volatile organics and the PACT will remove volatile organics and semivolatile organics. The metals are at such a low concentration that they can possibly be applied to the land.

The leachate will have a lower concentration of organics after air stripping. The metals can be adsorbed on the soil. The cation exchange capacity of the soil will come into play in the removal concentration of the metals. Table V-4 helps in the fate of the contaminant in the environment.

State and federal regulations should be checked to determine the allowable loading metals application on to the land. Also the soil properties, including the cation exchange capacity, should be determined.

2. Constructed Wetlands

Constructed wetlands may be a feasible and economical treatment process for the Navy to use on landfill leachate. The initial costs may be more expense than for a conventional system but the operation and maintenance costs will probably be less than a conventional system. Most Navy bases have land adjacent to the landfill which could be used to construct a wetland. This is a resilient system capable of handling fluctuating loading rates. An operator would have to ensure that the vegetation is in good condition, there are no dikes, and maintain the roads along the dike.

G. Costs: conventional approach

The following is a comparison of the cost for two treatment trains. The estimate is based on 50 gal/min and 1986 dollars.

TABLE V-4

EXPECTED FATE OF A CONTAMINANT

	FATE CODE					
	1	2	3	4	5	6
Acetone	+	+	+	?	?	?
Hexachlorobenzene	+	-	-	-	-	+
Phenanthrene	+	+	+	+	-	-
Pyrene	+	-	+	+	-	-
Silver	-/+	-	-	-	*+	+
Chromium	+	-	-	-	?	+
Mercury	+	+	-	-/+	-	+
Nickel	-/+	-	-	-	-	-
Zinc	+	-	+	-	+	+

Key:
+ : could be an important fate transport
- : not likely to an important process
1: Sorption
2: Volatilization
3: Biodegradation with Biosorption
4: Photolysis-Direct
5: Hydrolysis
6: Bioaccumulation

*: Above pH 7

Adapted from Mills et al., September 1985 and USEPA, July 1980.

The original conventional treatment train is:
precipitation/flocculation/sedimentation
air stripping
granular filtration
carbon adsorption

Technology	Capital Costs, $	Annual O&M, $
precip/floc/sed	229,000	30,000
air stripping	118,000	70,000
granular filtration	25,000	6,200
carbon adsorption	107,000	58,000
TOTAL	479,000	164,200

Cost estimate for the revised treatment train:
air stripping
ion exchange
carbon adsorption

Technology	Capital Costs, $	Annual O&M, $
air stripping	118,000	70,000
ion exchange	83,000	16,000
carbon adsorption	107,000	58,000
TOTAL	308,000	144,000

These estimates do not include the labor cost for the operators to run the system.

H. Performance Evaluation Criteria

The selected treatment trains will vary at each site due to it being a different environment and situation. A performance evaluation criteria can be conducted on each treatment train in order to determine if the selected process is suitable for the site. First the factors which are important performance characteristics for the treatment train should be determined. Once the factors are identified, the "Concordance Approach" may be utilized to assist in the development of a priority scheme.

Factors which are important in the selected treatment train can be discussed by selected Navy personnel.(NAVFAC, EFDs, NCEL, NEESA,) and the activities are the recommended parties who should be involved in the determination of the performance factors. Performance characteristics which may be of importance to the Navy are: technology effectiveness; contaminant interferences; technology versatility; time for decontamination; residual generation; safety; operability; cost of processing; technical feasibility; technology mobility; environmental impact; and regulatory impact (Bove , et al., 1984). Figure V-1 is a sample scoring card used to rank performance evaluation criteria. Table V-5 is a sample of the definitions of

		PERFORMANCE EVALUATION CRITERIA											
		Effectiveness	Contaminant Interference	Technology Versatility	Time for Decontamination	Residual Generation	Safety	Operability	Cost of Processing	Technical Feasibility	Technology Mobility	Environmental Impact	Regulatory Impact
PERFORMANCE EVALUATION CRITERIA	Effectiveness	X											
	Contaminant Interference		X										
	Technology Versatility			X									
	Time for Decontamination				X								
	Residual Generation					X							
	Safety						X						
	Operability							X					
	Cost of Processing								X				
	Technical Feasibility									X			
	Technology Mobility										X		
	Environmental Impact											X	
	Regulatory Impact												X

Figure V-1. Sample Scoring Card Used to Rank Performance Evaluation Criteria.

Table V-5. Definition of Performance Evaluation Criteria for Navy Landfills, After Bove et al, (1984)

1)	Effectiveness	- Removal and/or stabilization of contaminants from selected waste stream has been demonstrated by the process.
2)	Contaminant interference	- The process effectiveness has been demonstrated to be unaffected by the presence of various other types of contaminants in a single waste stream.
3)	Versatility of technology	- The technology demonstrates the ability to remove or stabilize a variety of organic and inorganic contaminants in a single waste stream.
4)	Time for decontamination	- The decontamination process will effectively treat the waste stream in an acceptable period of time.
5)	Residuals generated	- If residuals are generated as a result of the treatment process, they will be nonhazardous and will not significantly increase the volume of waste to be disposed.
6)	Safety	- The process does not pose a threat to Navy personnel or local residents during or after treatment.
7)	Operability	- The process can be properly operated or implemented with minimal skill and/or technical training.
8)	Cost of processing	- Operating and maintenance costs must be competitive when compared to legitimate alternatives.
9)	Technical feasibility	- The commercially available process can be immediately utilized for the treatment of foundry wastes without substantial alterations to its design.
10)	Mobility of technology	- The technology is mobile or easily transportable from base to base to facilitate on-site treatment of selected solid wastes.

performance evaluation criteria for Navy landfill leachate. These definitions may be changed, modified, added to, or deleted from according to the activities' needs. A survey is mailed out to participating parties, and they should prioritize the factors. Based on the results of the survey, the performance criteria for a treatment train are ranked.

The "Concordance Approach" utilizes forced comparisons combined with a binary rating system to determine relative importance among various factors. The concept of forced comparisons has root in the belief that the accuracy and reliability of ranking can be considerably improved by factors in pairs rather than as a total group. When forced comparisons are used, the evaluating judge is required to select the better of each pair. The approach reduces "central tendency," due to the assignment of too many tied values.

The "Concordance Approach" has many advantages which are (Knott, et al., 1985-1986):

- quantifies opinion;
- tests concordance among evaluators;
- reduces effects of bias;
- encourages participation of specified levels of management;
- reduces evaluation to binary decisions;
- incorporates knowledge of informed evaluators;
- generates confidence among users;
- identifies relative importance of factors;
- clarifies the purpose of the process;
- minimizes emotion; and
- proves to be analytical approach.

Appendix C explains the methodology of the "Concordance Approach."

VI. SUMMARY AND RECOMMENDATIONS

A. Summary

Limited analyses could be made from the data available. The age of the landfills are relatively old and the nature of the leachate is relatively dilute. The presence of elevated salinity and unidentified organics in the affected groundwater confound treatability predictions. The following observations can be made about the treatment of Navy leachate; based on available information:

(1) polishing type processes would probably be more efficient and economical in the treatment of Navy leachate (dilute wastestreams);

(2) treatability studies using bench-scale and pilot-scale systems should be conducted on the leachate in order to accurately establish treatment potential;

(3) pilot studies operated over a range of adverse conditions might be used to indicate the sensitivity of a candidate treatment train for maintaining quality control of the effluent steam when subjected to inadvertent operating difficulties;

(4) effluent standards are set and enforced by regulatory agencies and the selected treatment process should meet or exceed these objectives; and

(5) as related to (4), a performance evaluation program might be used to aid in the selection of candidate treatment trains that fulfill the Navy mission within budgetary and personnel limitations.

B. Recommendations

Further work should be carried out in this area. Laboratory work should be conducted using site-specific leachates in order to properly select the treatment train. Once a treatment train is selected further studies should be conducted to streamline the process.

The gases generated from the landfills and the residual solids generated from the treatment processes were not investigated but could involve impacts of concern due to the presence of hazardous and toxic components. Treatment or disposal of these residuals should also be addressed.

Also more research in the innovative processes of land treatment and engineered wetlands was suggested in order to investigate alternatives to conventional remediation treatment.

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APPENDIX A

OBSERVED CONCENTRATION RANGE

A1GW - MCAS, CHERRY POINT; GROUNDWATER; SITE 10

A1LW - MCAS, CHERRY POINT; LEACHATE WATER; SITE 10

A1LS/S - MCAS, CHERRY POINT; LEACHATE SOIL/SEDIMENT; SITE 10

A1PW - MCAS, CHERRY POINT; POTABLE WATER; SITE 10

A2GW1 - NAS, MOFFETT FIELD; GROUND WATER; SITE 1

A2S1 - NAS MOFFETT FIELD; SOIL; SITE 1

A2GW2 - NAS MOFFETT FIELD; GROUND WATER; SITE 2

A2S2 = NAS MOFFETT FIELD; SOIL; SITE 2

A3GW1 = NAVBASE, NORFOLK; GW; SITE 1

A3SW1 = NAVBASE, NORFOLK; SURFACE WATER; SITE 1

A4GW2 = NAVSHIP, NORFOLK; GROUND WATER; SITE 2

A4SW2 - NAVSHIP, NORFOLK; SURFACE WATER; SITE 2

A4SED2 - NAVSHIP, NORFOLK; SEDIMENTS, ROUND1; SITE 2

A4GW3-7 - NAVSHIP, NORFOLK; GROUND WATER; SITES 3 THROUGH 7

A4SW3-7 - NAVSHIP, NORFOLK; SURFACE WATER; SITES 3 THROUGH 7

A4SED3-7 - NAVSHIP, NORFOLK; SEDIMENTS, ROUND1; SITES 3 THROUGH 7

A4S3-7 - NAVSHIP, NORFOLK; SOIL; SITES 3 THROUGH 7

A5S - NCBC, PORT HUENEME; SOIL; SITE 14; DRAFT REPORT

A6GW1 = PMTC, POINT MUGU; GROUND WATER; SITE 1

A6S1 = PMTC, POINT MUGU; SOIL; SITE 1

A7GW7 = NWS, SEAL BEACH; GROUND WATER; SITE 7

A7S7 = NWS, SEAL BEACH; SOIL; SITE 7

A7SW7 = NWS, SEAL BEACH; SURFACE WATER; SITE 7

APPENDIX A10W
OBSERVED CONCENTRATION RANGE (MCAS, CHERRY POINT; GROUNDWATER; SITE 10)

COMPOUND	10EGW01	10EGW02	10EGW03	10EGW04	10EGW05	10EGW06	10EGW07	10EGW08	10EGW09	10EGW10	10EGW11	10EGW12
Organics												
2-Butanone					730							
4 Methyl-2-Pentanone					170							
Benzene		8			6				53-160	19-24	5-11	10
Toluene												
Ethylbenzene			21		50-120				25-92	8-1100		120
Total Xylenes					12				35		37	
Chlorobenzene		7			52-110				40-79	17		
1,1,1-Tri-Chloroethane			7		85-160	12-29		150	5	53-200	9-28	36-45
1,1-Dichloroethane		20-66	20-140		500-1000	11-50	8	94-120	13-57			
Chloroethane		14-100	15-29		110-2500	20-42		22	12-27			9
Tetrachloroethene		6-10			7			5				81-280
Trichloroethene		8-17	88		110-410	71-150		69-650				55-180
Trans-1,2-Di-chloroethane		41-120	29-55		280-1900	110-480	13-42		14-67	170-1300		12
1,1-Dichloroethene			14-17		70							
Vinyl Chloride			150		14				35-73	190-2600		
Methylene Chloride					430-560	5		56-530				
Chloromethane					56							
Acid/Base Neutrals												
Phenol					150							20
Diethylphthalate		15-33								13-24	13-25	
Napthalene					110-131				11			
1,2-Dichlorobenzene					12							
1,4-Dichlorobenzene									16	15-26	20	
Pesticides												
Beta-BHC						.34						
Inorganics												
Arsenic		7	14	1-6	47-68	17-20			6-33	3-11	12-45	3
Cadmium							8					
Chlomium				10						20		
Mercury	.4	.7										
Nickel					30-50					40-80		
Zinc	10-30	10	10-20	10	10-20	10-20	10	10-40	10-20	20	10	10-20
Cyanide			10		9	5	13		9	40	5	
Geochemical Parameters												
pH	4.93-5.48	6.45-6.5	6.44-6.65	6.71-6.8	6.48	6.26-6.65	7.15-7.45	5.5-6.09	6.17-6.55	6.38-8.63	6.19-6.67	6.44-6.61
specific condu (umhos/cm)	100-150	500-600	510-1400	340-640	710-880	200-300	280-370	170-280	610-1000	910-1200	950-1500	1000-1300
temp(C)	8.4 C-20.9 C	14.9-17	14-17	15.3-17	17	10.4-17	9.3-17	13.2-17	6.8-20.3	13-19.1	7.4-19.7	14.9-18.6
TOC (ppm)	1.6-18.0	12.4-94.9	12.9-87.3	5.4-66.8	15.3-229	4.2-37.4	1.4-37.5	2.4-109	26.3-211	29.4-168	31.1-194	12.8-170
TOX (as Cl)(ppb)	13	110-370	170-270	17-69	310-1800	55-420	26-28	130-290	130-200	150-510	140-150	40-360
Phenolics (ppb)		20-400		60	170-1700	30			40-70	130-200	20-60	50-240

In ppb unless noted otherwise.

APPENDIX A1LW
OBSERVED CONCENTRATION RANGE (MCAS, CHERRY POINT; LEACHATE WATER; SITE 10)

COMPOUND	10LW01	10LW02	10LW03	10LW04	10LW05	10LW06	10LW07
Organics							
1,1-Dichloroethane	26			6-13			
Chloroethane	23		5				
Chlorobenzene			7		72		
Benzene	68				12		
Acids							
2-4-Dimethyphenol					14		
Inorganics							
Arsenic	260	1-6	10	2-3	5-11	6	5
Copper					.04		
Zinc	10-130	10-30	10-20	10	100		
Cyanide				7	74	140	
Geochem. Parameters							
pH	6.33-6.57	7.28-7.43	6.6-6.68	6.39-7.4	6.16-6.41	6.74	6.99
Specific Conduc (umhos/cm)	450-2100	100-340	450-2000	230-350	550-670	160	140
Temp (°C)	5-21.7	5-21.7	5-20.3	5-19.7	13.8-19.5	14.7	13.4
TOC (mg/l)	16.8-22.5	6.4-36.5	11.6-32.3	6.1-57.6	13.4-48.7	20.6	27.9
TOX (as Cl)	80-130	25-140	28-120	30-56	100-140	140	90
Phenolics				20	40		

*In ppb unless noted otherwise.

APPENDIX 1LS/S

OBSERVED CONCENTRATION RANGE (MCAS, CHERRY POINT; LEACHATE SOIL/SEDIMENT; SITE 10)

COMPOUND	10LS01	10LS02	10LS04	10S05	10SD03	10SD06	10SD07
Solids (%)	69	74		21	72	75	78
Organics				560			
Chlorobenzene			9				
Phenolics		8000					
Methylene Chloride						16	
PCB-1245		300		810			
Inorganics							
Actimony	70	50	10-20	30	10-20		
Arsenic	.4-.44	2-6.7	2-6.6	.4-11.3	3.6		.3
Beryllium			.5	.4	2		
Cadmium	.8	1.3	1-1.3	1.5-1.6	1.6		
Chromium	2	6-11	10-23	-34	2-3		
Copper	2-4	4-29	4-11	31-39	2-3		
Lead	8	26-41	30-48	100-140			
Mercury			31	.1			
Nickel		8	5-13	9-18		3	
Silver			1	2			
Thallium				10			
Zinc	10-27	8-92	7-23	43-72	2-6	1	
Cr+6	1	3	4	.6-.34			

*In ppb unless noted otherwise.

APPENDIX A1PW
OBSERVED CONCENTRATION RANGE
(MCAS, CHERRY POINT; POTABLE WATER; SITE 10)

COMPOUND	10PW01	10PW02	10PW03	10PW04	10PW05	10PW08	109W11	10PW13	10PW14	10PW16	10PW17	10PW19
Inorganics												
Cadmium	7											
Chromium	20											
Copper	140											40
Nickel	40											
Zinc	10-24	10-50	20-60	20	20		20-40	20-40	40			10
Arsenic		2						2	20	3		2
Mercury							0.3					
Cyanide												
Geochem. Parameters												
pH	7.34-7.55	7.24-7.45	7.28-7.48	7.07	7.13-7.53	7.4	7.18-7.6	7.5-7.51	7.6	7.45-7.88	9.65	7.46-7.60
Specif. Conduct (umhos/cm)	430-780	450-560	400-540	460	390-480	410	410-440	390-410	480	380-420	170	430-450
Temp. (C)	16-18.9	16-24.1	15-18.7	16	16-17	18.9	17-19.4	18-18.1	19.2	16-17.6	18	17-18.7
TOC (ppb)	4800-124000	7400-55500	6700-53800	8500	8900-52600	6800	7200-7900	7300-7900	6900	7400-8100		7600-8300
TOX (as Cl) (ppb)	17	48	16		16							

*In ppb unless noted otherwise.

APPENDIX A2GW1
OBSERVED CONCENTRATION RANGE (NAS, MOFFETT FIELD; GROUND WATER; SITE 1)

	W1JS	W01-05(A)	W01-06(A)	W01-07(A)	W01-08(A)
Organics (ppb)					
1,2-Dichloroethenes					
1,3 Dichlorobenzene					
1,4 Dichlorobenzene					
2,4 Dimethylphenol					
2-Butanone					
2-Chlorophenol		36			
2-Methylphenol					
4-Chloro-3methylphenol		22			
4-Methyl-2-pentanone					
2-Methylnaphthalene					
4 Methylphenol					
Acetone	4-7	13	3-4		3
Benzene					
Benzoic Acid					6
Bis(2-Ethylhexyl)phthalate	3	4	2-3	8	
Chloroform					
Di-n-butylphthalate					
Diethylphthalate					
Ethyl Benzene					
Methylene chloride	6-59	7-13	3-11	5	2-13
N-nitroso-dipropylamine					
N-nitrosodiphenylamine				2	
Pentachlorophenol		24			
Phenol		33			
Tuluene		2			
Naphthalene					
Total Xylenes					
Inorganics (ppb)					
Aluminum	1040	34.7	58.5-1200	25-25.3	639
Antimony		155-676	559-1670	86.9-88.9	480-554
Arsenic	6				6
Barium		44.9-271	126-311	16.8-16.9	64.9-111
Beryllium			1.2		5
Bicarbonate		2100	820-1200	680-690	1500
Cadmium		43	10		42
Calcium	4360000	37200-322000	434000-570000	31400-32500	370000-430000
Carbonate		2000			
Chloride	21000	22000-94000	22000-30000	27000-30000	23000-26000
Chromium		173	10		157
Cobalt		62.1	10.9-19.6		69.6
Copper		26.5	5.6		30.6
Fluoride	59	57	63-35		70
Iron		1750	357-4800	181-197	2070-2670
Lead			139		
Magnesium	1320000	149000-1600000	1360000-1820000	93600-97000	1570000-1590000
Manganese		190-1430	2150-7060	363-377	1420-1570
Mercury					0.4
Nickel		117	9.2		121
Nitrate					340000-378000
Potassium	498000	32400-328000	372000-449000	17400-18100	
Selenium		5.9			
Silver		5.2-25.9	163	4.8-5.6	29.2-64.6
Sodium	10000000	1280000-11600000	1100000000-13000000	81000-842000	11700000-12100000
Sulfate	30000	6.9-640	2300-3100	3600-4300	1400-1700
TDS	>20000	>20000	>20000	>20000	>20000
Thallium					90
Vanadium		88.9	43-520		90.4-138
Zinc		12.1-26	6.6-9.6	4.3-4.9	27.1-32.7

APPENDIX A2GW1-CONTINUED
OBSERVED CONCENTRATION RANGE (NAS, MOFFETT FIELD; GROUND WATER; SITE 1; CONTINUED)

	W01-09(F)	W01-10	W01-11	W01-12	W01-13
Organics (ppb)					
1,2-Dichloroethenes				2	
1,3 Dichlorobenzene					
1,4 Dichlorobenzene	19			12-35	
2,4 Dimethylphenol	240	64	370	2	
2-Butanone	120-1000	290-49000	46		
2-Chlorophenol					
2-Methylphenol	21	13	23-2000		
4-Chloro-3methylphenol					
4-Methyl-2-pentanone	24-220	8300	16-84		
2-Methylnaphthalene			5		
4 Methylphenol	1900-7900	85	37		
Acetone	210-1500	2700	180-950		12-16
Benzene			9		3
Benzoic Acid	1800-11000	20			37
Bis(2-Ethylhexyl)phthalate		23		4	19-31
Chloroform					
Di-n-butylphthalate					
Diethylphthalate			22		
Ethyl Benzene	18		11		6-9
Methylene chloride	11-130	22-1300	22-47		6-22
N-nitroso-dipropylamine	54				
N-nitrosodiphenylamine	19	16	25		14
Pentachlorophenol					
Phenol	28-98		87		
Toluene	17-130	38-660	67-340		2
Naphthalene			14		
Total Xylenes	6-56	9	47		10-11
Inorganics (ppb)					
Aluminum	11.9-136	625	46.1-2110	1840	573-704
Antimony	84.2-593	25.9-351	114-1490	1610	30-386
Arsenic	11	9-29.2	19		7
Barium	317-4480	66.1-1060	315-4200	407	39.5-994
Beryllium					0.7
Bicarbonate	2200-2600	1200	2200	1300	2400-2500
Cadmium			6.7	5.2	
Calcium	28000-535000	-334000	11600-240000	457000	12600-227000
Carbonate					
Chloride	29000-32000	4900-6800	48000-53000	25000	7500-15000
Chromium	10.5	10.3	20.9	41.1	10.9-11.2
Cobalt	6.1	17.6			7.6
Copper				41.1	
Fluoride	140	38	12		27-160
Iron	584-27500	8290	8.3-108000	10200	12.2-5000
Lead			91		
Magnesium	91800-1460000	27800-488000	124000-1460000	1510000	39700-582000
Manganese	35.6-629	8.9-3600	45.2-1770	4000	26.7-410
Mercury					
Nickel	23	63.8		44.7	18-26
Nitrate		4	20		
Potassium	17800-284000	4050-67600	56400-50000	361000	14400-191000
Selenium					
Silver			65.3	276	3
Sodium	751000-12300000	153000-2190000	1640000-16400000	11000000	359000-4870000
Sulfate	26	61-68	30	2100	160-620
TDS	>20000	10000-10800	>20000	>20000	16020-20000
Thallium	130		140	90	
Vanadium				152	
Zinc	11.5-186	3.6-296	10.8	65.5	3.2-99.5

APPENDIX A2S1

OBSERVED CONCENTRATION RANGE (NAS, MOFFETT FIELD; SOIL; SITE 1)

	EMB-01	EMB-02	EMB-03	EMB-04	SED-01	SED-02	W01-05(A)	W01-06(A)
Organics (ppb)								
1,2,4-Trichlorobenzene	66							
1,2-Dichloroethenes								
2-Butanone							8-27	
4-Chloro-3-methylphenol	180							
4-Methyl-2-pentanone								
4-Methylphenol								690
2-Nitrophenol	850							
AROCLOR-1242								
AROCLOR-1254	3200			2200				
AROCLOR-1260		100						
Acenaphthene	90							
Acetone		12	13	13	290	120	26-180	18-110
Bis(2-Ethylhexyl)phthalate	2400	350						38-75
Butyl benzyl phthalate								
Carbon disulfide						6	13-36	2-9
Chlorobenzene								
Chrysene	100							
Di-n-butylphthalate	100							
Di-n-octylphthalate								
Diethylphthalate								
Ethylbenzene								
Fluoranthene					110			
Methylene chloride	29	11	10	7	25	19	18-23	12-30
Naphthalene								
Pentachlorophenol	410							
Phenol								
Pyrene	270				190			
Tetra chloroethene								
Toluene	19	5	3	4				
Total Xylenes								
Trichloroethene								
Inorganics (ppm)								
Aluminum	19200	25000	32000	25200	34500	20400	26200-38900	13600-27100
Antimony	57.9	71.2	84.2	73.1	88.1	63.6	16.9-24.7	23.7-72.2
Arsenic							5.5-10.1	1.9-11.1
Barium	396	217	272	203	105	93.8	61.7-102	43.2-193
Beryllium			0.35				1.7-2.0	
Cadmium	3.5	1.1						
Calcium	50500	38000	21900	56100	9990	9720	3780-5420	3490-11100
Chromium	54	89.3	90.4	99.2	94.2	66.6	90.5-118	23.7-70
Cobalt	12.9	18.6	19.2	21.2	11.9	15.9	14.7-19.6	4.31-24.1
Copper	54	40.8	45.8	49.3	38.1	31.2	37.5-121	9.48-40.2
Iron	28100	34400	41300	37500	38800	38000	40200-45300	9160-31300
Lead	128	19.7	16.4	14.2	78.2	14.9	21.6-41.5	2.9-7.3
Magnesium	11500	17400	19800	19100	20500	16100	12800-17400	5060-13200
Manganese	527	633	653	713	388	638	282-643	186-403
Mercury	4.6	0.2	0.2	0.2	0.7	0.6	.7-1.2	.2-.3
Nickel	54.8	84	87.2	90.1	81.8	78.6	93.7-116	32.9-76.9
Potassium	1400	2440	1730	1710	6190	3500	3100-5690	1740-4170
Selenium					1.2			
Silver	4.9	3.4		2.2				1.26-2.4
Sodium	806	2090	392	1460	45000	13000	2270-17400	332-18700
Thallium			0.43		0.75		1.5-2.0	.44-.71
Vanadium	56.8	82.3	83.6	86.9	84.6	63.7	79.3-100	27.1-83
Zinc	255	78.3	84.9	86.8	86.3	78.5	103-202	24.5-62.6
pH	8.3	9.1	8.3	8.6	7.5	8.3	4.3-8.1	3.1-8.4

APPENDIX A2S1-CONTINUED
OBSERVED CONCENTRATION RANGE (NAS, MOFFETT FIELD; SOIL; SITE 1; CONTINUED)

	W01-07(A)	W01-08(A)	W01-09(A)	W01-10(A)	W01-11(A)	W01-12(A)	W01-13(A)
Organics (ppb)							
1,2,4-Trichlorobenzene							
1,2-Dichloroethenes				1			
2-Butanone	2-50		27-87	80		3	3-16
4-Chloro-3-methylphenol							
4-Methyl-2-pentanone					3		
4-Methylphenol			890-14000	61-670	4300		
2-Nitrophenol							
AROCLOR-1242			220		540		
AROCLOR-1254			150				
AROCLOR-1260			180	230-18000			
Acenaphthene							
Acetone	14-930	42-120	26-760	76-430	14-120	8	26-93
Bis(2-Ethylhexyl)phthalate	310	170	140-1100	55-320	120-27000	370	480-530
Butyl benzyl phthalate			110	760	980		
Carbon disulfide	14-20	9-28	7	4-10			2
Chlorobenzene			18				
Chrysene							
Di-n-butylphthalate					740		
Di-n-octylphthalate					9700		
Diethylphthalate		230					
Ethylbenzene			14-38	55-68			9-10
Fluoranthene		73					96
Methylene chloride	13-75	29-93	11-73	12-28	8-12	27	9-33
Naphthalene				50	360		
Pentachlorophenol							
Phenol					2500		
Pyrene		110			190		
Tetra chloroethene				7	1		1
Toluene	2-13	3-5	3-8	2-89	1-3		1-3
Total Xylenes			48-110	110-220	20		4-15
Trichloroethene				3			
Inorganics (ppm)							
Aluminum	13900-29400	18800-41500	15200-19800	16500-32100	21600-25400	27800	16100-22800
Antimony	13.2-16.1	13.3-26.9	11.8-16.2	13.0-25.6	13.3-23.3	71.6	43.9-63.6
Arsenic	4.7-11.1		3.6				
Barium	62.2-267	39.8-113	134-218	159-370	74.7-221	74.6	83.3-172
Beryllium	1.2-1.5		.66-.99			5	2.2-3.3
Cadmium	2.9				1.2-2.0		2.2
Calcium	3990-20500	3390-4860	40500-7900	11800-57300	20100-37200	3410	19300-52600
Chromium	38.7-91.1	52.6-115	49.8-65.1	56.1-82.6	51.0-68.6	90.9	37.8-76.9
Cobalt	8.5-16.2	9.4-21.7	13.1-18.5	10.6-24.2	17.2-27.0	12.9	13.2-30.2
Copper	25.8-38.9	20.1-42.2	44.8-129	31.2-257	38.2-241	137	45.8-73.9
Iron	24600-34500	19100-51200	21300-30900	20700-45500	30600-42200	39100	29200-41100
Lead	10.5-49.5	10.7-24.3	9.1-120	13.4-50.7	15.5-259	17.2	7.3-69
Magnesium	6600-15900	8700-19100	13300-17100	13400-18600	13900-19100	14900	11100-16900
Manganese	308-493	190-484	282-604	424-537	398-531	271	344-808
Mercury	.2-.3	.3-.4	.2-6.0	.3-.7	.2-.9	0.9	.2-.5
Nickel	37.2-108	43.6-118	56.1-68.4	43.9-95.8	55.6-66.5	86.2	37.5-84
Potassium	1970-5860	3280-8230	991-2210	927-4750	1010-4020	5210	416-2820
Selenium	.98-1.2						
Silver			11.5	1.1	63-4.2		
Sodium	3580-19000	2460 19200	1030-5840	1040-7370	465-11200	11100	322-6610
Thallium	1.3-2.2	.81-.93	.68-1.4	.54-.79	.73-.92		
Vanadium	39.3-83.6	49.7-102	58.5-72.4	46.6-91.2	71.8-106	75.9	60.4-75.1
Zinc	79.5-98.2	52.8-116	52.2-225	63.1-393	78.3-553	134	84.7-427
pH	7.8-8.7	3.9-8.4	6.8-8.3	8.2-8.6	7.4-8.1	7.2	8.2-9.0

APPENDIX A2GW2
(NAS, MOFFETT FILED; WATER; SITE 2)

	WOZ JAGEL SLOUGH	FIRE HYDRANT (SOURCE WATER)	W02-05	W02-06	W02-07	W02-08	W02-09	W02-10	W02-11
Organics (ppb)									
1,2-Dichloroethenes						16-20			
2-Methylnaphthalene								3-5	
Acetone	4	12	11	2	2-10	16	2	4	11
Benzene						34-38		6-8	
Benzoic Acid								11	
Bis(2-t-thylhexyl)phthalate	7			5	9	2	4-9	3-5	2
Bromodichloromethane		1							
Butyl benzyl phtalate								2	
Chlorobenzene						5			
Chloroform	59								
Chloromethane	3								
Di-n-butylphthalate								3	
Ethylbenzene						2		15-20	
Methylene Chloride	3	16	6-11	3-9	3-20	6-11	4-10	2-18	8-16
N-nitrosodiphenylamine								3	
Naphthalene								42-50	
Tetrachloroethene						4			
Toluene		1				2		2	2
Total Xylenes								14-15	
Trichloroethene						8			
Vinyl Chloride						21-42		1	
Inorganics (ppb)									
Aluminum	1170	64.3	18.6-25.6	26.3-2360	152-368	34.8-470		426-24500	963
Antimony			78.4-269	923.4	968-1560	322-325	242-247	343-1480	302-429
Arsenic								1150-6200	
Barium			69.8-122	240.8	174-219	169-223	48.9-51.6	479-2550	21.2-78.3
Beryllium			0.93						
Bicarbonate		6	510		340-370	250-260	550-570	250	440-450
Calcium	44600	5380	248000-258000	197-434000	119000-1460000	227000-257000	300000-307000	263000-366000	430000-495000
Carbonate		8						97	
Chloride	22000	3.1	1800-2400	6500-12000	13000-14000	3600-4000	1900-2000	2600-3900	3600-3700
Cobalt			6.2						
Copper								46.4	
Fluoride	59		6.6-7.0	32-46	40	9.5	6.7-7.8	6.1	14
Iron	42.7	123.3	170-196	157-2940	22.3-26.8	1600-91700	46.8-665		
Lead					3	462			
Magnesium	1360000	436	218000-269000	764400-918000	1130000-1620000	469000-572000	318000-319000	161000-1490000	453000-519000
Manganese			1980-2040	4492-4950	1500-1870	485-569	19.6-19.7	1810-2200	281-410
Mercury			0.4	0.3				0.5	
Nickel			9						
Nitrate		0.12				1.0-1.3	-0.3		2.8-3.6
Potassium	452000	1600		70190-176000	9930	12200-28300		89900-300000	7340
Silver		6.5	6-6.9	45.5	19.2-50	4.8-74.6		69	
Sodium	10300000	1590	708000-709000	86.3-6061000	4410000-5010000	1020000-1100000	761000-798000	930000-11500000	1340000-1350000
Sulfate	3700	1.2	280-310	110-14000	1600-1800	340-450	470-530	5.4-12	81-790
TDS	20000	40	3640-4120	19700-20000	20000	5420-5490	4230-4440	4090-4300	6920-7120
Thallium					35		2		
Vanadium		4.4	9.4			94.3		65	
Zinc		9.8	7.2		69.5	71	7.9	25.5-978	7.2

APPENDIX 2S2
OBSERVED CONCENTRATION RANGE
(NAS, MOFFETT FIELD; SOIL; SITE 2)

COMPOUND	SED-03	W02-05(A)	W02-06(A)	W02-07(A)	W02-08(F)	W02-09(A)	W02-10(F)	W02-11(F)
Organics (ppb)								
AROCLOR-1242					680			
AROCLOR-1254					2000		730-28000	
AROCLOR-1260						100		
Acetone	170	14-19	10-25	23-87	24-78	35-77	13-21	11-26
Benzo(a)anthracene								200
Benzo(a)pyrene				110				220
Benzo(b)fluoranthene				190		100		390
Bis(2-Ethylhexyl)phthalate	100	150-750	65-1100	140-340	91-280			130
Chrysene								190
Di-n-butylphthalate			84-140					
Diethylphthalate			74					
Ethyl benzene						2		
Fluoranthene						42		160
Methylene chloride	48	11-21	7-12	17-36	14-21	11-17	9-15	11-15
Pyrene				75				230
Styrene					16			
Tetrachloroethene	3				2-3			
Toluene		2-3		1	3-4	1-2		1
Total Xylenes						10		
Tri chloroethene							3	
Inorganic (ppm)								
Aluminum	32000	13400-25800	10500-20900	13600-27900	18500-30500	18500-22900	20700-26300	12900-24200
Antimony	79.2	37.9-69.9	37.2-148	11.5-19.9	15.7-28.8	16.5-18.3	52.3-83.9	
Arsenic	8	2.6	39.6	2.7-35.1	1.4-4.1	3.2-4.6	17.6	2.6-4.4
Barium	97.5	71.5-296	111-1470	65.2-304	217-324	144-262	179-492	120-290
Beryllium					0.97-1.8	1.2-1.3		
Cadmium			1.7-218		2.8	1.3-4.1	1.7-21.5	1-3
Calcium	4910	9210-81100	19400-83800	24500-40400	11500-95100	23500-97600	17700-59800	14000-29000
Chromium	98	44-74.1	43.8-81.6	50.3-78.7	51.8-119	52.8-75.1	62.7-137	46-84
Cobalt	16.4	10-28.6	11.3-16.3	12.8-19.5	11.8-36.4	13.8-23.3	13.9-20.9	10-20
Copper	49.6	29.2-74.6	21.9-941	32.7-93.2	25.7-79.1	34.7-45.5	40.6-786	20-70
Iron	41700	22300-44000	35700-106000	22500-34200	21200-53300	28500-35200	28200-64600	23100-31600
Lead	18.8	5.2-29.2	6-1370	7.7-27.3	5.6-69	9.4-45	11.3-1350	
Magnesium	16300	11200-19700	9180-14800	9430-18900	13700-21800	10900-17700	13200-18000	11000-16000
Manganese	363	312-1260	331-5930	280-583	470-2120	326-671	523-743	420-550
Mercury	0.9		0.4	0.2-0.3	0.2-0.5	0.2-0.6	0.3	
Nickel	105	48.9-101	50.9-221	44.7-78.6	53.5-150	62-89.4	64.1-112	52-66
Potassium	4460	501-2170	970-1490	609-2260	843-1730	867-1710	1580-2690	1000-2000
Selenium			1.1					
Silver			5.4				5.6	
Sodium	13500	271-813	859-2470	316-946	344-1390	275-1550	327-2880	
Thallium			0.55	0.55-1.1	1.1-1.3	0.98-1.3	0.58-0.72	
Vanadium	77.7	0.085-72.2	20.1-66.3	54.8-88.4	43.1-123	63.8-78.4	57.6-83.8	50-80
Zinc	91.8		46.8-43000	48.9-72.6	60.4-149	77.9-105	62.2-1710	56-110
pH	8.5	8.1-8.7	7.0-8.8	8.0-8.2	7.9-8.1	7.3-7.9	8.2-8.4	7.8-8.1

APPENDIX A3GW1
OBSERVED CONCENTRATION RANGE
(NAVBASE, NORFOLK; GROUND WATER; SITE1)

	01GW-01	01GW02	01GW-03	01GW-04	01GW-05	01GW-06	01GW-07	01GW-EW	01GW-B20W
Volatile Organics				18-79					2000-5400
Vinyl Chloride				96-24000			17		
Methylene Chloride				1700-2300					
Trichlorofluoromethane				20	17-170				
1,1-Dichloroethane				16-340					14000-46000
Trans-1,2-Dichloroethane	10			11-74					
1,1,1-trichloroethane				24	95				
Trichloroethylene				34-640					620-5600
Benzene				29-390					280-1200
1,1,2,2,-Trichloroetane									
Toluene				23-290			18		8600-34000
Ethylbenzene				12-430					
Acid Extractable Organics									
Phenol				44-67					360-51000
2,4-Dimethylphenol				170-190					410-11000
Pentachlorophenol				110					
Base-Neutral Extract.Org									
Naphthalene				1200					36-82
Bis(2-Ethylhexyl)phthalate		97	15				52		
Metals (ppm)									
Antimony			1.8						
Arsenic	0.3	0.33	0.9		0.36	0.06			.04-.09
Cadmium	.02-.03	.03-.05	.10-.54	0.05	.02-.08	0.02-0.06	0.03		.01-.08
Chromium	.01-2.3	0.12	0.06-117	1.0-1.7	0.07-1.6		0.10	.3-.4	0.07
Copper	.10-.21	.10-.62	.12-1.3	0.21	0.1		0.20		.12-.13
Lead	.05-.40	.14-1.7	.99-5.8	1.88	0.11-0.50	.20-.29	.12-.14	0.12	.18-.29
Mercury	0.0014	0.0003		0.0004	.0002-.00041	0.00049		0.0003	
Nickel		0.1	.16-.30	0.1			0.1		
Sellenium									0.034
Thallium		0.06	0.42	0.27	0.1	0.18	0.1		
Zinc	.02-.49	.24-2.5	1.4-7.7	.09-0.9	.05-0.5	.05-.2	.04-.36	.23-2.6	.57-.63
Cyanide				.12-.92			0.014		.06-.38
Phenols	.01-.044	.01-.018		0.28-1.8	0.01		.001		13-60

* In ppb unless noted otherwise

APPENDIX A3SW1
OBSERVED CONCENTRATION RANGE
(NAVBASE, NORFOLK; SURFACE WATER; SITE 1)

COMPOUND	01SW-08	01SW-09	01SW-10	01SW-11
Volatile Organics				
Vinyl Chloride				11-33
Methylene Chloride			14	12
Trichlorofluoromethane				16
1,1-Dichloroethane				
Trans-1,2-Dichloroethane			17-24	19-82
1,2,-Dichloroethane				
1,1,1-trichloroethane				
Trichloroethylene			15-18	16-52
Benzene				
1,1,2,2,-Trichloroetane			13-20	
Toluene				
Ethylbenzene				
Acid Extractable Organics				
Phenol		66		
2,4-Dimethylphenol				
Pentachlorophenol				
Base-Neutral Extract.Org				
Naphthalene				
Bis(2-Ethylhexyl)phthalate			13	15
Metals				
Antimony				
Arsenic		70	500	340
Cadmium	20	30	20-80	10-180
Chromium	400	70-220	100-150	50-180
Copper		100	140-600	950
Lead	50	120-330	310-1300	200-210
Mercury		0.9	0.3	0.3
Nickel			100	100
Sellenium			100	
Thallium			240	
Zinc	50-80	20-250	84-1800	270-4700
Cyanide		2	14-20	40-60
Phenols	10-24	10-40	10	10-240

* In ppb unless noted otherwise.

APPENDIX A4GW2
OBSERVED CONCENTRATION RANGE
(NAVSHIP, NORFOLK; GROUND WATER; SITE 2; DRAFT REPORT)

COMPOUND	OBSERVED CONCENTRATION RANGE (ppb)
VOLATILE ORGANICS	
Acetone	32
Methylene chloride	6.8-8.9
SEMIVOLATILE ORGANICS	
Bis (2-ethylhexyl) phthalate	260
Di-n-butyl phthalate	12
Di-n-octyl phthalate	33
PESTICIDES AND PCBs	
Aroclor 1254	1.3
GENERAL CHEMISTRY	(pH units)
pH	5.44-8.44
METALS	
Antimony	9-180
Arsenic	1-220
Beryllium	6-11
Cadmium	7-11
Chromium	10-210
Copper	10-17000
Lead	6-4100
Mercury	.2-2.1
Nickel	50-2200
Silver	10-20
Zinc	80-12000

APPENDIX A4SW2
OBSERVED CONCENTRATION RANGE
(NAVSHIP, NORFOLK; SURFACE WATER; SITE 2; DRAFT REPORT)

COMPOUND	OBSERVED CONCENTRATION RANGE (ppb)
VOLATILE ORGANICS	
Acetone	24
Carbon disulfide	13-14
Methylene chloride	7.5
SEMIVOLATILE ORGANICS	
Bis (2-ethylhexyl) phthalate	10-53
GENERAL CHEMISTRY	(pH units)
pH	6.64-6.90
METALS	
Antimony	10-180
Cadmium	5-13
Chromium	50
Copper	20-40
Lead	9-80
Mercury	.3-.5
Nickel	60
Selenium	7
Silver	20-100
Thallium	1
Zinc	60-110

APPENDIX A4SED2
OBSERVED CONCENTRATION RANGE
(NAVSHIP, NORFOLK; SEDIMENTS; SITE 2; DRAFT REPORT)

COMPOUND	OBSERVED CONCENTRATION RANGE (ppb)
SEMIVOLATILE ORGANICS	
Bis(2-ethylhexyl)phthalate	530-6,500
PESTICIDES AND POLY-CHLORINATED BIPHENYLS	
Aroclor 1254	240
METALS	
Arsenic	5600-2500
Beryllium	1300
Cadmium	1040-1400
Copper	22000-35000
Lead	23000-26000
Mercury	330-470
Nickel	16000-31000
Selenium	200
Silver	1800
Zinc	94000-120000

APPENDIX A4GW3-7
OBSERVED CONCENTRATION RANGE
(NAVSHIP, NORFOLK; GROUND WATER; SITES 3 THROUGH 7; DRAFT REPORT)

COMPOUND	OBSERVED CONCENTRATION RANGE (ppb)
VOLATILE ORGANICS	
Acetone	11-900
Benzene	5.4-21
2-Butanone	21-6800
Carbon disulfide	20
Chlorobenzene	5.0-17
Chloroethane	10-15
1,1 Dichloroethane	6.1-6.7
Ethylbenzene	5.1-190
Methylene Chloride	5.9-12
Tetrachloroethylene	5.7-12
Toluene	11-110
Trans-1,2-Dichloroethylene	6.4
Trans-1,3-Dichloropropene	5.6
Total xylenes	5.8-2100
SEMIVOLATILE ORGANICS	
Acenaphthene	10-61
Acenaphylene	14
Anthracene	13
Bis (2-chloroisopropyl) ether	17
Bis (2-ethylhexyl) phthalate	11-270
4-Chloroaniline	10-34
Dibenzofuran	11-56
1,2-Dichlorobenzene	23
1,4-Dichlorobenzene	16-22
2,4-Dichlorophenol	25
Diethyl phthalate	12
2,4-Dimethylphenol	150-510
Di-n-butyl phthalate	14-320
Di-n-octyl phthlate	13
Fluorene	13-25
2-Methylnaphthalene	14-76
4-Methylphenol	11-140
Naphthalene	19-69
Phenanthrene	10-93
Phenol	17-18
PESTICIDES AND PCBs	
Aroclor 1242	3.3
Aroclor 1254	5.2-36
GENERAL CHEMISTRY	
Cyanide	90
Hexavalent Chromium	10-100
Oil and Grease	300-94000
	(pH units)
pH	6.25-12.08
METALS	
Antimony	1-1400
Arsenic	2-300
Beryllium	5-8
Cadmium	5-51
Chromium	10-1700
Copper	10-1200
Lead	8-8800
Mercury	0.2-16
Nickel	30-4100
Selenium	10-20
Silver	10-40
Thallium	6-11
Zinc	10-22000

APPENDIX A4SW3-7
OBSERVED CONCENTRATION RANGE
(NAVSHIP, NORFOLK; SURFACE WATER; SITES 3 THROUGH 7; DRAFT REPORT)

COMPOUND	OBSERVED CONCENTRATION RANGE (ppb)
VOLATILE ORGANICS	
Carbon disulfide	6.7-18
Trans-1,3-Dichloropropene	7.7
SEMIVOLATILE ORGANICS	
Bis (2-ethylhexyl) phthalate	18-92
Chrysene	10
N-Nitrosodiphenylamine	11
GENERAL CHEMISTRY	
Oil and Grease	400-7600
	(pH units)
pH	6.59-7.46
METALS	
Antimony	150-290
Arsenic	5-50
Cadmium	15-100
Chromium	50-200
Copper	20-340
Lead	6-470
Mercury	0.2-1.8
Nickel	30-170
Selenium	12-40
Silver	10-60
Thallium	2-13
Zinc	50-970

APPENDIX A4SED3-7
OBSERVED CONCENTRATION RANGE
(NAVSHIP, NORFOLK; SEDIMENTS; SITES 3 THROUGH 7; DRAFT REPORT)

COMPOUND	OBSERVED CONCENTRATION RANGE (ppb)
SEMIVOLATILE ORGANICS	
Benzo(a)anthracene	460
Bis(2-ethyhexyl)phthalate	660-2,300
Fluoranthene	940
GENERAL CHEMISTRY	
Oil and Grease	22,000-1,200,000
METALS	
Arsenic	5.6-31
Beryllium	1.3
Cadmium	1.3-1.7
Chromium	27-39
Copper	20-140
Lead	30-320
Mercury	0.16-1.8
Nickel	24-31
Silver	1.8
Thallium	0.1
Zinc	93-290

APPENDIX A4S3-7
OBSERVED CONCENTRATION RANGE
(NAVSHIP, NORFOLK; SOIL; SITES 3 THROUGH 7; DRAFT REPORT)

COMPOUND	OBSERVED CONCENTRATION RANGE (ppb)
VOLATILE ORGANICS	
Total xylenes	53-61
SEMIVOLATILE ORGANICS	
3,4 Benzofluranthene	2,800
Bis (2-ethylhexyl) phthalate	12,000
Di-n-octyl phthalate	4,400
Fluoranthene	1,700
Naphthalene	2,100
Pyrene	1,500-2,200
PESTICIDES AND PCBs	
4,4'-DDT	120
Chlordane	3,000
Aroclor 1254	2,100-2,700
Aroclor 1260	1,000-3,700
GENERAL CHEMISTRY	
Oil and Grease	530000-20,000,000
METALS	
Antimony	500-33000
Arsenic	2300-18000
Beryllium	800-9200
Cadmium	1200-29000
Chromium	2600-400,000
Copper	31000-69,000,000
Lead	33,000-23,000,000
Mercury	490-8200
Nickel	4900-660,000
Selenium	110-220
Silver	1600-4100
Thallium	100-200
Zinc	90,000-13,000,000

APPENDIX A5S
OBSERVED CONCENTRATION RANGE
(NCBC, PORT HUENEME; SOIL; SITE 14; DRAFT REPORT)

COMPOUND	Detection Limit	S14-B1	S14-B2	S14-B3	S14-B4	S14-B5	S14-B6	S14-B7	S14-B8	S14-B9	S14-B10	S14-B11
Organophosphate Pesticide												
monocrotophos												
(detect limit 300 g/kg)												
Volatile Organic Cmpds (g/kg)												
methylene chloride	2	3-4	4-6	4	4	4-17	6	11	3-4	8	8	10
acetone	2	6-17	4-7	29	11-40	7-200	16	18	6-47	12	40	30
carbon disulfide	2				2				2-4			
2-butanone	10					22						
Semivolatile Org. Cmpds (g/kg)												
napthalene	33		69		370-5300							
2-methylnaphthalene	33				100-1800							
acenaphthene	33		170		87-2100							
acenaphthylene					68							
dibenzofuran	33		75		200-1600							
fluorene	33		70		71-2100							
n-nitrosdiphenylamine					170							
phenanthrene	33		110		220-6500							
anthracene					300-2100							
di-n-butylphthalate	160	190	290-380		340-850	390-930	430		270-680			160
fluoranthene	33		180		130-3700							
pyrene	33		310		110-2800							
benzo(a)anthracene	33		110		180-1100							
bis(2-ethylhexyl)phthalate	33	100-200	550-1400		1100-2100	970-1700	92	80	82	100		
chrysene	33		140		180-1200				110			
benzo(b)fluoranthene	33				98-590							
benzo(k)fluoranthene	33				90-590							
benzo(a)pyrene	33		140		100-600							
PCB&pesticides												
4,4-DDT	16	55				45						
aroclor-1260	160	710	1300									
Physical Charac.												
pH	0.100pH	7.64-8.45	7.68-8.87		7.91-8.46	7.50-8.43	8.54	8.32	7.72-8.19	8.35	7.47	8.31
Metals(mg/kg)												
Cadmium	0.5	1.20-7.65	0.9-7.2		1.05-3.20	1.05-11.4	0.75	1.25	1.25-2.40	1.00	1.55	1.15
Chromium	0.5	6.35-24.8	8.55-24.1		6.40-22.1	4.45-146	5.4	5.65	4.45-13.4	4.5	7.65	6.90
Copper	0.5	3.95-47.0	9.65-71.4		7.95-105	24.7-169	9.0	31.1	6.2-63.1	174	29.5	44.0
Mercury	0.125	0.153-0.182	.278-.299		.278-.341	.299-.341						
Nickel	0.5	5.5-26.1	4.55-16.8		4.95-10.9	4.2-80.4	4.85	6.45	5.4-10.7	5.05	8.20	4.95
Lead	0.125	1.21-17.6	1.59-9.95		1.29-60.7	1.02-15.3	1.42	1.18	1.46-9.72	1.14	1.42	1.11
Antimony	3.0				-.5-3.50						3.50	
Selenium	0.125	0.245			0.175				0.389	0.18		
Thallium	0.125											
Zinc	0.5	15.8-72.8	23.1-178		28.5-203	38-203	16.3	31.8	17.8-69.6	92.7	64.6	38.8
Silver	0.5				-.7-1.15							
Arsenic	0.125	1.21-1.99	0.74-5.31		.609-2.99	.43-5.41	0.979	0.667	1.38-1.61	0.511	2.70	1.11
Beryllium	0.5					0.6						

* In ppm unless noted otherwise.

APPENDIX A5S-CONTINUED
OBSERVED CONCENTRATION RANGE
(NCBC, PORT HUENEME; SOIL; SITE 14; DRAFT REPORT; CONTINUED)

COMPOUND	S14-B12	S14-B13	S14-B14	S14-B15	S14-B16	S14-B17	S14-B18	S14-B19	S14-W2	S14-W3	S14-W4	S14-W5	S14-W6	S14-3
Organophosphate Pesticide														
monocrotophos														
(detect limit 300 g/kg)	660													
Volatile Organic Cmpds (g/kg)														
methylene chloride	4	12	4	4	3	10	10	4-6	4	4	3	5	4	4
acetone	9	70	4	9	10	58	47	6-11		180	14	2	8	12
carbon disulfide										13				
2-butanone										42				
Semivolatile Org. Cmpds (g/kg)														
napthalene														
2-methylnaphthalene														
acenaphthene														
acenaphthylene														
dibenzofuran														
fluorene														
n-nitrosdiphenylamine														
phenanthrene														
anthracene														
di-n-butylphthalate	160							200				580		
fluoranthene														
pyrene														
benzo(a)anthracene														
bis(2-ethylhexyl)phthalate				98					210	70		1800		
chrysene														
benzo(b)fluoranthene														
benzo(k)fluoranthene														
benzo(a)pyrene														
PCB&pesticides														
4,4-DDT														
aroclor-1260														
Physical Charac.														
pH		7.78	7.66	8.23	8.42	7.62		7.66-7.77	8.41	8.47	8.68	8.59	8.24	
Metals(mg/kg)														
Cadmium		1.55	4.65			1.75	1.00	1.10-3.50	2.8	2.55	1.10	0.90	0.950	
Chromium		8.6	19.4			8.5	6.05	4.75-17.5	14.4	13.4	4.25	8.20	4.60	
Copper		12.4	19.9			17.5	26.3	11.0-45.0	14.4	170	65.2	7.30	15.4	
Mercury												0.278		
Nickel		8.15	18.1			7.45	5.65	4.8-13.1	2.3	8.35	2.95	4.10	4.05	
Lead		1.43	5.59			1.92		.972-7.37		1.22	0.697	0.91	1.18	
Antimony														
Selenium										0.184	0.918			
Thallium														
Zinc		29.3	59.7			45.6		34.8-76.2	46.1	124	43.5	15.3	20.5	
Silver														
Arsenic		11.4	8.71			17.3		.904-3.83	5.06	12.5	0.545	0.36	0.523	
Beryllium														

* In ppm unless noted otherwise.

APPENDIX A6GW1
OBSERVED CONCENTRATION RANGE (PMTC, POINT MUGU; GROUNDWATER; SITE 1)

COMPOUND	OBSERVED CONCENTRATION RANGE (ppb)
Volatile Organic Compound	
Acetone	4-11
Semi Volatile Organic Compound	
Bis(2-ethylhexyl)phthalate	2-110
Phenanthrene	2
Base-Neutral Extract Organics	
1,4-Dichlorobenzene	2
Acid Extractable Organics	
Phenol	48
Pesticides and PCB's	
4,4-DDE	0.13
4,4-DDD	0.11-0.16
Aroclor-1016	2.7
Metals	
Barium	1270-2340
Cadmium	11-164
Chromium	59-728
Selenium	12-48
Copper	1550
Lead	990
Zinc	5100
Silver	140
Arsenic	906-1370

APPENDIX A6S1
OBSERVED CONCENTRATION RANGE
(PMTC, POINT MUGU; SOILS; SITE 1)

COMPOUND	OBSERVED CONCENTRATION RANGE (ppb)
Pesticides	
4,4'DDE	65
4,4'DDD	170
4,4'DDT	39
Metals	
Arsenic	6210-6510
Barium	127000
Cadmium	1550-12900
Copper	28500-134000
Nickel	22400-41200
Lead	6000-77000
Thallium	7500-15500
Vanadium	24300-72200

APPENDIX A7GW7
OBSERVED CONCENTRATION RANGE
(NWS, SEAL BEACH; GROUND WATER; SITE 7)

Water Samples	W41-7	W42-7	W43-7	W44-7	W45-7	W46-7	S47-7	S48-7	S49-7
Volatile Organic Cmpds									
Methylene Chloride									
Acetone	99-130								
Carbon disulfide									
4-Methy-2-pentanone									
Semi-Volatile Organic Cmpds									
Benzo(a)anthracene									
Bis(2-ethylhexyl)phthalate									
Di-n-butyl phthalate									
Hexachlorobenzene				11					
Phenanthrene				15					
Pyrene				11					
N-nitrosodiphenylamine									
4-bromophenyl-phenylether									
Metals									
Silver			252						
Chromium	78.3-112	136	77.2	402	194	188	65.3	47.8-72.3	69.1
Mercury	8.1								
Nickel	67-86.5	89.3		270	168	122	82	63.3-74.2	104
Lead									
Zinc	180-194	261	132	932	438	403		23-118	

* In ppb unless noted otherwise.

APPENDIX A7S7
OBSERVED CONCENTRATION RANGE
(NWS, SEAL BEACH; SOIL; SITE 7)

	W41	W42	W43	W44	W45	W46	S47	S48	S49
temp (C)	21.3	19.8	19.6	19.8	18.3	17.6			
pH	6.00	6.77	6.41	6.60	5.94	6.94	7.64	7.68	7.58
Sp Cord (umhos/cm)	442000	48000	>50000	22800	44200	41200	39700	38400	38200
Sal (parts/thousand)	31.8	35.0	40.0	15.7	33.6	31.9	32.2	31	31.6

APPENDIX A7S7
OBSERVED CONCENTRATION RANGE
(NWS, SEAL BEACH; SOIL; SITE 7)

Soil Samples	W41-7	W42-7	W43-7	W44-7	W45-7	W46-7	S47	S48	S49
Volatile Organic Cmpds									
Methylene Chloride	0.4-0.6	0.31-0.38							
Toluene			0.0093-0.19	0.017-0.065	0.12-0.46	0.013-0.038	41-550	300-480	160-1200
Metals									
Silver			5.6	2.4-3.4			4.3		
Arsenic	2.6-4.4	1.5-15.5	9						
Cadmium		0.7							
Chromium	17.5-32.3	11.8-86.6	24.3-53.4	25.8-51.7	24.1-36.4	28.2-41.0	22-35.1	27.8-44.1	25.2-34.4
Copper	26.0-64.2	9.6-68.8							
Mercury	0.15	0.91	0.5-0.67	0.39-0.59	0.5-1.5				
Nickel	12.0-21.0	7.0-21.0	16.8-27.4	13.7-50.8	15.6-22.3	18.5-30.7	17.2-27	24.1-33.9	19.5-29
Lead	14.0-28.0	9.0-2080.0	2.8-6.6	2.8-13.1	6.1-9.8	4.7-6.8	2.4-75	3.7-24.1	4.6-28.9
Zinc	65.0-126.0	43.0-437.0	66.6-112	74.3-134	84.6-110	86.5-104	63.6-115	78.1-156	81.2-106
Semi-Volatile Organic Cmpd									
Di-n-butyl phthalate			0.17						
Fluoranthene			0.12						
4-chloro-3-methylphenol				0.12					
Chrysene			0.16						

* In ppm unless noted otherwise.

APPENDIX 7SW7
NAVAL WEAPONS STATION, SEAL BEACH (WATER, SITE 7, DRAFT REPORT)

Waste Compound	Maximum (ppb)	California Drinking Water Standards (ppb)
Volatile Organic		
Acetone	130	----
Semi-Volatile Organic		
Hexachlorobenzene	11	
Phenanthrene	15	----
Pyrene	11	
Metals		
Silver	252	50
Chromium	402	50
Mercury	8.1	2
Nickel	270	----
Zinc	932	500
pH	6.9	
Specific Conductance (umhos/cm)	>50000	
Salinity (parts/thousand)	40.0	
TOC(calculated)	88	
TOX(calculated)	8	

APPENDIX B

SUMMARY OF NOTATIONS AND PREDICTIVE EQUATIONS FOR THE TREATMENT PROCESSES

LIST OF NOTATIONS

Pretreatment

v_t = velocity
u = kinematic viscosity
g = gravity
P_1 = density of water
P_s = density of the particle
d = diameter of the particle
Q = rate of flow through the tank
A = surface area of the tank
C_{ss} = concentration of ss at any time and depth in the filter
L = length (depth) of the filter
a = filter coefficient which varies with time and depth in the filter
v = superficial velocity
e = porosity of the clear filter (dimensionless)
d = volume of specific deposit per unit filter volume

Biological Treatment

F/M = food to microorganism ratio
Q = flow
S = organic concentration
V = volume of aeration basin
X = mixed liquor SS (MLSS)
V = volume of aeration tank
F = flow rate
X = mixed liquor volatile solids
S_i = influent BOD, COD, TOC, or specific organics
S_e = effluent BOD, COD, TOC, or specific organics
U_{max} = biokinetic constants
K_B = biokinetic constants
A = surface area of biological tower or rotating biological contactor
S_e = effluent substrate concentration
S_o = influent substrate concentration
D = depth of the medium
k = treatability constant relating to the wastewater and the medium characteristics
n = coefficient relating to the medium characteristics
k_T = reaction rate coefficient at system temperature
k_{20C} = reaction rate coefficient at $20^{\circ}C$
T = temperature of the system

Physical/Chemical Technologies

X = mass of organic adsorbed
m = mass of activated carbon
C_e = equilibrium concentration of organics
K = experimental constant
n = experimental constant
a = mass of adsorbed organic required to completely saturate a mass of carbon K = experimental constant

C_o = initial concentration of organic materials in solution
C = concentration of organic materials after contact with activated carbon
m = concentration of activated carbon
k = constants, values of which vary with organic solute and temperature
n = constants, values of which vary with organic solute and temperature
C = effluent pollutant concentration
C_o = influent pollutant concentration
K_1 = rate constant
Q = flow rate
A_o = adsorption capacity
M = mass of carbon
V = throughput volume
N_o = total concentration of particles in suspension at time 0
n = collision efficiency factor representing the fraction of the total number of collision
k = Boltzmand's constant
k_p = rate coefficient
a_p = collision efficiency factor
M = mass of substance transferred per unit time and volume
K_L = coefficient of mass transfer
a = effective area
$C_L - C_g$ = driving force (concentration difference between liquid phase and gas phase)
P = partial pressure of substance in the air mixture in contact with the water at equilibrium
H' = Henry's law constant
C = concentration of substance in the water at equilibrium
C_t = concentration at time t
C_o = concentration at time 0
k_{vol} = volatilization mass transfer coefficient
k = overall rate coefficient
y = depth of liquid
K = sorption coefficient expressed on an organic carbon basis
K_s = sorption mass transfer coefficient
= percentage of organic carbon present in the system
K = octanol/water partition coefficient
K_p = partition coefficient
x_{oc} = mass fraction of organic carbon in sediment
k_{sv} = overall rate constant
C = pollutant concentration
B = bacterial concentration
Y = biomass produced per unit pollutant concentration assumed
U_{max} = maximum specific growth rate
K_e = half-saturation constant
K_{B2} = second-order biodegradation rate constant
K_B = first-order biodegradation rate constant
$K_B(T)$ = specific biodegradation rate constant at temperature T
$K_B(T_o)$ = specific biodegradation rate constant at temperature T_o
T = ambient temperature
T_o = reference temperature O_B = temperature coefficient for biodegradation

$K_B(C_p)$ - specific biodegradation rate constant at dissolved inorganic phosphorous concentration

C_p - dissolved inorganic phosphorous concentration

$K_B(C_p*)$ - non-nutrient limited biodegradation rate constant

C_w = pollutant concentration in the aqueous phase

a_w - decimal fraction of the total analytical pollutant concentration which is in the aqueous phase (a_w = 1 - fraction sorbed)

C_t - concentration at time t, mg/l (or ug/l)

C_o - initial concentration at t = o, mg/l (or ug/l)

k_{vol} = volatilization mass transfer coefficient, cm/h

= ky

k - overall rate coefficient, h^{-1}

y - depth of liquid, cm

$t_{1/2}$ = $0.693y/k_{vol}$.

C_o - influent BOD concentration, mg/l

C_e = effluent BOD concentration, mg/l

a = $(1+4ktD)^2$

k - first order reaction rate constant, $days^{-1}$

t = hydraulic residence time, days

D = dimensionless dispersion number

= $H/vL = Ht/L^2$

H = axial dispersion coefficient, area per unit time

v = fluid velocity, length per unit time

L - length of travel path of a typical particle

Ne = total nitrogen in the system effluent

No = total nitrogen applied to the wastewater

k = rate constant dependent upon the temperature and plant density

t = detention time in the system

L_N = hydraulic loading, limited by nitrogen removal

N_e = nitrogen concentration required in system effluent

N_o = nitrogen concentration in influent to hyacinth basins

L_P = hydraulic loading, limited by phosphorous removal

P_e = phosphorous concentration required in system effluent

P_o = phosphorous concentration in influent to hyacinth basins

C_e = effluent BOD, mg/l

C_o = influent BOD, mg/l

A = fraction of BOD not removed as settleable solids near headworks of the system (as a decimal fraction)

K_T = rate constant in $days^{-1}$ at water temperature T (in °C), given by $KT - 0.005(1.1)^{(T-20)}$

A_V = specific surface area for microbial activity)

L = length of system

W = width of system

d = design depth of system

n = porosity of system (as a decimal fraction)

Q = average flow in the system

= $(Q_{influent} + Q_{effluent})/2$

S = slope or hydraulic gradient of flow system, (as a decimal fraction)

t = hydraulic residence time in the system

C_o = influent BOD concentration C_e = effluent BOD concentration

K^1 - reaction rate constant

d = design water depth in the system
$L_{w,n}$ = wastewater hydraulic loading rate controlled by nitrogen as the LDF
C_p = percolate nitrogen concentration
C_n = nitrogen concentration in applied wastewater
ET = evapotranspiration rate
P_r = precipitation rate
P_w = percolation rate
U = crop uptake
f = fraction of applied nitrogen lost to denitrification, volatilization, and soil storage
ET = crop evapotranspiration
P_r = precipitation
LR = leaching requirement
E = efficiency of the irrigation system
A = field area
Q = annual flow
V_s = net loss or gain in stored wastewater volume due to precipitation on and evaporation and seepage from the storage ponds
C = constant = 100
L_w = design hydraulic loading rate based on the LDF
L_w = hydraulic loading rate
q = application rate per unit width of the slope,
p = application period
Z = slope length
C_z = effluent BOD concentration at point Z
c = residual BOD at end of slope
C_o = BOD of applied wastewater
Z = slope length
q = application rate
K,n = empirical constants
L_{BOD} = BOD loading rate
L_w = hydraulic loading
q = application rate
P = application period
W = width of application slope
Z = length of application slope
m = conversion factor
C_o = BOD of applied wastewater
A_s = field (surface) area required
Q = wastewater flow rate
Z = slope length
q = application rate
P = period of application
C = conversion factor
V_s = net loss or gain in storage volume due to precipitation, evaporation, and seepage,
D = number of operating days per year
L_w = design hydraulic loading
C' = conversion factor
A_s = field area C_o = BOD of applied wastewater
C" = conversion factor
Q_a = design flow rate to the OF site

L_{LBOD} = limiting BOD loading rate
A = application area
C = conversion factor
Q = average wastewater flow
L_w = annual loading rate
PACT = powdered activated carbon treatment
mg = milligram
L = liter
mg/L = milligram per liter
ft^3 = cubic feet
MLVSS = mixed liquor volatile suspended solids
SRT = solids residence time
HRT = hydraulic residence time
SS = suspended solids
hp = horsepower
lb = pound
BOD = biochemical oxygen demand
COD = chemical oxygen demand
TOC = total organic carbon
m = meter
gal = gallon
RBC = rotating biological contactor
mm = millimeter
SBR = sequencing batch reactor
gal/day = gallon per day
min = minutes
g = grams
sec = second
^oK = degrees Kelvin
cm = centimeter
hr = hour
VSB = vegetated submerged bed (wetland)
LDF = limiting design factor

APPENDIX B

PREDICTIVE EQUATIONS

PRETREATMENT SYSTEMS

Sedimentation

$V_t = [g(P_s - P_l)d^2]/[(18)(u)]$
where u = kinematic viscosity
g = gravity
p_l = density of water
p_s = density of the particle
d = diameter of the particle.
V_t = tank depth/detention time
= depth/[tank volume/flow rate]
= depth/[(area x depth)/flow rate] = Q/A
where Q = rate of flow through the tank
A = surface area of the tank.

Ideal discrete particles which have settling velocites greater than V_t will be removed completely. But particles with a settling velocity, V_f, less than V_t will only have a portion of the particles removed. That portion removed can be defined by V_f/V_t. The overflow rate, V_t, is expressed as: $V_t = Q/A$.

Granular-Media Filtration

$-dC_{ss}/dL = aC_{ss}$
where C_{ss} = concentration of suspended solids at any time and depth in the filter
L = length (depth) of the filter
a = filter coefficient which varies with time and depth in the filter.

There is an accumulation of deposit in the filter pores which is due to the removal of suspended solids in the filter. The decrease in quantity of suspended matter in a filter lamina must equal the increase in deposited matter in that lamina. The following equation (Weber, 1972) describes the above situation:

$v(dC_{ss}/dL) = d_d/dt + (e - {}_d)(dC_{ss}/dt)$
where V = superficial velocity (Q/A)
${}_d$ = volume of specific deposit per unit filter volume (dimensionless)
e = porosity of the clear filter (dimensionless)
dC_{ss}/dt = the change in the amount of material in suspension within the pores and time, this value is generally insignificant and the term is therefore omitted.

Biological Systems

Activated Sludge

$$V = \frac{(FS_1/X)}{[U_{max}\ S/_i(S_i - S_e) - K_B)}$$

where V = volume of aeration tank (m^3)
F = flow rate (m^3/day)
X = mixed liquor volatile solids (mg/L)
S_i = influent BOD, COD, TOC or specific organics (mg/L)
S_e = effluent BOD, COD, or specific organics (mg/L)
U_{max} and K_B = biokinetic constants (day^{-1})
A = surface area of biological tower or rotating biological contractor (m^2)

Biokinetic constants are determined by conducting lab or pilot plant studies.

Trickling Filter

$$S_e/S_o = \exp[-kD/Q^n]$$

where S_e = effluent substrate concentration, BOD_5 (mg/L)
S_o = influent substrate concentration, BOD_5 (mg/L)
D = depth of the medium (m)
k = treatability constant relating the the wastewater and the medium characteristics (min^{-1})
n = coefficient relating to the medium characteristics

The formula is commonly used and is applicable at 20°C.

The values of the treatability constant, k, ranges from 0.01 to 0.1.

A correction for temperatures other than 20°C can be made by adjusting the treatability factor:

$$k_T = k_{200}(1.035)^{T-20}$$

where k_{20c} = reaction rate coefficient, $days^{-1}$ values usually range from 0.2 to 1.0
k_T = reaction coefficient at the system temperature
T = temperature of the system

Rotating Biological Contractor

Table III-6 (Peavy, Rowe, and Tchobanoglous, 1985), shows and efficiency and loading rate relationship for Bio-Surf medium treating municipal wastewater for RBC systems. If the influent and effluent BOD and the hydraulic loading rate are known, then the disk area can be determined.

$$A = FS_i / [(U_{max})/(S_i - S_e)] - K_B$$

where V = volume of aeration tank (m^3)
F = flow rate (m^3/day)
X = mixed liquor volatile solids (mg/L)
S_i = influent BOD, COD, TOX or specific organics (mg/L)
S_e = effluent BOD, COD, TOC or specific organics (mg/L)
U_{max} and K_B = biokinetic constants (day^{-1})
A = surface area of RBC (m^2)

Physical/Chemical Process

Carbon Absorption

$$(C_o - C)/m = kC^{1/n}$$

where C_o, C - concentration of organic materials in solution, initially and after contact with activated carbon $[FL_{-3}]$
m - concentration of activated carbon $[FL^{-3}]$
k, n - constants, values of which vary with organic solute and temperature

$$\ln [(C_o/C)-1] = [(K_1A_oM)/Q] - [(K_1C_oV_3)/Q]$$

where C - effluent pollutant concentration (g/m^3)
C_o - influent pollutant concentration (g/m^3)
K_1 - rate constant (m^3/day/g)
Q - flow rate (m^3/day)
A_o - adsorption capacity (g/g)
M - mass of carbon (g)
V - throughput volume (m^3)

Typical breakthrough curves are determined by pilot studies.

Precipitation/Flocculation/Sedimentation

$$t_{1/2} = (3u)/(4a_pkTN_o)$$

where N_o - total concentration of particles in suspension at time 0
n - collision efficiency factor representing the fraction of the total number of collision which are successful in producing aggregate
k - Boltzmann's constant - 1.36×10^{16} ergs/R
k_p - rate coefficient (cm^3/sec)
T - ^oK
a_p - collision efficiency factor
erg - dyne-cm - $(g\text{-}cm^2)/sec^2$

The mass fraction in the percentage that is removed at the ith depth at jth time interval is:

$$x_{ij} = (i - C_{ij}/C_o) \times 100$$

Air Stripping

$$M = K_La(C_L - C_g)$$

where M - mass of substance transferred per unit time and volume (g/hr/m3)
K_L - coefficient of mass transfer (m/hr)
a - effective area (m2/m3)
$(C_L - C_g)$ - driving force (concentration difference between liquid phase and gas phase (g/m^3)

$$H = P/C$$

where H = Henry's law constant (atm-$m^{3/mole}$)
P = partial pressure of substance in the air mixture in contact with the water at equilibrium (atm)
C = concentration of substance in the water at equilibrium (mole/m^3)

NATURAL SYSTEMS

$C_t / C_o = \exp(-k_{vol} t/y)$
where C_t = concentration at time t, mg/L (or ug/L)
C_o = initial concentration at $t=0$, mg/L (or ug/L)
k_{vol} = volatilization mass transfer coefficient, cm/hr
= ky
k = overall rate coefficient, hr^{-1}
y = depth of liquid, cm

$t_{1/2}$, expressed in hour, is the time at which the final concentration is half the initial concentration. $t_{1/2} = 0.693y/k_{vol}$.

$\log K_{oc} = 1.00 \log _{ow} - 0.21$
where K_{oc} = sorption coefficient expressed on an organic carbon basis = $K_{sorb}/(OC)$, cm/hr
K_{sorb} = sorption mass transfer coefficient, cm/hr
OC = percentage of organic carbon present in the system
K_{ow} = octanol/water partition coefficient

The K_p can be determined by the following expression:
$K_p = K_{oc} X_{oc}$
where X_{oc} = mass fraction of organic carbon in sediment

The combined removal by sorption and volatilization is described by the following:

$C_t/C_o = \exp(-k_{sv} t)$
where k_{sv} = overall rate constant

The Monod equation is:
$-dC/dt = (1/Y)(dB/dt) = (U_{max}/Y)[(BC)/(K_s + C)]$
where C = pollutant concentration
B = bacterial concentration
Y = biomass produced per unit C assumed
U_{max} = maximum specific growth rate
K_s = half-saturation constant
The following expresses the biodegradation in cometabolism:
$-dC/dt = K_B C$
where C = pollution concentration
K_B = first order biodegradation rate constant

Temperature dependence of biodegradation:

$K_B(T) = K_B(T_o)\, O_B^{(T-To)}$
where $K_B(T)$ = specific biodegradation rate constant at temperature T
$K_B(T_o)$ = specific biodegradation rate constant at temperature To
T = ambient temperature, ^oC
T_o = reference temperature, ^oC
O_B = temperature coefficient for biodegradation

The value of 1.047, which is also used for BOD decay, is adequate for O_B.

Michaelis-Menten equation:

$K_B(Cp) = K_B(Cp^*)\ [(0.0277)(Cp)/(1 + 0.0277)(Cp))]$

where $K_B(Cp)$ = specific biodegradation rate constant at dissolved inorganic phosphorous concentration, ug/L
C_p = dissolved inorganic phosphorous concentration, ug/L
$K_B(Cp^*)$ = non-nutrient limit biodegradation rate constant

This relationship is a good indicator of possible phosphorous limitation of biodegradation in the environment.

The following equation represents the sorption of the compound onto the soil:

$dC_T/dt = K_B C_W - a_W K_B C_T$

where C_W = pollutant concentration in the aqueous phase
a_w = decimal fraction of the total analytical pollutant concentration which is in the aqueous phase (a_w = 1 - fraction sorbed)
K_B = biodegradation rate constant

Stabilization Ponds

It is recommended to us the following equation developed by Wehner and Wilhelm (1956) as cited by Reed et al., for chemical reactor design:

$C_e/C_6 = [4a \exp(1/2D)]/[(1+a)^2 (\exp(a/2D) - (1-a)^2\exp(-a/2D)]$

where C_o = influent BOD concentration, mg/L
C_e = effluent BOD concentration, mg/L
$a = (1+4ktD)^2$
k = first order reaction rate constant, days^{-1}
t = hydraulic residence time, days
D = dimensionless dispersion number
= $H/vL = Ht/L^2$
H = axial dispersion coefficient, area per unit time
v = fluid velocity, length per unit time
L = length of travel path of a typical particle

Table III-9 is the Wehner and Wilhelm equation chart of the term kt versus BOD remaining. If the chart is not used, the equation can be solved on a trial and error basis.

Aquaculture Systems

The following estimates the nitrogen removal in pond systems:

$Ne/No = \exp(-kt)$

where Ne = total nitrogen in the system effluent, mg/L
No = total nitrogen applied to the wastewater, mg/L
k = rate constant dependent upon the temperature and plant density (Table 11, adapted by Reed et al., 1988) 1/days
t = detention time in the system, days.
$L_N = 760/(1-N_e/N_o^{1.72}$
where L_N = hydraulic loading, limited by nitrogen removal, m^3(ha-day)
N_e = nitrogen concentration required in system effluent, mg/L
N_o = nitrogen concentration in influent to hyacinth basins, mg/L

$Lp = (9353)[(P_e - 0.778_o)/(P_o - P_e)$
where Lp - hydraulic loading, limited by phosphorous removal, $m^3/(ha\text{-}day)$
P_e - phosphorous concentration required in system effluent, mg/L
P_o - phosphorous concentration in influent to hyacinth basins, mg/L

Wetland Systems

The following general model applies to wetlands:
$C_e/C_o = 0.52 \exp [(-0.7\ K_T\ (A_V)^{1.75}\ LWdn)Q]$
where C_e - effluent BOD, mg/L
C_o - influent BOD, mg/L
A - fraction of BOD not removed as settleable solids near headworks of the system (as a decimal fraction)
K_T - rate constant in days^{-1} at water temperature T (in °C), given by $KT = 0.005(1.1)^{(T-20)}$
A_V - specific surface area for microbial activity, $m^2/m_3)$
L - length of system, m
W - width of system, m
d - design depth of system, m
n - porosity of system (as a decimal fraction)
Q - average flow in the system, m_3/day
$= (Q^{influent} + Q_{effluent})/2$

When the bed slope or hydraulic gradient is equal to 1 percent or greater, the model should be adjusted accordingly:
$C_e/C_o = 0.52 \exp [(-0.7K_T\ (A_V)^{1.75} LWdn)/(4.638^{1/3}Q)]$
S - slope of hydraulic gradient of flow system, (as a decimal fraction)

The hydraulic residence time and design surface area for wetland model are:
$t = [(\ln C_o - \ln C_e) - 0.6539]/(65K_T)$ and
$A = [Q(\ln C_o - \ln C_e - 0.6539)]/(65K_{Td})$

If the bed slope or hydraulic gradient is greater than 1 percent then:
$t = [(\ln C_o - \ln C_e) - 0.6539]/(301K_{TS1/3})$ and
$A = [Q(\ln C_o - \ln C_e - 0.6539)](301KTd)$
where t - hydraulic residence time in the system, days
C_o - influent BOD concentration, mg/L
C_e - effluent BOD concentration, mg/L

K^T = reaction rate constant, days^{-1}
$= K_{20}(1.1)^{(T-21)}$
d = design water depth in the system

Land Treatment Systems (Slow rate system)

Relating the water balance equation and the applied nitrogen to the nitrogen-limited hydraulic loading rate, $L_{w,}$, for the Type 1 SR system the following equation applies:
$L_{w,n} = [Cp(P_r - ET) + 10U]/[(1 - f)C_n - C_p]$
where $L_{w,n}$ - wastewater hydraulic loading rate controlled by nitrogen as the LDF, cm/year

C_p = percoalte nitrogen concentration, mg/L, usually set at 10 mg/L
C_n = nitrogen concentration in applied wastewater, mg/L
ET = evapotranspiration rate
P_r = precipitation rate
P_w = percolation rate
U = crop uptake, kg/(ha-year)
f = fraction of applied nitrogen lost to denitrification, volatilization, and soil storage

For Type 2 systems, the following equation incorporates the leaching factor and irrigation efficiency:

$L_W = (ET - P_r)(1 + LR)(100/E)$

where ET = crop evapotranspiration
P_r = precipitation
LR = leaching requirement
E = efficiency of the irrigation system

The leaching requirment may require from 0.05 to 0.30, depending on the crop, the amount of precipitation, and the total dissolved solids (TDS) in the wastewater. Table IV-12, shows the relationship between wastewater TDS, crops, and the leaching requirement fraction.

The land area requirement can be calculated by the following equation:

$A = (Q + V_s)/(CL_w)$

where A = field area, ha
Q = annual flow, m^3/year
V_s = net loss or gain in stored wastewater volume due to precipitation on and evaporation and seepage from the storage pond, m^3/year
C = constant = 100
L_w = design hydraulic loading rate based on the LDF, cm/year

Land Treatment System (Overland Flow)

The relationship between the hydraulic loading rate and the application rate is shown in the following equation:

If the organic loading rate is limiting, the field area can be calculated by the following equation:

$A_s = [C_o C''Q_a]/L_{LBOD}$

where A_s = field area, ha
C_o = BOD of applied wastewater, mg/L
C" = conversion factor = 0.1 (metric units)
Q_a = design flow rate to the OF site, m^3/day
L_{LBOD} = limiting BOD loading rate
= 100 kg/(ha-day)

Land Treatment System (Rapid Infiltration)

The application area can be calculated by the following equation:

$$A = [CQ(365 \text{ days/year})]/L_W$$

where A = application area, ha
C = conversion factor = 10^{-4} ha/m^3
Q = average wastewater flow, m^3/day
L_W = annual loading rate, m/year

APPENDIX C

THE CONCORDANCE APPROACH

Appendix C

List of Illustrations

Note: This portion of the report has been adapted from "Method of Site Evaluation for Sand Reclamation."[32] From Fontaine, M.C. Pennsylvania Foundries: Management of Non-Sand Solid Wastes. Unpublished M.E. report in Environmental Engineering, The Pennsylvania State University, University Park, PA 16802 (December, 1987).

Introduction

Although numerous evaluation techniques exist for ranking the importance of factors, the "Concordance Approach" was selected because of its numerous advantages[32]. These include:

(1) quantifies opinion;
(2) tests concordance among evaluators;
(3) reduces effects of bias;
(4) encourages participation of specified levels of management;
(5) reduces evaluation to binary decisions;
(6) incorporates knowledge of informed evaluators;
(7) minimizes the time required by evaluators;
(8) generates confidence among users;
(9) identifies relative importance of factors;
(10) clarifies the purpose of the process;
(11) minimizes emotion; and
(12) proves to be an analytical approach.

Another appealing aspect of the "Concordance Approach" was that its simplistic nature lends itself well to a mail survey. This precluded the necessity of conducting the evaluations in a group setting; thereby, permitting the participants to complete the survey at their leisure.

The "Concordance Approach" was the first introduced to the PRC project as a method to evaluate prospective sand reclamation sites[32]. The statistical basis of the method was first defined by Kendall[33], and further illustrated by Ferraco et al.,[34] through practical application. Only the aspects of the Concordance Method, which were directly applicable to the PEC survey were presented here.

A.1 Forced Comparisons and the Binary Rating System

The "Concordance Approach" utilizes forced comparisons combined with a binary rating system to determine relative importance among various factors. The concept of forced comparisons has root in the belief that the accuracy and reliability of ranking can be considerably improved by ranking factors in pairs rather than as a total group[34]. When forced comparisons are used, the evaluating judge is required to select the better of each pair. The approach reduces "central tendency," due to the assignment of too many tied values. The concepts of forced comparisons and binary rating are illustrated through the following example.

Say, for instance, selected judges are asked to evaluate five factors. For the sake of example, the factors to be evaluated will be identified as A, B, C, D, and E. These factors are entered into a rating chart for comparison as shown in Figure A.1.

Next, the factors are subject to forced comparison. The judge is required to compare the factors in each row against the factors in each column. The comparisons are conducted on a pair-by-pair basis, thus constituting a forced comparison. For instance, row factor A is compared against column factor B. Following this comparison, row factor A is compared to each of the column factors C thru E. The comparisons continue until each row factor has been compared to each column factor on a paired basis. When comparing factors, the judge indicates the importance of a row factor over a column by entering the numeral 1 in the square which is common to both the row factor and the column factor. If the judge decides the column factor is of greater importance, a 0 is entered in the square.

In this particular example, the binary indicators, 1 and 0, show the evaluating judge determined that row factor A is of greater importance than column factor B, and, moving to the right, that column factor C is more important than row factor A.

Each row is then summed to give a score and the ranking of the factors can then be established on the basis of lowest score, lowest rank[32]. These procedures have been illustrated in Figure A.2.

A.2 Ranking by Several Judges

The concepts outlined above can be extended to evaluations by several judges. Say, four judges evaluate the same five factors, A, B, C, D, and E, by ranking. The scores and ranks for these four judges would be tabulated as shown in Figures A.3 and A.4.

		FACTOR				
		A	B	C	D	E
FACTOR	A	X				
	B		X			
	C			X		
	D				X	
	E					X

Figure A.1 Scoring Card for an Individual Judge (32)

		FACTOR						
		A	B	C	D	E	SCORE	RANK
FACTOR	A	X	1	0	0	1	2	3
	B	0	X	0	0	1	1	2
	C	1	1	X	1	1	4	5
	D	1	1	0	X	1	3	4
	E	0	0	0	0	X	0	1

Figure A.2 Ranking of Five Factors by a Single Judge Using Forced Comparisons (32)

FAC	JUDGE				ROW TOTAL
	I	II	III	IV	
A	3	3	3	4	13
B	2	2	0	2	5
C	0	1	2	2	3
D	1	1	2	2	6
E	4	3	3	3	13
TTL.	10	10	10	10	40

Figure A.3 Scores by Four Judges,
Using Forced Comparisons (32)

FAC	JUDGE				ROW TOTAL	d^2	E_i
	I	II	III	IV			
A	4	3	3	5	15	9	0.091
B	3	2	1	2	8	16	0.162
C	1	1	2	1	5	49	0.494
D	2	1	2	3	8	16	0.162
E	5	3	3	4	15	9	0.091
					Σd^2	99	1.000

Figure A.4 Determining the Concordance
and Coefficient (32)

A.3 Emphasis Coefficient

The rank data for each factor can be used to calculate a ratio referred to as the "emphasis coefficient" (Ei)[32]. The emphasis coefficient is considered to be the weighted average given to a particular factor by the evaluating group and is calculated by means of the generalized rank matrix shown in Figure A.5 where:

$$Ei = \frac{\sum_{j=1}^{m} R_{ij}}{\sum_{i=1,}^{n} \sum_{j=1}^{m} R_{ij}}$$

Number of factors = i, $i = 1, \ldots, n$

Number of judges = j, $j = 1, \ldots, m$

Individual cell ranks = R_{ij}

FAC	JUDGE			ROW TOTAL	E_i
	1	j	m		
1	R_{11}	R_{1j}	R_{1m}	$\sum_{j=1}^{m} R_{ij}$	$\frac{\sum_{j=1}^{m} R_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{m} R_{ij}}$
i	R_{i1}	R_{ij}	R_{im}		
n	R_{n1}	R_{nj}	R_{nm}		

A.5 Generalized Rank Matrix for Calculating the Emphasis Coefficient (32)

This ratio can then be used to rank n factors in intergers from 1 through n; to rank n factors according to a non-linear scale; and, to provide a basis for a rating scale[32].

A.4 Testing Concordance of Judgement

Since inconsistencies in judgement will occur for single judges, and more commonly between judges, it is necessary to determine if there exists an acceptable level of agreement between the judges[32]. The determination of the level of concordance is based upon the rankings of the judges and the generalized matrix illustrated in Figure A.6:

Number of factors ≈ i, $i = 1, \ldots, n$

Number of judges ≈ j, $j = 1, \ldots, m$

FAC	JUDGE			ROW TOTAL	d_i^2
	1	j	m		
1	R_{11}	R_{1j}	R_{1m}	$\sum_{j=1}^{m} R_{ij}$	${E(R) - \sum_{j=1}^{m} R_{ij}}^{2}$
i	R_{i1}	R_{ij}	R_{im}		
n	R_{n1}	R_{nj}	R_{nm}		

Figure A.6 Generalized Rank Matrix (32)

It is possible to calculate an average ranking, E(R), as follows:

$$E(R) = \frac{m}{2}(n + 1)$$

Then the square of the deviation, d_1^2, of each row total from E(R) is calculated by:

$$d_i^2 = \left[E(R) - \sum_{j=1}^{m} R_{ij}\right]^2$$

The d_1^2 are summed to give a value T. The maximum value, T', which can be attained by summing the squares of these deviations can be calculated as[33].

$$T' = \frac{m^2}{12}(n^3 - n)$$

Then the measure of agreement between the judges, 'the coefficient of concordance' (W), is equal to the ratio between T and T'[33]. This reduces to:

$$W = \frac{12T}{m^2(n^3 - n)}$$

If the level of concordance between the judges is perfect, W = 1. As the level of concordance between the judges decreases, the value of W approaches zero[32].

A.5 Significance of Concordance

By establishing a limiting value, it can be determined whether the judges' rankings are random or biased[33]. This limiting value (C), can be calculated by the following equation for $n > 7$:

$$C_{05} = \frac{mn}{12}(n + 1)\chi^2_{05}$$

The subscript in the equation given above indicates the level of significance, and values for X^2 are obtained from standard tables with the degrees of freedom equal to $(n - 1)$. Then, if $C < T$, $(T = di^2)$, it can be said that a significant difference exists between judges[32].

References for Appendix C.

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33. Kendall, M.J., "Rank Correlation Methods," Charles Griffin and Company, Ltd., London 1975.

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