

The Pennsylvania State University

The Graduate School

AN ASSESSMENT OF THE ENVIRONMENTAL  
IMPACTS FROM THE DISCHARGE OF BILGE WATER IN THE  
NORFOLK NAVAL STATION HARBOR

A Report in  
Environmental Engineering

by

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of the Requirements  
for the degree of

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## Table of Contents

	<u>Page</u>
Table of Contents.....	iv
List of Tables.....	vi
List of Figures.....	vii
Appendices.....	viii
List of Abbreviations.....	ix
Acknowledgement.....	xi
Chapter 1 - Introduction.....	1
1.1 Statement of Problem.....	1
1.2 Objective.....	1
1.3 Rational.....	2
Chapter 2 - Background.....	3
2.1 General.....	3
2.2 The Site.....	3
2.3 Pier Complex.....	4
2.4 Bilge Water Production and Composition....	7
2.5 Current Bilge Water Handling Practices....	9
Chapter 3 - Fate and Transformation of Contaminants	10
3.1 Water Quality Criteria.....	10
3.2 Factors Affecting the Bioavailability of Metals.....	10
3.3 Modeling the Fate of Contaminants.....	19
3.4 Ultimate Fate of Metals.....	23
3.5 Ultimate Fate of Conventional Pollutants..	24
Chapter 4 - Modeling the Naval Station Harbor.....	25
4.1 Estuary Model.....	25

## Table of Contents

4.2 Model Validation.....	29
Chapter 5 - Environmental Assessment.....	32
5.1 Biological Assessment.....	32
5.2 Human Assessment.....	32
Chapter 6 - Federal Policy.....	34
6.1 Background.....	34
6.2 The Clean Water Act as Amended of 1987....	37
Chapter 7 - Options.....	40
7.1 Options for Bilge Water Practice.....	40
7.2 Minimization of Bilge Water.....	40
Chapter 8 - Treatment Schemes for Bilge Water.....	42
8.1 Design Considerations.....	42
8.2 Type and Concentration of Bilge Water.....	42
8.3 Treatment Scheme Evaluation.....	43
8.4 Sequencing Batch Reactor.....	44
8.5 Laboratory/Pilot Studies.....	47
8.6 Precautions.....	48
Chapter 9 - Conclusions and Recommendations.....	49
9.1 Conclusions.....	49
9.2 Recommendations.....	51
References.....	52

## List of Tables

	<u>Page</u>
Table 1 Ships/Submarines in Port, All Berths Full..	4
Table 2 Estimated Typical Bilge Water and Annual Production.....	8
Table 3 Proposed Water Criteria for Metals.....	11
Table 4 Longitudinal Dispersion Coefficient.....	22
Table 5 Calculated Maximum Contaminant Concentrations.....	29
Table 6 Recommended Maximum Contaminant Levels.....	30
Table 7 Decision Table for Bilge Water Treatment...	44
Table 8 Typical Design Bilge Water Characteristics.	49

## List of Figures

	<u>Page</u>
Figure 1 Naval Station Complex Site Plan.....	5
Figure 1a Blow-up of Naval Station Complex.....	6
Figure 2 Copper Speciation Diagram.....	12
Figure 3 Adsorption Front.....	18
Figure 4 Gouy-Chapman Model.....	18
Figure 5 Estuary Contaminant Profiles.....	21
Figure 6 Estuary Contaminant Profile - Chromium....	26
Figure 7 Estuary Contaminant Profile - Copper.....	26
Figure 8 Estuary Contaminant Profile - Iron.....	27
Figure 9 Estuary Contaminant Profile - Zinc.....	27
Figure 10 Estuary Contaminant Profile - BOD.....	28
Figure 11 Recommended Slack Tide Sampling Plan.....	31
Figure 12 Typical Batch Growth Curve.....	45

## Appendices

	<u>Page</u>
Appendix 1 Bilge Water Test Data.....	53
Appendix 2 Calculation of Net Nontidal Velocity....	57
Appendix 3 Illustrated Contaminant Profile Calculation.....	60
Appendix 4 Sequencing Batch Reactor Flow Diagram...	62
Appendix 5 EPA Treatability Manual Excerpts.....	64
Appendix 6 Sequencing Batch Reactor Operation Pattern.....	70

## List of Abbreviations

Ac	Acre - 43,560 square feet
BOD	Biochemical Oxygen Demand
BW	Bilge Water
C	Concentration
CBA	Chesapeake Bay Agreement of 1987
CHT	Collection Handling Transfer System
COD	Chemical Oxygen Demand
CS	Contact Stabilization
CWA	Clean Water Act of 1987 as Amended
D	Depth
DO	Dissolved Oxygen
DOD	Department of Defense
E	Longitudinal Dispersion Coefficient
$f_s$	Fraction in Solid Phase
EPA	Environmental Protection Agency
FFS	Federal Facilities Strategy of the Chesapeake Bay Program
FWPCA	Federal Water Pollution Control Act of 1972
gpd	Gallon Per Day
I	Emissions
k	First Order Decay Coefficient
$K_p$	Partition Coefficient
$k_s$	Salting-out Coefficient
M	Moles Per Liter
m	Meter

## List of Abbreviations

MCL	Maximum Contaminant Level
MDL	Maximum Discharge Level
MG	Million Gallons
mg/L	Milligram Per Liter, ppm
OWS	Oil-Water Separator
POL	Petroleum Oils and Lubricants
Q	Flow
RBC	Rotating Biological Contactor
QA/QC	Quality Assurance/Quality Control
SBR	Sequencing Batch Reactor
smpd	Square Miles Per Day
SRT	Solids Retention Time
t	Time
TCLP	Toxic Characteristic Leaching Procedure
TF	Trickling Filter
TKN	Total Kjeldahl Nitrogen
TSS	Total Suspended Solids
u	Ionic Strength
U	Net Non-tidal Velocity
ug/L	Micrograms Per Liter, ppb
$V_n$	Net Settling Velocity
VSS	Volatile Suspended Solids
W	Mass Loading

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## Chapter 1 Introduction

1.1 Statement of Problem. Discharges of effluents containing conventional and priority pollutants into streams and estuaries is one of the nations most pressing environmental problems. The Federal Water Pollution Control Act of 1972 (FWPCA) and the Clean Water Act as Amended of 1987 (CWA) were both established to restore and maintain the chemical, physical, and biological integrity of the Nations waters (CWA 1987, p.1). Today, there are no effluent limitations for bilge water (BW) as described in sections 301 and 302 of the CWA. However, the current push to be environmentally responsible and the objective of the CWA to eliminate the discharge of pollutants into navigable waters has compelled the Navy to assess the impacts of BW on the harbor environment.

1.2 Objective. The overall objective of this report was to perform a risk assessment of the environmental impacts caused by the discharge of BW in the harbor at the Norfolk Naval Station in Norfolk, Virginia. The specific objectives were:

1. estimate the daily production of BW from a representative fleet in pct during peacetime operations;
2. summarize the concentrations of pollutants in typical bilge water (BOD, COD, fecal coliform, heavy metals, oil and grease, etc.), based on available data;
3. determine a representative depth and volume for Naval Station harbor;

4. determine the fate of pollutants in BW;
5. assess the significant acute and chronic environmental impacts to the biota and humans of representative pollutants;
6. based on the assessment, determine appropriate effluent limitations which provide for the protection and propagation of the biota and which permit recreation in and on the water; and
7. Evaluate possible treatment schemes to economically achieve the discharge limitations.

1.3 Overview of Methodology. This assessment required site specific data, calculations and predictions of pollutant fate, ambient water quality criteria for aquatic life and human risk, typical BW production and contaminant levels, and the area and volume of the harbor impacted. Site specific data included analytical results for BW samples from six different ships and for a limited number of harbor water samples. Ambient water quality criteria was from the Environmental Protection Agency (EPA). An EPA pollutant fate model based on water quality assessment was used to evaluate the partitioning of contaminants into various environmental compartments (Mills 1985, p. 211).

## Chapter 2 Background Data

2.1 General. The United States Navy has been discharging bilge water (BW) into navigable waters since its formation in 1775. BW initially consisted mostly of saltwater. With the advent of steam ships, BW became increasingly more polluted with petroleum, oils and lubricants (POL). Today, BW is contaminated with POL, trace metals and in some cases synthetic organic chemicals.

2.2 The Site. The Norfolk Naval Station, as shown in Figures 1 and 1a, is situated on the south eastern shore of the Hampton Roads harbor at the mouth of the James River basin. The Chesapeake Bay is 3 miles north of the Naval Station. The Norfolk Harbor reach (Elizabeth River) is some 200 feet from the ends of the piers and is maintained at a minimum depth and width of 45 feet and 1600 feet respectfully. The Naval Station Harbor is also maintained at an average depth of 45 feet. Tides in this area average 2.5 feet on approximate 12 hour cycles (Virginia Pilot Assoc. 1991, p. 7).

Most of the volume of water in the Elizabeth river in the vicinity of the Naval station is contained in the Norfolk Harbor channel. Because of this, the passage of shipping, tidal oscillation, and wind stresses tend to maintain a completely mixed volume of water and disperse pollutants. The contributions of fresh water from the Elizabeth and Lafayette watersheds are small in comparison

to the total volume of the estuary which is approximately 35420 MG. This volume was estimated from plots derived from USGS 7.5 minute topographic-Bathymetric charts dated 1986. Discharges from the watersheds annually contribute 566 MG (estimated by multiplying the watershed area by the average annual runoff). The fresh water discharges are small because of the small area of the watersheds which is approximately 85,000 Ac. Annual runoff based on USGS charts is 15 inches. These discharges further indicate that the estuary is well mixed because of the absence of any significant stratification between fresh and salt water.

2.3 Pier Complex. Ships of the Atlantic fleet are homeported at Norfolk. Table 1 lists the types and numbers of ships/submarines which would be in port if all berths were occupied. Propulsion plants on the ships range from nuclear to gas turbine. This situation of having all berths full would probably never occur because ships are constantly rotating through deployments.

Table 1. Ships/Submarines in Port, All Berths Full.  
(Based on FY 91 Berthing Plan)

Vessel Type	Quantity
Aircraft Carrier	3
Cruisers	6
Destroyers	10
Amphibious Assault	11
Auxiliary Support	13
Frigates	7
Submarines	14

The pier complex extends some 2.3 miles south from

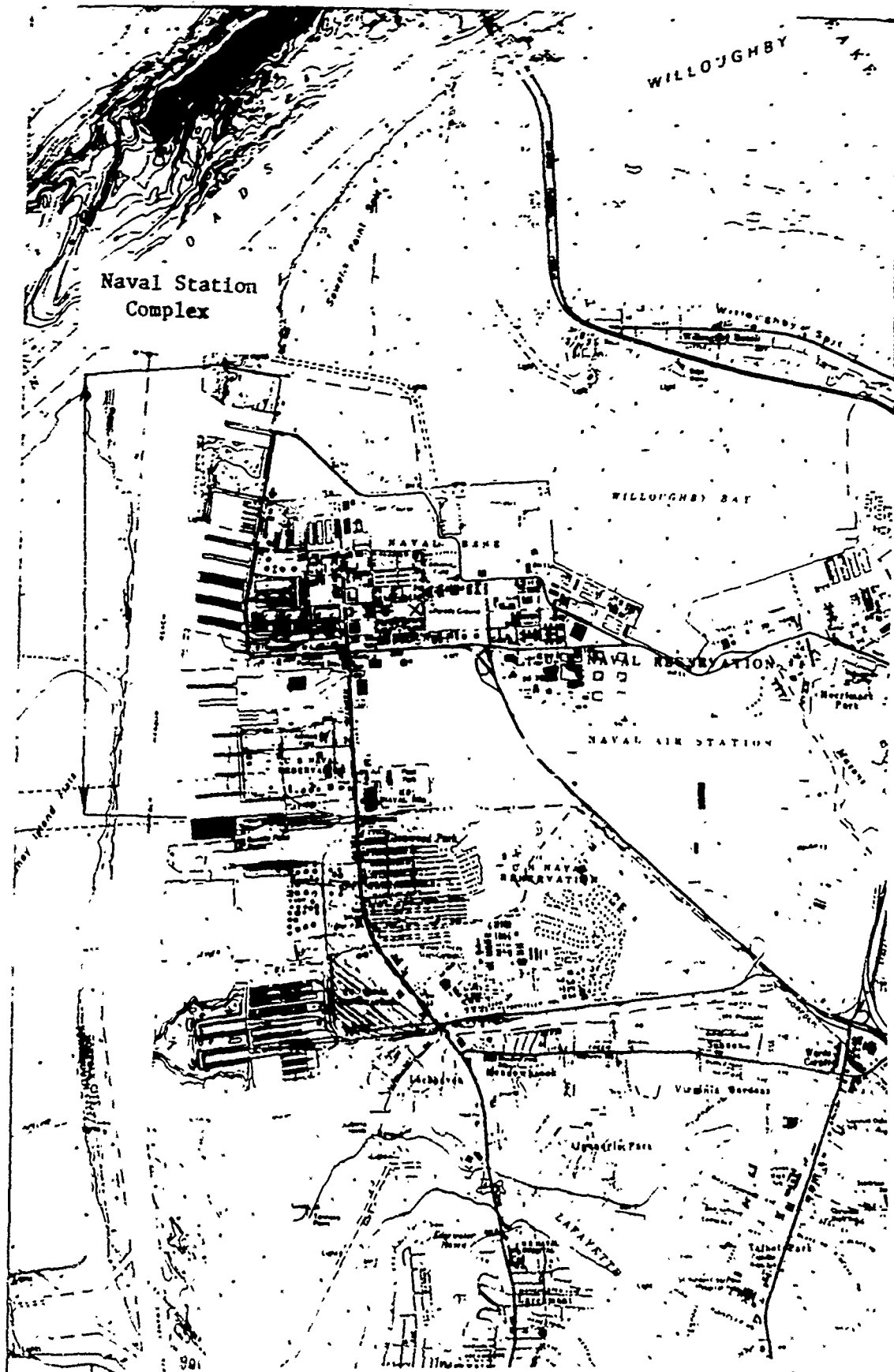


Figure 1. Naval Station Complex  
Norfolk, Virginia

Scale  
1" = 1 mile

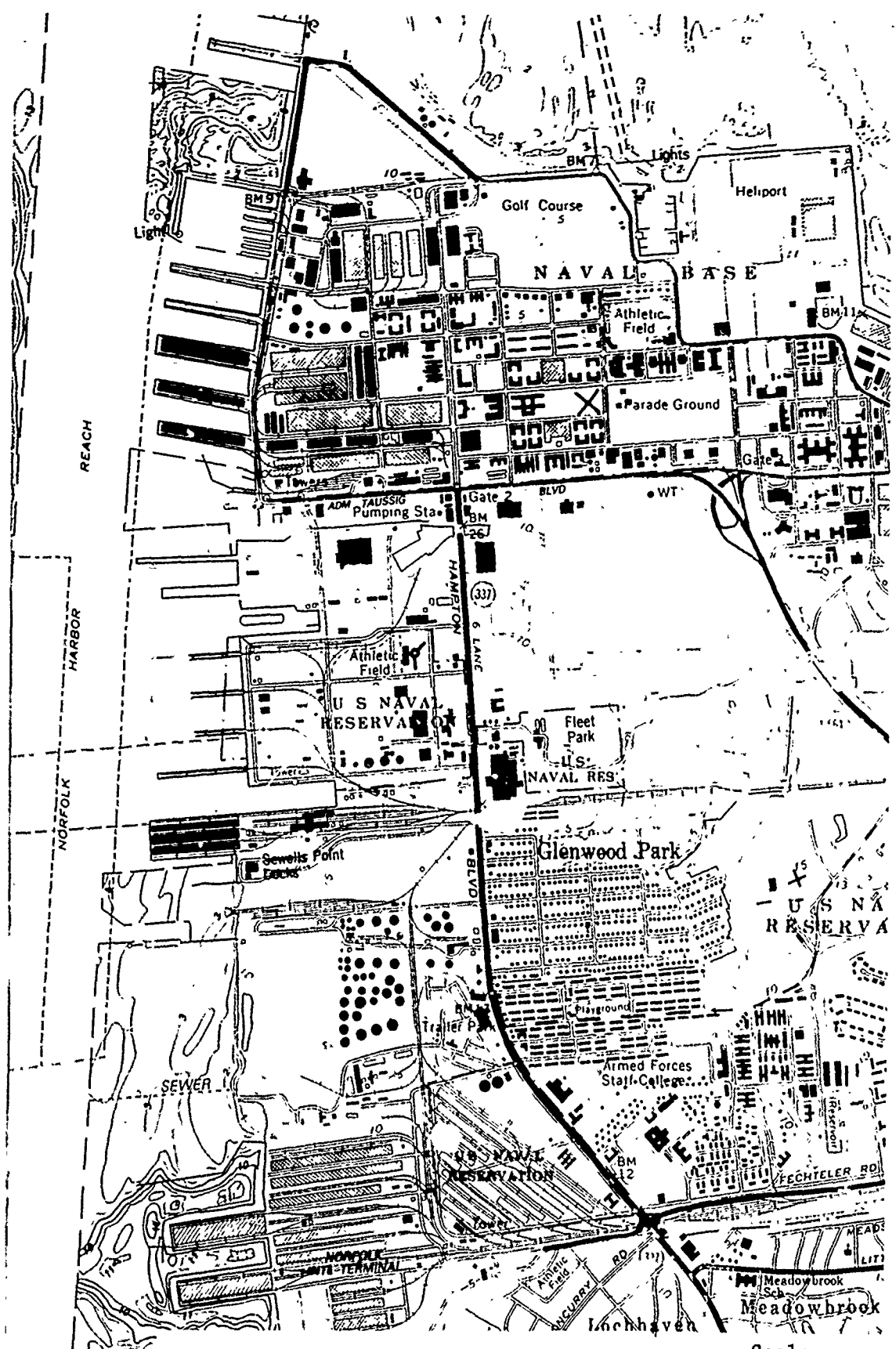


Figure 1 a. Blow-up of Naval Complex

Scale  
1" = 2000 ft

Sewells point and consists of 12 major structures that average 1300 feet in length. All piers have the capability of supplying utilities to the ships. These utilities include potable water, electric power, steam, and sanitary sewer.

2.4 Bilge Water Production and Composition. Bilge water comes from the engine and mechanical spaces of ships and submarines and is transported in the ship's main drain system. BW comes from leaking fuel lines, condensate return lines, saltwater intrusion, and wash down operations. Appendix 1 summarizes the chemical composition of BW on six ships ranging from a nuclear aircraft carrier to amphibious assault ships. The data indicate that the major contaminants are BOD, copper, chromium, ammonia, fecal coliform, nickel, fuel oil and grease, TSS, and zinc. The majority of the BOD and ammonia were probably the result of cross-connections between the main drain system and the ship's collection handling transfer system which carried the sanitary wastes. The severity of contamination varied significantly. Therefore, for the purposes of this report an estimate of a typical BW was needed.

Table 2 contains an estimate for the typical BW and annual contaminant production. This estimate of a typical BW was based on an assumption that ships of similar displacement and propulsion type produce similar BW. The estimated typical BW was a weighted average using data shown

in Appendix 1 and on vessel number and displacement. The daily production of BW at the Naval Station complex was approximately 167 m<sup>3</sup>/d (44,000 gpd) ± 100% (Naval Station Port Operations Repair Officer interview of 22 Jan 1991).

Table 2. Estimated Typical Bilge Water and Annual Contaminant Production.

Contaminate	Typical <sup>a</sup> BW mg/L	Annual Production <sup>b</sup> Kg/year	Daily <sup>c</sup> Mass Loading Kg/d
Arsenic	0.0006	0.037	----
BOD	49.7	3020	8.27
Barium	0.0079	0.48	----
Cadmium	0.0040	0.24	----
Cyanide	0.0031	0.19	----
COD	396.00	24100	66
Chromium	0.0386	2.35	10-2.19
Copper	0.218	13.3	10-1.44
Iron	1.29	78.40	0.22
Mercury	0	0	0
Manganese	0.0758	4.61	----
Ammonia	0.726	46.3	0.13
Nickel	0.0819	4.98	10-1.86
Oil & Grease	156.00	9500	26
Lead	0.0370	2.25	----
Phenol	0.0211	1.28	----
Antimony	0	0	0
Selenium	0.0017	0.10	----
Thallium	0	0	0
TOC	40.76	2480	6.79
TSS	152.00	9240	25.3
Zinc	0.32	19.5	10-1.27

a. Based on statistical analysis of data in appendix 1.

b. Kg/year=mg/l X 0.044 MGD X 365 d/year X 8.34 X 0.454 Kg/lb

c. Dashed lines (----) indicate that the value is below accurate measurement limits.

This analysis was incomplete because it lacked results for alkalinity, salinity, VSS, TKN, and total phosphorus all of which were important for characterizing the treatability

of a wastewater. BOD<sub>5</sub> is a bioassay parameter which is sensitive to the toxic effects of metals and organics. Therefore, the actual value for BOD<sub>5</sub> may be higher than the above estimated value.

2.5 Current Bilge Water Handling Practices. BW has been handled by one of two methods. The BW was pumped into either a barge or a "donut", a floating oil-water separator. The BW pumped directly to a barge was then transported to an oil-water separating (OWS) facility on Sewells point. The effluent from the OWS was discharged to the harbor. Ships with OWS systems discharge their effluents directly to the harbor and pump the oily waste to the barges. Finally, the oily waste was tested for toxicity and transported to Craney Island for treatment/recovery.

## Chapter 3

### Fate and Transformation of Contaminants

3.1 Water Quality Criteria. Generally speaking, all trace metals are toxic at some threshold of bioavailability (Rainbow 1990, p 4). At the same time, many metals were recognized as being essential for life (Harrison 1980, p. 4). The Environmental Protection Agency (EPA) was required by the Clean Water Act of 1987 to publish criteria for water quality based on the kind and extent of all identifiable effects of toxic pollutants on health and welfare. Proposed criteria for ambient water concentrations to protect aquatic life are listed in Table 3. The following factors should be noted:

1. Generally, the criteria for saline systems were less restrictive than that for freshwater; and,
2. The criteria for metals was often dependent on the chemical characteristics of the water (alkalinity, pH, hardness, etc.).

Normally, the toxic effects were associated with the free metal ion in solution ( $\text{Cu}^{+2}$ ,  $\text{Pb}^{+2}$ , etc.) (Simkiss 1983, p. 63). The free metal ion was believed to be most toxic because it was usually the most strongly sorbed by biological tissues.

3.2 Factors Affecting the Bioavailability of Metals. Several factors to be considered in determining the bioavailability of metals in aquatic systems were:

1. Complexation with organic and inorganic ligands
2. Solubility
3. pH, ionic strength, alkalinity
4. Sorption processes with suspended solids
5. Settling rates for suspended solids.

These factors would be interactive with one another.

Complexation with organic and inorganic ligands

Table 3. Proposed Criteria for Metals (Mills 1985, p. 8).

Metal	<u>Freshwater</u> 24 hr.		<u>Saline Water</u> 24 hr.	
	Average ug/L	Maximum ug/L	Average ug/L	Maximum ug/L
Arsenic	40	44	LD	508
Cadmium	a	b	4.5	59
Chromium	0.29	21	18	1260
Copper	5.6	c	4	23
Lead	d	e	25	668
Mercury	0.2	4.1	0.1	3.7
Nickel	f	g	7.1	140
Selenium	35	260	54	410
Silver	0.009	1.9	0.26	2.3
Zinc	47	h	58	170

- a The value should not exceed  $\exp[1.05 \ln(\text{hardness}) - 8.53]$  where hardness is expressed as mg/l  $\text{CaCO}_3$ .
- b The value should not exceed  $\exp[1.05 \ln(\text{hardness}) - 3.73]$  where hardness is expressed as mg/l  $\text{CaCO}_3$ .
- c The value should not exceed  $\exp[0.94 \ln(\text{hardness}) - 1.23]$  where hardness is expressed as mg/l  $\text{CaCO}_3$ .
- d The value should not exceed  $\exp[2.35 \ln(\text{hardness}) - 9.48]$  where hardness is expressed as mg/l  $\text{CaCO}_3$ .
- e The value should not exceed  $\exp[1.22 \ln(\text{hardness}) - 0.47]$  where hardness is expressed as mg/l  $\text{CaCO}_3$ .
- f The value should not exceed  $\exp[0.76 \ln(\text{hardness}) + 1.06]$  where hardness is expressed as mg/l  $\text{CaCO}_3$ .
- g The value should not exceed  $\exp[0.76 \ln(\text{hardness}) + 4.02]$  where hardness is expressed as mg/l  $\text{CaCO}_3$ .
- h The value should not exceed  $\exp[0.83 \ln(\text{hardness}) + 1.95]$  where hardness is expressed as mg/l  $\text{CaCO}_3$ .

may be a significant process in limiting the free metal ion

concentration. All metals would be complexed to some extent by naturally occurring ligands. The most common ligands are hydroxide ( $\text{OH}^-$ ), bicarbonate ( $\text{HCO}_3^-$ ), carbonate ( $\text{CO}_3^{2-}$ ), and humic materials.

Humic materials are associated with color in natural waters and account for the bulk of the organic matter in natural waters and soils (Snoeyink 1980, p. 232). The pH was usually the dominant factor in determining the speciation and complexation of metals. Generally, as the pH decreases the free metal ion concentration increases. This was illustrated in graphical form for copper (Figure 2). The results were calculated based on equilibrium data for different copper complexes and used the assumption that

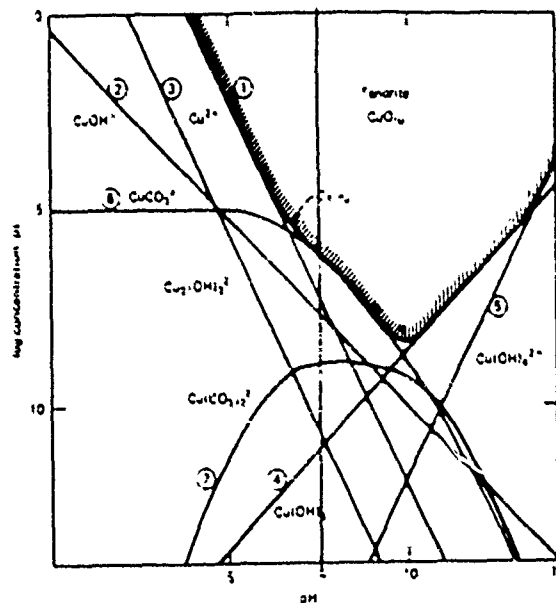


Figure 2. Copper species distribution in a water containing total inorganic carbon,  $C_{T,\text{CO}_3} = 10^{-3}\text{M}$ . (Snoeyink 1980, p.221)

the precipitation of Tenorite controls the free ion concentration. This type of information can be used to estimate the concentrations of predominant species for different pH values. For example, over the pH range of 6.5 to 8.0 the dominant copper complex was predicted to be  $\text{CuCO}_3$  in concentrations ranging from  $10^{-5.5}$  to  $10^{-6}$  moles/liter. The free copper ion was present at concentrations of  $10^{-5.8}$  to  $10^{-9}$  M (100 ug/l to 0.06 ug/l).

Figure 2 represents the solubility of copper in a laboratory prepared solution of distilled water with the anions that were indicated. By adding complexing agents, such as humic materials, the apparent metallic solubility would be increased in proportion with the binding strength and concentration of the complexing agent. The apparent solubility can be calculated by summing the copper complexes in Figure 2 vertically at a specific pH. An example of this would be the apparent solubility of copper at pH = 7:

$$C_{T,Cu} = [\text{CuCO}_3] + [\text{Cu}^{+2}] + [\text{CuOH}^+] + [\text{Cu}(\text{CO}_3)_2^{-2}] +$$

$$[\text{Cu}_2(\text{OH})_2^{+2}] + [\text{Cu}(\text{OH})_3^-]$$

$$C_{T,Cu} = 10^{-5.5} + 10^{-6.2} + 10^{-6.5} + 10^{-9} + 10^{-10.5} + 10^{-10.8}$$

$$C_{T,Cu} = 10^{-5.4}$$

The total filtrable metal in a lab analysis usually corresponds with this result. The total metal concentration should therefore not be construed to represent the total concentration of free copper ion in the water, but used in conjunction with equilibrium data to estimate copper

species concentration or activity.

By looking at the values in Table 3 and the speciation of curves in Figure 2, it became apparent that alkalinity was an important factor for establishing the free ion concentration for many metals. This correlates with the observation that copper is more toxic to fish in soft water than in hard water (Snoeyink 1980, p. 222). Noting that BW may have a high alkalinity, more of the  $Cu^{+2}$  would be complexed by the increased carbonate concentration, reducing the metallic toxicity of the copper and other metals in general to the local biota, although the alkalinity is usually determined by the composition of the receiving waters.

Ionic strength also plays an important role in the solubility of metals in natural waters. As the ionic concentration in a solution increases, the electrostatic interactions increase and the measured concentration was greater than the predicted ionic activity. Therefore, the activity coefficients for ionic species will be less than 1 for ionic strengths of greater than  $10^{-4}$ . The effects of ionic strength on uncharged species was related to an experimentally determined salting-out coefficient  $k_s$ .

$$\text{Log } \gamma = k_s u \quad \begin{array}{l} \gamma - \text{Activity coefficient} \\ u - \text{ionic strength} \end{array}$$

$k_s$  generally fall in the range of 0.01 to 0.15.

This salting-out has the effect of increasing the activity of uncharged species, thereby reducing the ratio of

concentration to activity at higher ionic strengths. An example of this would be the solubility of dissolved oxygen (DO) in freshwater verses saltwater. In a typical freshwater the saturated concentration of DO at 25 degrees Celsius is 8.4 mg/L. In a typical saltwater the saturated DO under similar conditions is 6.8 mg/L.

Where freshwater streams mix with saline waters increasing ionic strength may create a turbid mixing zone where the colloidal solids carried in the freshwater might be coagulated. This turbid mixing zone should oscillate with the ebb and flow of the tides and distribute adsorbed metals to the bottom in proportion to the settling and resuspension velocities of the particles. Adsorption onto mobile or fixed adsorbents was often the controlling factor in the fate of trace metals in natural waters (Dzombak 1987, p. 430). The adsorption of metals was modeled as a coordination process which involved interactions between the metal ion and specific surface sites. The hydrous metal oxides, clays and carbonates were typically the most common inorganic adsorbents. Hydrous metal oxides have the greatest affinity for ions because of their charged surface sites and high surface area. Hydrous metal oxides were often present as coatings on particles such as organic matter and clays. The dominant hydrous metal oxides in natural systems were the oxides of iron, manganese, aluminum, and silicon (Dzombak 1987, p. 431). Desorption

from suspended solids must also be considered. The same factors which control adsorption will conversely control desorption. Any change in the equilibrium conditions which favor desorption will cause an increase of the total filtrable metal. The most important example of desorption occurs in freshwater streams that experience acidic rain episodes. When the pH in the stream drops, the solubility of metals in the bottom sediments is increased. This in turn results in the desorption of the metals to the water phase. Because the free ion is predominant for most metals at low pH, the desorbed metals will have the maximum potential to exhibit toxic effects.

Finally, the rate of reactions for complexation and adsorption must be addressed. As mentioned earlier adsorption reactions are considered to be coordination reactions with fast reaction rates on the order of seconds, minutes, or hours. Adsorption of ions on oxides was usually a two step process which consists of a rapid initial uptake followed by a slower step that may take hours or weeks to reach equilibrium. The effect of the second slow step can be minimized by having a large excess of surface sites with respect to sorbate concentrations. Generally, the time frames of concern were of the order of weeks or months and the surface site density was one to two orders of magnitude greater than the sorbate concentration. This means that the use of equilibrium equations and models would yield

representative results for real world problems but careful consideration must be taken when high quantities of adsorbates are present.

Factors that influence adsorption onto metal oxides were as follows:

1. Solubility - contaminants with low solubilities were usually hydrophobic and tend to sorb onto the solid phases;

2. Competitive reactions such as complexation with humic materials tended to increase the solubility and limit adsorption onto the solid phase. However, some complexes may sorb more strongly or the same as the naked cations;

3. The pH of the water has the most significant effect on the adsorption of metals. As a general rule, metals were more strongly sorbed at a higher pH. Figure 3 is a plot of percent adsorption verses pH.

Adsorption theory for ionic species is based on the diffuse double layer model. Figure 4 represents the qualitative concept of the Gouy-Chapman model. Computer programs based on equilibrium chemistry and the Gouy-Chapman model are available from the EPA. One such program is MINTEQA2 which allows for the modeling of adsorption while considering the effects of competing reactions, solubility, and pH.

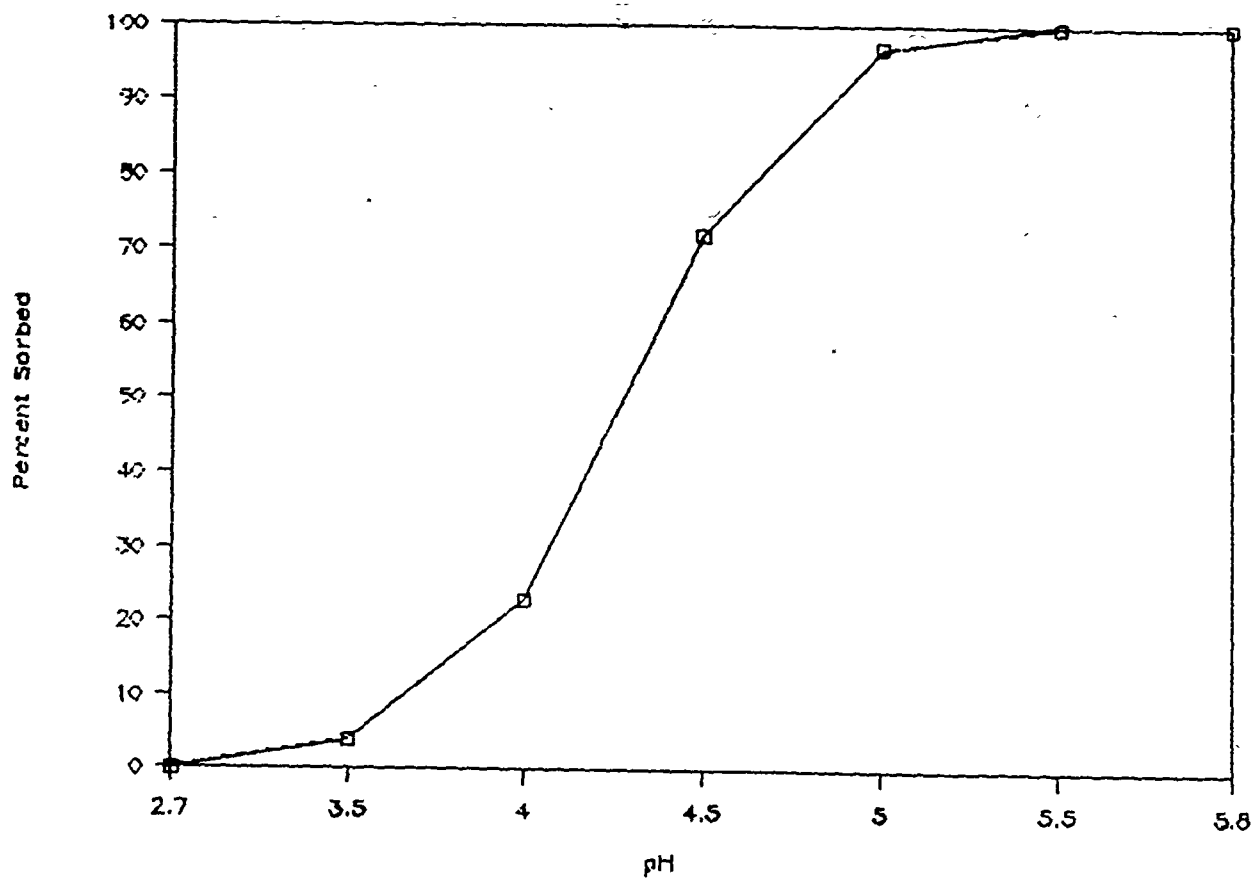


Figure 3. Percent Adsorbed vs pH  
Copper onto ferric metal oxides.

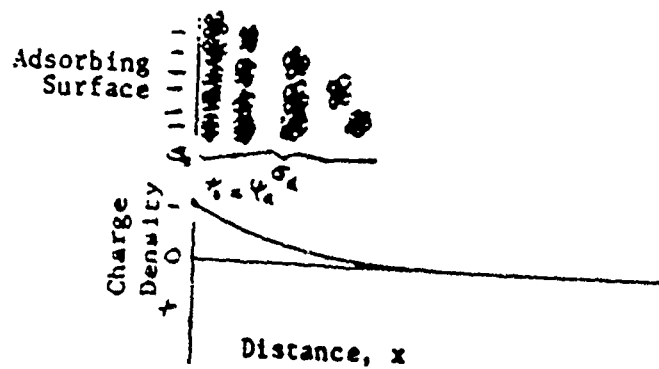


Figure 4. Gouy-Chapman Model

3.3 Modeling the Fate of Contaminants. Since data specific to the study site are limited, a simple fate and transformation model has been used to perform a baseline assessment of the effects of BW on the harbor environment. The relatively simple model that was used follows:

$$\frac{dC}{dt} = -U \frac{dC}{dx} + E \frac{d^2C}{dx^2} - k C + I = 0 \quad (\text{Eq.1})$$

Where: U = velocity, L/T  
 E = dispersion coefficient, L<sup>2</sup>/T  
 k = first order decay rate constant, 1/T  
 I = emissions, M/T  
 C = concentration, M/L<sup>3</sup>  
 dC/dt = 0, steady state conditions.

Biodegradation, volatilization, and photolysis were believed to be insignificant transformation factors for this application. Therefore, the decay coefficient was related to the fraction of metal sorbed to the suspended solids and the net settlement velocity of the solids. It must be pointed out that this model was one dimensional and assumed instantaneous cross-sectional mixing of the estuary.

For an estuary, equation (1) can be solved for the following boundary conditions (Thomann 1987, p. 106):

$$C = C_0 \text{ at } X = 0 \text{ and } C = 0 \text{ at } X = \pm \text{infinity}$$

to yield

$$\begin{aligned} C &= C_0 \exp(j_1 X) & X \leq 0 \\ C &= C_0 \exp(j_2 X) & X \geq 0 \end{aligned} \quad (\text{Eq.2})$$

where

$$j_1 = \frac{U(1+a)}{2E} \quad j_2 = \frac{U(1-a)}{2E} \quad C_0 = \frac{W}{Qa}$$

$$a = (1 + 4kE/U^2)^{1/2}$$

$a$  = estuary lumped parameter  
 $W$  = mass loading, kg/d  
 $U$  = net non-tidal velocity,  $U = Q/A$ , m/d  
 $E$  = tidal dispersion coefficient,  $m^2/d$   
 $k = (v_n * f_s)/D$      $f_s = K_p S/(1+K_p S)$   
 $= 1/d$   
 $D$  = Average estuary depth, m  
 $v_n$  = Sedimentation velocity, m/day  
 $Q$  = Net nontidal flow,  $m^3/d$   
 $S$  = Suspended sediments concentration, mg/L  
 $K_p$  = partition coefficient, L/mg

This equation can be used to generate contaminant profiles for average concentrations in the estuary versus distance from the discharge point. The fraction of total metal in the particulate phase,  $f_s$ , can be selected from an adsorption front calculated with a concentration of total sorption sites analogous to the suspended solids in the system and the system pH. If an adsorption front is not available, then the partition coefficient,  $K_p$ , has been estimated to be in the range of  $10^4$  to  $10^5$  L/kg (Thomann 1987, p. 508).  $K_p$  can also be determined from water samples by the following:

$$K_p = \frac{\text{conc. in sediments (mg/mg)}}{\text{conc. in water (mg/L)}} = \text{L/mg}$$

The sedimentation rate can be estimated by Stoke's law for discrete particles but a better estimate would be based on the results of a column settling test.

If the net non-tidal flow is zero, then  $U=0$  and a purely dispersive system results and Equation 1 solves to

(Mills 1985, p. 211):

$$j_1 = j_2 = (k/E)^{1/2} \quad (\text{Eq. 3})$$

$$C = C_0 \exp. [-(k X^2/E)^{1/2}]$$

$$C_0 = \frac{W}{2A (kE)^{1/2}}$$

A = cross sectional area of estuary

Both equations 2 and 3 can be used to generate contaminant profiles for different conditions. Typical contaminant profiles for differing conditions of advection (U) and decay (k) are shown in Figure 5.

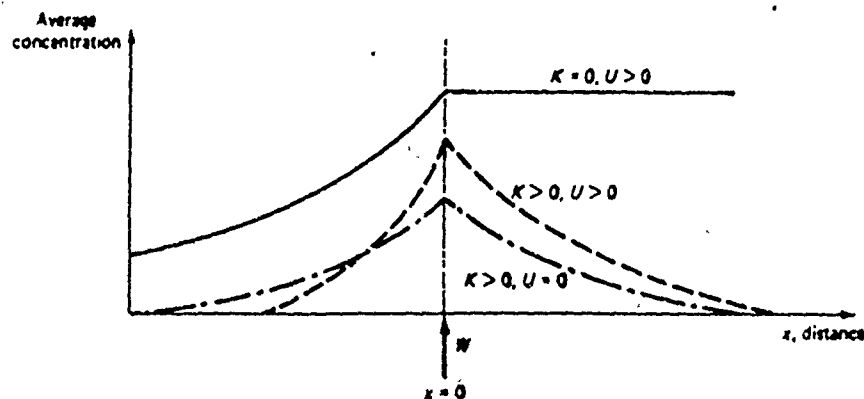


Figure 5. Estuary contaminant profile (Thomann 1987, p. 109)

Therefore, given the freshwater flow, Q, an average cross-sectional area, A, the suspended solids concentration, S, and estimates of the partition coefficient,  $K_p$ , and dispersion coefficient, E, a contaminant profile can be generated. Table 4 contains some dispersion coefficients

for various estuaries.

Estuary	Flow (cfs)	Dispersion coefficient (smpd)
Hudon River, NY	5,000	20
East River, NY	0	10
Cooper River, SC	10,000	30
South River, NJ	23	5
Houston Ship Channel, TX	900	27
Cape Fear River, NC	1,000	2-10
Compton Creek, NJ	10	1
Wappinger and Fishkill Creek, NY	2	0.5-1
River Foyle, N. Ireland	250	5

Table 4. Longitudinal Dispersion Coefficients  
(Thomann 1987, p. 117)

The dispersion coefficients were estimated by several approaches:

1. Use salinity data as a tracer of tidal mixing.
2. Use dye as a tracer of tidal mixing.
3. Use hydrodynamic theory incorporating velocity shear and salt diffusion mechanisms.

Since the net non-tidal velocity in the Elizabeth river approaches zero ( $U=0$ ), approach 2 would be the most accurate and practical. The equation used to evaluate the dispersion of a conservative tracer is:

$$C = \frac{W}{2 A (3.14 E t)^{1/2}} \exp \left[ -\frac{(X-Ut)^2}{4 E t} \right] \quad (\text{Eq. 4})$$

By discharging the mass of dye quickly across a cross section of the estuary during slack water before flood and then collecting samples up and down estuary after one tidal

cycle the dispersion coefficient can be estimated. A plot of  $\ln C$  vs.  $(X - Ut)^2$  should yield a line with a slope equal to  $[-(4Et)^{-1}]$ . Therefore, the dispersion coefficient,  $E$ , will equal:

$$E = (\text{Slope} \times 4 \times t)^{-1}$$

3.4 Ultimate Fate of Metals in Bilge Water. Metals are not degradable and will exist in the local environment indefinitely unless physically moved. The toxic species of metals will be naturally limited by the complexing ligands in most natural waters. The fate of metals in the natural environment is strongly affected by sorption processes, alkalinity, and pH. Metals are transported as dissolved species in the aqueous phase or as adsorbed complexes on mobile suspended solids. If environmental conditions change significantly, such as, the pH drops below 5 significant quantities of metals will be desorbed because of the increased solubility of metals with decreasing pH. Most estuaries are large enough in size and alkalinity to resist any drastic changes in pH. Therefore, once a metal is sorbed to a particle in the estuary it will stay sorbed.

The ultimate fate of metals would be final deposition and burial with sediments on the floors of estuaries and oceans. Therefore, sorption onto suspended solids and the settlement of these solids to the bottom was believed to be the dominant factor in dispersing toxic discharges and

maintaining metal concentrations below acute and chronic toxicity levels. However, processes that disturb the bottom sediments (e.g. dredging) can increase the concentration of metal contaminants in the water column.

### 3.5 Ultimate Fate of Conventional Pollutants.

Conventional pollutants in BW (BOD, COD, fecal coliform, SS) are present in concentrations ranging from 45 to 160 mg/l for a typical bilge water. These pollutants are all biodegradable or are easily removed from the environment. The ultimate fate of BOD in BW will be conversion to carbon dioxide and water by assimilation in bacteria. The SS will settle to the bottom and add to the bottom sediments. Any nondegradable pollutants would be dispersed as conservative pollutants by natural mixing processes.

Chapter 4  
Modeling the Naval Station Harbor

4.1 Estuary Model. As detailed in Chapter 3 the following information was required to run the model. Details regarding the evaluation of net velocity are given in Appendix 2.

1. Net non-tidal velocity,  $U = 15.22$  m/d  
See Appendix 2 for calculation.
2. Average depth of estuary,  $D = 13.8$  m (45 ft)
3. Net sedimentation rate,  $V_n = 20$  m/d
4. Partition Coefficient for metals,  $K_p = 0.1$  L/mg
5. Biological first order decay rate,  $k = 0.1$  hr<sup>-1</sup>
6. Mass loadings for pollutants,  $W$ , see Table 2
7. Tidal dispersion coefficient,  $E = 1$  smpd  
(1 smpd =  $2.59 \times 10^6$  m<sup>2</sup>/d)
8. Suspended sediments concentration,  $S = 15$  mg/L

Since the net non-tidal advective flow is small, the estuary will act as a purely dispersive system. Therefore, substitution into Equation 3 will generate the contaminant profiles shown in Figures 6 to 10. Appendix 3 shows an illustrated calculation.

Table 5 lists the maximum concentration for each contaminant as calculated by Equation 3.

A comparison of the values in Table 3 and Table 5 indicate that the concentrations of BW pollutants in the estuary would be four to five orders of magnitude below the criteria to protect aquatic life. Therefore, based on the

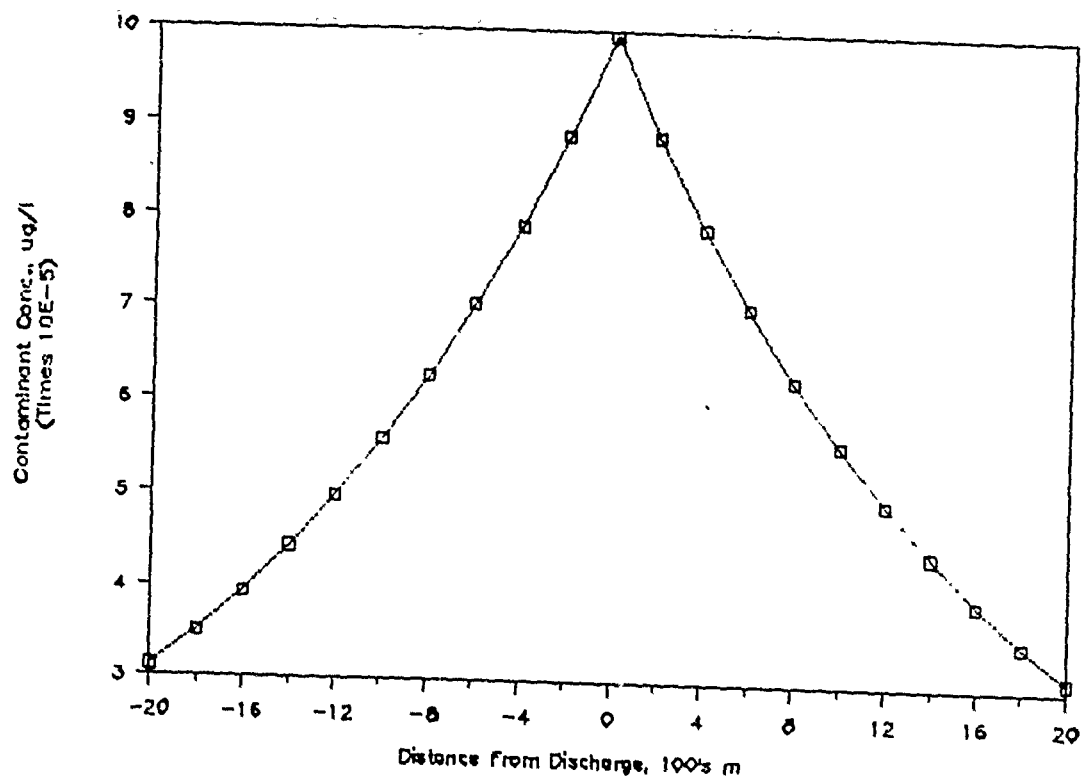
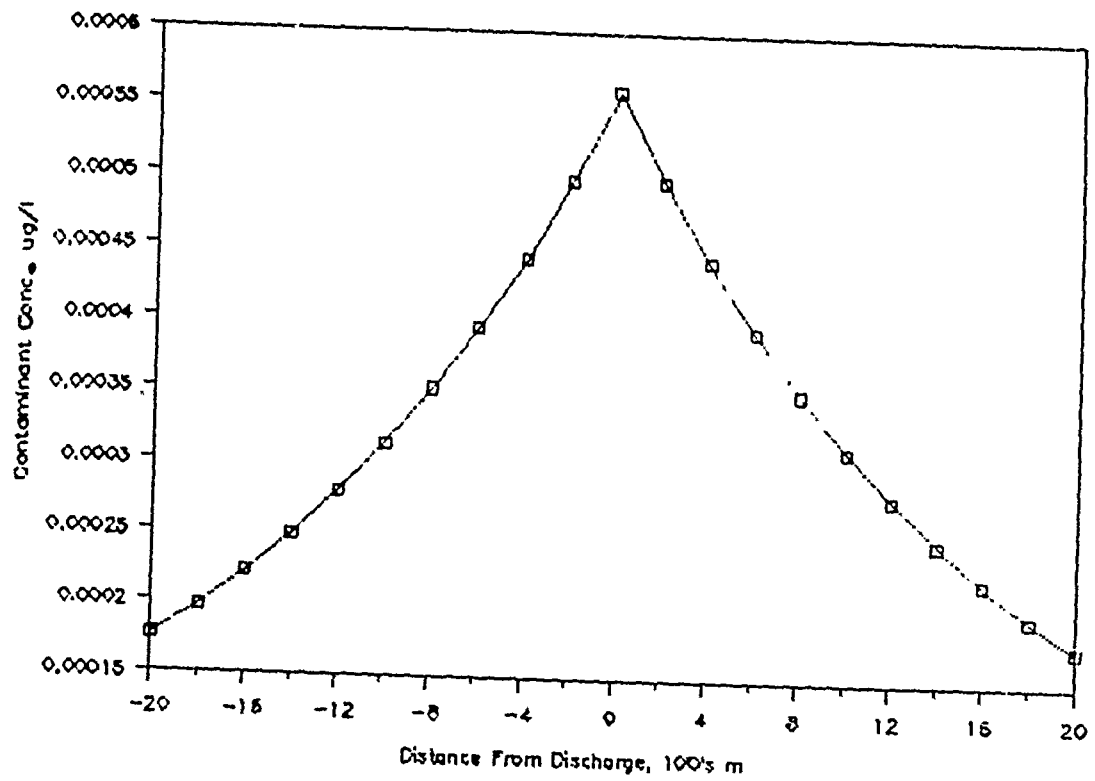


Figure 6. Estuary Contaminant Profile-Chromium



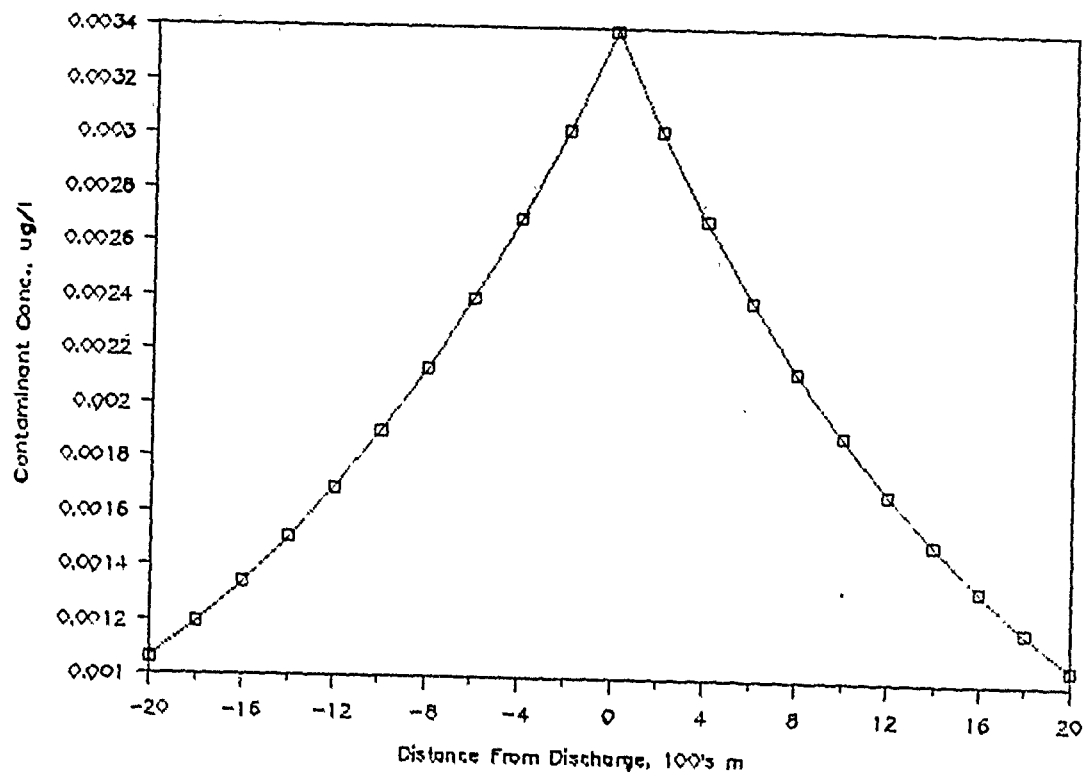


Figure 8. Estuary Contaminant Profile-Iron.

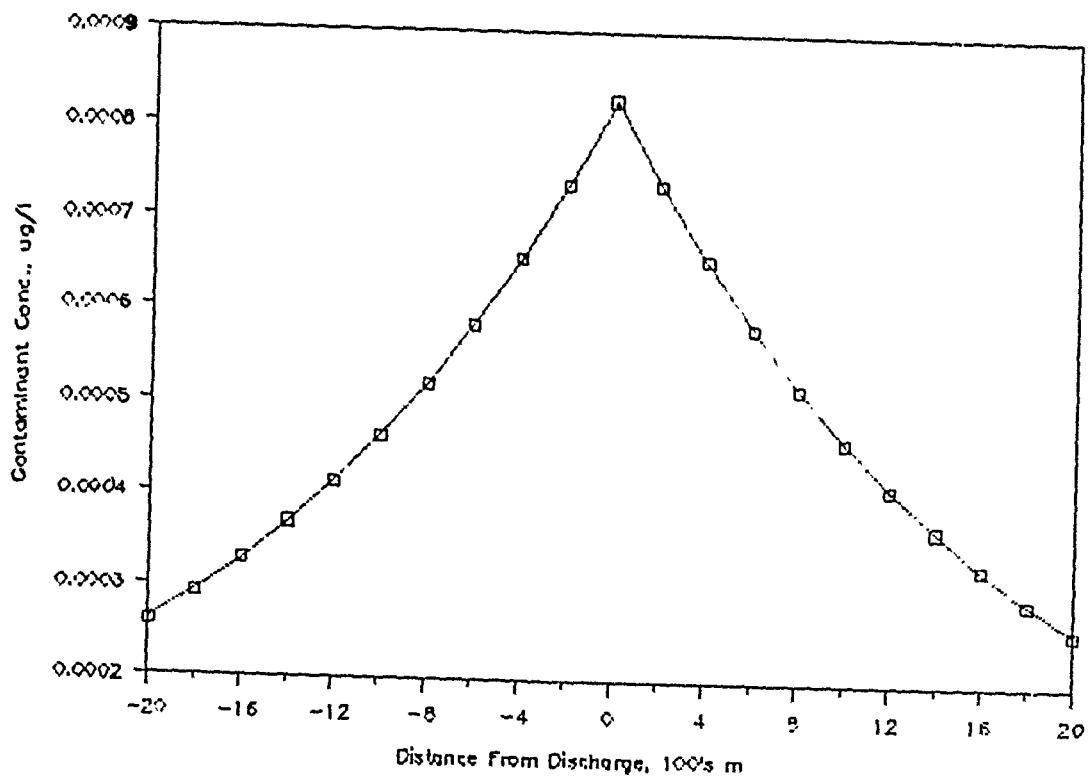


Figure 9. Estuary Contaminant Profile-Zinc.

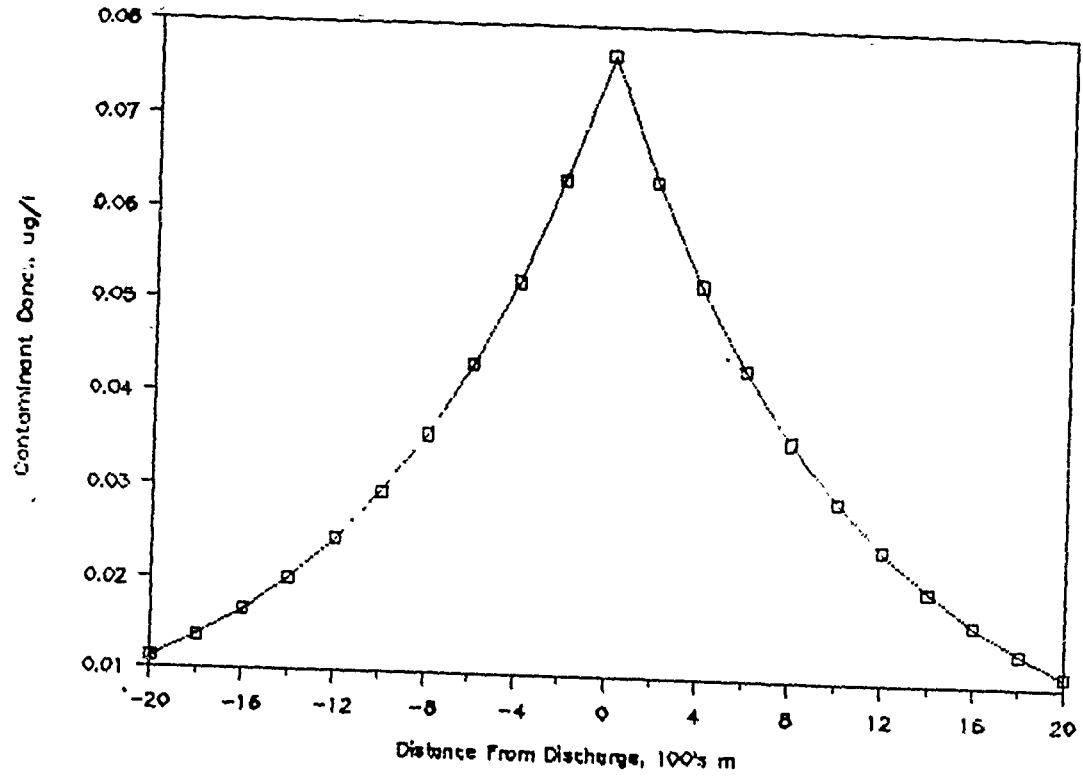


Figure 10. Estuary Contaminant Profile-BOD.

Table 5. Calculated Maximum Contaminant Concentrations

Contaminant	C <sub>o</sub> ug/l	Dilution Factor <sup>a</sup>
BOD	7.7x10 <sup>-2</sup>	6.5x 10 <sup>5</sup>
Chromium	9.9x10 <sup>-5</sup>	3.9x 10 <sup>5</sup>
Copper	5.6x10 <sup>-4</sup>	3.9x 10 <sup>5</sup>
Iron	3.3x10 <sup>-3</sup>	3.9x 10 <sup>5</sup>
Zinc	8.2x10 <sup>-4</sup>	3.9x 10 <sup>5</sup>

a - Dilution Factor = Typical BW concentration / C<sub>o</sub>

dilution factors and the proposed criteria in Table 3, discharge limits can be calculated. Table 6 contains the recommended maximum discharge levels (MDL) for the metals listed. An average value for a dilution factor of 39 was used for all the metals which assumes a safety factor of 10,000.

4.2 Model Validation. The above model and results were based on estimates believed to be reasonable and on limited test data. The above results may be appropriate for a quick assessment of the impact of BW. In order for the model to be truly representative of the environment being studied it must be validated against field testing results. First, the parameters of the model must be accurately determined and then new contaminant curves can be

Table 6. Recommended Maximum Discharge Levels (MDL)

Metal	Saline Water MCL Criteria		MDL	
	24 hr. Average ug/L	Maximum ug/L	24 hr. Average mg/L	Maximum mg/L
Arsenic	LD	508	LD	20
Cadmium	4.5	59	0.2	2.3
Chromium	18	1260	0.7	49
Copper	4	23	0.2	0.9
Lead	25	668	1	26
Mercury	0.1	3.7	0.004	0.1
Nickel	7.1	140	0.3	5.5
Selenium	54	410	2.1	16
Silver	0.26	2.3	0.01	0.09
Zinc	58	170	2.3	6.6

The discharge limits for BOD and SS should meet secondary treatment requirements of 30 mg/L each.

LD denotes lack of data.

calculated. Then field testing must be done to determine if the predicted values from the model correlate to field conditions. Figure 11 is a recommended sampling scheme for a point source discharge which should give results in a format that can be compared to the contaminant profiles. If the data does not correlate, then the constants must be adjusted and the validation process repeated until an acceptable variance is reached.

● Composite Sample Point - Take samples at D-1', D/2, and at the surface.

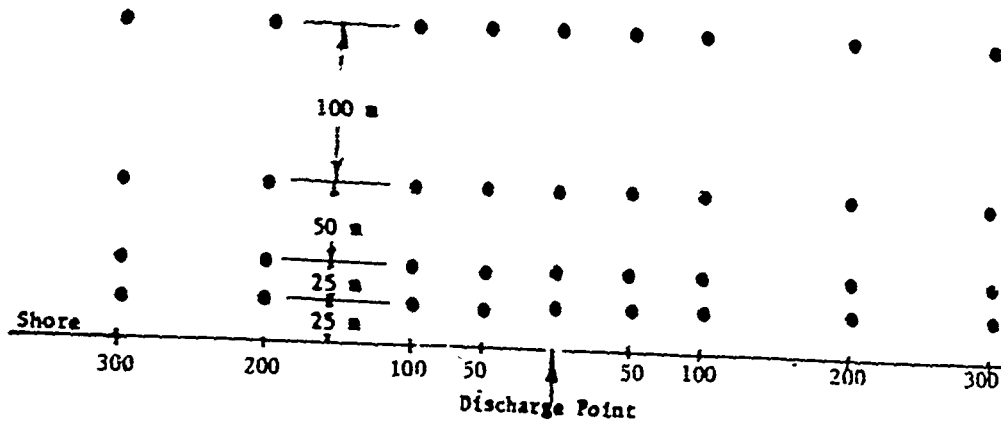


Figure 11. Recommended Slack tide sampling plan.

## Chapter 5 Environmental Assessment

5.1 Biological Assessment. According to the model that was applied in chapter 4, the contaminant concentrations in the harbor water column were predicted to be at least four orders of magnitude less than the proposed acute or chronic toxicity criteria. Given that the assumed parameter values were very conservative indicates that no toxic criteria would be exceeded by the discharge of BW. Therefore, the discharge of BW would not have any measurable acute or chronic harmful effect on the local or regional harbor environments due to metals or other chemicals that were included in the model. The primary basis for this assessment was that the mass loadings for the contaminants were small when compared to the mass of water in the estuary.

5.2 Human Assessment. Human exposure and risk from BW may be through the food chain via the consumption of fish and shellfish which bioaccumulate or biomagnify trace metals or petroleum products. However, several factors may diminish the potential impacts. Because the loadings of these contaminants was small, the opportunity for the fish and shellfish to bioaccumulate may be reduced. The BW discharges would be within the bounds of the Naval complex which is an active port facility where fishing is not practiced. Contaminants would probably not reach the

commercial fishing areas because of the distance to the Chesapeake Bay (3 miles north of Sewells Point). Therefore, only limited acute or chronic risks to humans would be expected because of the discharge of BW to the Naval Harbor Complex.

## Chapter 6 Federal Policy

6.1 Background. The Federal and state policies/legislation governing the Chesapeake Bay have developed from a series of legislation and federal and state cooperative programs. The Federal Water Pollution Control Act of 1972 stated as its first objective the elimination of pollutant discharges into navigable waters. The FWPCA was the cornerstone for Federal policy in the Chesapeake Bay. The Chesapeake Bay Commission which was formed in 1980 as an interstate legislative planning and program coordination committee later became the basis for the formation of the 1987 Chesapeake Bay Agreement (CBA). The CBA was entered into by the governors of Pennsylvania, Maryland, Virginia, the Mayor of the District of Columbia, and the EPA acting for the Federal government on 14 December 1987. The CBA contained statements of goals, objectives, and specific commitments in six major areas (Chesapeake Bay Agreement, 1987, p. 2). Those areas included living resources, water quality, population growth and development, public information, education and participation, public access, and governance. The water quality commitments were founded on the requirements of the Clean Water Act as Amended in 1987.

The Chesapeake Executive Council governs the activities of the Chesapeake Bay Program. Each commitment in the CBA generated a series of reports which gave information on

progress towards their specific goals. One such commitment report was the Federal Facilities Strategy (FFS) which was in response to water quality commitment number 5 of the CBA. Commitment 5 states "...by July 1988, the EPA, acting for the Federal government, will develop, adopt and begin implementation of a strategy for the control and reduction of point and nonpoint sources of nutrient, toxic and conventional pollution from all Federal facilities." The FFS recognized that federal departments would initially select those facilities which have the greatest potential to affect the Bay and require action plans be designed and implemented as a first priority (FFS 1988, p.1). The FFS report gives information on the different environmental programs which were important to the Chesapeake Bay. Therefore, the Chesapeake Bay Commission through the EPA and FFS may place significant pressure on Federal facilities to implement more extensive actions to meet the goals set in the CBA. However, the CBA is not a law and cannot be used by a regulatory body as a basis for enforcement.

The Department of Defense (DOD) has since 1974 been a leader in pollution abatement projects and natural resource programs in the Bay region. From 1974 to 1988 DOD spent more than \$235 million on Bay pollution abatement projects (FFS 1988, p. 3-1).

The Navy has its own goal of pollution free ships by the 21<sup>st</sup> century and has been diligently working towards

that end. Unfortunately, incidents like the USS Nassau dumping medical waste off the shores of North Carolina in 1988 and the fact that the Navy is a federal entity has afforded the press with ample opportunity to portray the Navy as an environmentally irresponsible organization. Because of this bad press the Navy has to be "above all reproach" in order to correct this perception and proactively stave off any unreasonable and costly regulations/litigation which may be inspired by news media.

Now with many states being granted RCRA and CERCLA primacy by the EPA, increasing pressure is being placed on all municipal and industrial dischargers to accelerate advanced wastewater plant modifications. Unfortunately, additional funds were not being appropriated to construct or upgrade facilities, leaving many municipalities and industries facing fines or construction costs which they could not afford.

Many regulatory agencies have been under-educated on the actual physical and biological processes which occur in nature and were generally very hesitant to approve new technology or make decisions which were not very conservative. Because of this regulatory philosophy discharge limits were set without through consideration of the fate, transport, toxicity or the technology required to meet the limits. At times these limits were sometimes below detectable limits for most common analytic procedures. This

requires the discharger to expend unreasonable amounts of funds needed for quality control/quality assurance. For example, toxic contaminant leachate procedures (TCLP) tests may range in cost from \$1000 to \$1300 per sample. If a composite test were taken once per week, then the annual cost will be from \$52,000 to \$67,600. These types of testing procedures do nothing to help the operator of the wastewater facility to control the treatment process on a day to day basis because of the normal turn around time required to obtain the results and therefore serve no purpose but to document the file. This documentation may or may not help to stave off the wrath of a zealous regulator after a random composite sample is collected and tested by the state testing laboratory. Therefore, treatment systems have been designed with technology and safety factors which perform at removal levels far below the criteria so that if problems do occur no permit limits could be exceeded.

6.2 The Clean Water Act as Amended of 1987. BW was not specifically addressed in the CWA. Oil is one of the major contaminants of BW and therefore must be addressed with respect to the regulations in the CWA. Section 311, "Oil and Hazardous Substance Liability", prohibited the discharge of oil or hazardous substances into or upon navigable waters of the United States. However, the syntax of this section and all sections of the CWA indicate that the law pertains to the discharge of POL in its concentrated

form not to waters contaminated with POL. Section 311, paragraphs (3) and (4) state that only quantities of oil which may be harmful as determined by the President were prohibited.

It was obvious that the intent of section 311 is to prohibit the gross discharge of POL in quantities which would have significant adverse acute and chronic impacts on the environment. Therefore, by virtue of the fact that Naval vessels have been installing OWSs to minimize oil discharges from bilges shows the intent of the Navy to comply with the CWA.

The other pollutants in BW are addressed in the CWA but only with respect to discharges from NPDES permitted facilities. Naval vessels are not NPDES permitted facilities which can be regulated by the states. However, states may apply to the EPA for no-discharge zones. These no-discharge zones only apply to the discharge of sewage as stated in section 312 (f)(4)(A).

The bottomline is that the CWA is not clear with respect to BW and therefore lends itself to advantageous interpretation by both the states and the Navy. This can be the start of an extensive legal battle with adverse media coverage for the Navy. In these instances politics, not scientific knowledge, usually governs the resulting resolutions/regulations. The answer to the problems above are complex and need to be addressed by both parties. The

Navy must review and evaluate its procedures to minimize environmental impacts from spills and improper handling of wastes. The states must invest in their regulatory agencies additional technical education funds so that more reasonable informed decisions can be made while recognizing that the Navy does not have a bottomless pocket. Both organizations need to work together so that maximum benefit is achieved for the funds available in a reasonable time frame. In the past, decisions on environmental issues have been finalized by lawyers which have no technical knowledge of environmental engineering or the environmental impacts which can result from a misinformed decision.

Therefore, based on the objectives of the CWA, the benefits associated with good public relations and DOD's support of the Chesapeake Bay Program a BW treatment process should at some time be constructed to handle BW produced at the Naval Station Norfolk Complex.

## Chapter 7 Options

7.1 Options for BW Practices. Based on the assessments in chapter 5 and the policy established by both the CWA and public opinion the following options were proposed:

1. Minimize or eliminate the production of BW.
2. Continue with the installation of oil water separators and force the state to establish legal authority to regulate naval vessel discharges.
3. Continue with the installation of oil water separators but collect all BW and treat it at a NPDES permitted shore facility using biological-physical-chemical processes.

7.2 Minimization of BW. In theory option 1 may be the most prudent but because of the age of many of the ships involved may not be completely feasible. However, the development and implementation of a minimization program would be paramount to any solution to the BW issue. Since BW is the result of leaks, an aggressive program which places an emphasis on preventative maintenance (PM) and early detection of mechanical breakdowns is required. Ships with good engineering officers should already have similar systems in place but may require some assistance with fine tuning their PM programs so that all the work can be efficiently performed. Data management systems like DBASE

IV can greatly improve the efficiency of any maintenance program by balancing the workload with the available crew.

Between options 2 and 3 above, option 3 maybe the best for the following reasons:

1. Option 1 requires the collection of the OWS oily waste overflow which must be treated as a hazardous waste.

2. The OWS effluent would continue to add metals to the bottom sediments where they would remain until disturbed.

3. Option 3 is in keeping with the objectives of the FWPCA and is the most advantageous for the harbor environment and Navy public relations.

4. Option 3 would probably be acceptable to the Virginia State Water Control Board and may prevent the outlay of a considerable amount of legal manpower and funds.

5. Option 3 allows for direct monitoring and control of the treatment process.

6. Option 3 can be staffed with trained operators that are skilled in wastewater treatment and plant operations.

## Chapter 8 Treatment Schemes For Bilge Water

8.1 Design Considerations. The design considerations which were made are as follows:

1. Type and concentration of wastewater.
  - a. toxic and shock loadings
  - b. biological and physical/chemical treatability
2. Quantity and variation of waste flows.
  - a. highly variable flows
3. Flexibility and ease of operation.
  - a. biological nutrient removal
4. Sludge production and disposal.
  - a. Minimize sludge production
5. Capital and operation costs.
6. Maintenance costs.

8.2 Type and Concentration of Bilge Water. The test data did not include results for volatile suspended solids (VSS), but if the TSS (150 mg/L) were assumed to be 70% volatile, the estimated VSS would be 106 mg/L. Table 2 lists the typical BW characteristics.

The BOD test is a bioassay which is susceptible to the toxic effects of metals and organics. Therefore the measured value maybe decreased with respect to the actual value. The value for TOC appeared to be decreased. Generally, TOC is greater than COD and COD is greater than  $BOD_5$ . Also, as a general rule  $BOD_{ult} = 1.5 \times BOD_5$  or  $BOD_5 = 0.67 \times BOD_{ult}$  ( $k = 0.1$ ). One final general rule is that if all of the contaminants are biodegradable, then  $COD =$

BOD<sub>ult</sub>. A conservative assumption that 70% of the COD is biodegradable will be made for the purposes of design. Based on the assumptions and the data in table 2, BW can be considered a high particulate waste (VSS/BOD<sub>s</sub> > 50%).

8.3 Treatment Scheme Evaluation. Biological treatment schemes like trickling filters (TF), rotating biological contactors (RBC), contact stabilization (CS), and extended aeration (sequencing batch reactor, SBR) all perform well with high particulate wastes. Each treatment scheme was evaluated for application to BW treatment along with coagulation, flocculation, and sedimentation processes that may be required for sludge thickening and handling. Chemical stabilization processes, such as, chlorination or ozonation were not be considered because of excessive costs and chemical handling risks to humans and the environment. A decision table was created to evaluate different treatment schemes based on selected considerations/criteria (Table 7).

Each criteria was then prioritized and ranked for each treatment scheme based on the writer's experience. Then the rankings were multiplied by the priority and summed. The rankings and priorities ranged from 1 - 5 with 5 representing the highest rank or priority.

Table 7. Decision Table for Bilge Water Treatment

Criteria	Priority	TF	Process		
			RBC	CS	SBR
A. Sensitive to Shock/Toxic Loadings	5	2	2	3	3
B. Can Consistently Meet Permit Requirements	5	3	3	4	5
C. Requires Flow Equalization	5	1	1	1	5
D. Easy Maintenance	4	4	4	2	5
E. Allows for Flexible Ops.	3	2	2	3	4
F. Minimum Sludge Production	3	3	3	4	5
G. Minimize Capital & Operating Costs	2	4	3	1	4
Sum of Rank X Priority		69	67	71	120

The analysis of the different treatment schemes concludes that the SBR may be the optimal treatment scheme. Appendix 4 contains a flow diagram for the SBR treatment scheme. Appendix 5 are excerpts from the EPA Treatability Manual which contain wastewater average achievable treatment concentrations for major the trace metals for various treatment processes. These tables indicate that activated sludge processing of BW will easily meet the recommended MDLs.

8.4 Sequencing Batch Reactors. The SBR works on a

draw and fill process. The process steps are as follows:

1. Fill/Reaction cycle: Air on/off, mixing on, 0-3 hrs.
2. Settling cycle: Air off, mixing off, 1 hr.
3. Decant cycle: to draw off clear effluent, 1 -2 hrs.
4. Sludge wasting can be done during the react cycle or preferably after settling, 0 - 20 minutes.

Appendix 6 is a pictorial description of the SBR process.

The SBR is a relatively new "old" technology which was based on batch growth. The SBR can trace its roots to the first draw and fill activated sludge systems in England in the late 1800's. Figure 12 is a typical batch growth curve. Most activated sludge (AS) processes operate in the declining growth and endogenous growth phases. Moving across the curve from the addition of some BOD at time zero the microbes first experience log growth where substrate is not limited. AS systems that operate in the log growth phase will have poor BOD stabilization efficiencies and produce large quantities of voluminous poor settling sludges. Next, the microbes experience the declining growth

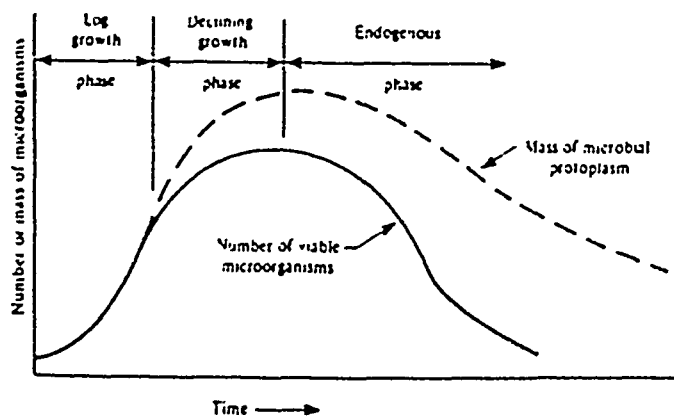


Figure 12. Typical Batch Growth Curve.

phase where substrate is limiting. AS systems operating in the declining growth phase are often referred to as high rate systems. High rate systems have good BOD stabilization (> 70%) efficiencies and produce significant quantities of good settling sludge. Finally, the microbes will experience the endogenous growth phase where substrate is at a minimum and the microbes utilize their protoplasm as an energy source. The cells get old, die and lyse releasing nutrients back into solution. The action of cell lysis decreases the volume of sludge produced and maximizes BOD stabilization (> 90%). The sludge generally has good settling characteristics.

Because of the SBR's basis on batch growth it will have the highest conversion of BOD to carbon dioxide and water with the minimum sludge production. However, since it is an extended aeration process, air requirements and energy costs will be greater than other conventional AS systems. Some other advantages of SBRs are:

1. The reactor acts as an equalization basin to dampen variable flows and BOD loadings.
2. Hydraulic controls are simple level indicators.
3. No sludge recycle system is required.
4. With automated controls, the system can be safely operated with minimal operator attention.
5. Minimal hardware requirements result in low construction and operation costs.

6. Biological nutrients can be easily removed by controlling the oxygen supply.

7. Solids retention time (SRT) is the process control parameter and is regulated by simple volumetric sludge wasting techniques.

8. All settling takes place under quiescent conditions. Therefore, lab settling tests results can be directly applied to SBRs.

9. SBRs can be purchased as package units which reduces engineering and construction costs.

10. SBRs can be used as a rapid mix/sedimentation basins should all of the microbial population die from a shock loading. This is a second back up to assure that no discharges exceed permit requirements.

The disadvantages of SBRs are:

1. If the mixed liquor does not settle properly the decant cycle will pass solids in the effluent.

2. Both floating and fixed decant mechanisms can pass solids in the beginning of the decant cycle.

3. In cold climates surface freezing of decant mechanisms and controls may occur during the settling and decant cycles.

4. Equalization tankage may be required for following filtration/disinfection processes.

8.5 Laboratory/Pilot Studies. Laboratory and pilot studies can be easily constructed and evaluated. The

results of these tests can then be directly applied to the design of the facilities and hardware because the SBR process is a direct scale up of the laboratory reactor. This results in cost effective process evaluation without scale up uncertainties due to field conditions differing from laboratory conditions.

8.6 Precautions. Any biological treatment selected should have included in the design provisions for dilution of concentrated wastes, provisions for the addition of nutrients (nitrogen and phosphorus) and alternate BOD sources (black/gray water) to provide food for the microorganisms when BW is not available.

Chapter 9  
Conclusions and Recommendations

9.1 Conclusions. The following summarizes the results for the objectives as determined from this research:

1. The estimated daily production of BW from a representative fleet in port during peacetime operations is 44,000 gpd  $\pm$  100%.
2. A typical bilge water will have the following concentrations of pollutants:

Table 8. Typical Design Bilge Water Characteristics.

<u>Contaminant</u>	<u>Conc. mg/L</u>
BOD <sub>5</sub>	190
COD	400
NH <sub>3</sub>	1
O&G	156
TSS	150
VSS	106

Metals listed in Table 2.

3. The Naval station complex has a characteristic depth and cross-sectional area of 13.7 m (45 ft) and 21540 m<sup>2</sup> respectively.
4. After dilution in receiving waters, trace metals in BW would likely be complexed with humic materials and adsorbed to suspended solids with ultimate deposition and burial in the bottom sediments. The oils and greases would be dispersed by tidal mixing, volatilization, photolysis, and sorption onto suspended solids with ultimate burial in bottom sediments. Conventional pollutants would be converted to carbon

dioxide, water and inert materials. The inert material would include dead microorganisms and coagulated organic material which settle to the bottom sediments.

5. Based on water quality criteria for the protection of aquatic life and the contaminant dispersion model in chapter 4, the contaminant levels associated with BW disposal would be significantly below both acute and chronic toxicity levels for aquatic organisms that are published by the EPA. Because the daily mass loadings from BW disposal were small and the commercial fishing areas are approximately 3 miles down estuary, there was insignificant accumulation of contaminants in fish and shellfish. Therefore, the environmental impacts from the discharge of BW to the harbor waters was minimal. However, because of aesthetic issues and to avoid public condemnation, all BW should be primarily treated by oil-water separation as a minimum.

6. MDLs for treatment discharges were calculated and tabulated in Table 5. An average dilution factor of 90 was calculated for the trace metal contaminants. The calculated maximum discharge concentrations provide protection, permit propagation of the biota and would permit recreation in and on the water.

7. Objectives and goals established by the FWPCA and public opinion would support requirements for BW treatment facilities. BW production and contamination

are highly variable. After analyzing four alternative treatment processes, SBRs were proposed as the most applicable treatment scheme.

9.2 Recommendations. The following are recommendations for developing plans of action for the handling of BW:

1. Perform testing to determine accurate values for the estuary model parameters  $K_p$ ,  $E$ , and  $f_s$ . Evaluate composite samples of bilge water for VSS, TKN, and phosphorus.
2. Establish and implement a BW minimization program.
3. Continue with the installation of oil-water separators and assure that proper operational training and maintenance requirements are met.
4. Appropriate planning documents for BW treatment facilities should be developed and submitted for prioritization and funding.
5. Perform benchscale laboratory tests to determine BW treatability and settling characteristics. This information would be needed for the design of SBRs to cost effectively treat BW.

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Appendix 1  
Bilge Water Contaminant Concentrations

The analytical results shown were taken from actual tests performed on composite samples from six different ships. The data shown is for trace metals, BOD, COD, fecal coliforms, TOC, and TSS. The results from the priority pollutant list tests (EPA 624 and EPA 625) did not indicate that any priority pollutants were present in detectable quantities and therefore were not included in this appendix.

Some of the data is not compatible with known standards and was addressed in the report.

The distribution factors and equations used to estimate a typical BW are also included.

APPENDIX 1

BILGE WATER CONTAMINANT CONCENTRATIONS  
WITHOUT OIL-WATER SEPARATION BY SHIP TYPE  
mg/L

CONTAMINANT	AIRCRAFT CARPIER (NUCLEAR)	CRUISER 16 CLASS	CRUISER 47 CLASS	DESTROYER SPRUANCE CLASS	AMPHIB ASSAULT 1179 CLASS	AMPHIB ASSAULT 36 CLASS
	CUN	C6	C6	ID	LST	LSD
ARSENIC	0.004	0.003	0.004	0.007	0.005	0.004
BOR	325.000	583.000	79.000	0.000	341.000	101.000
BARIUM	0.106	0.170	0.070	0.000	0.040	0.030
CAESIUM	0.027	0.067	0.009	0.155	0.017	0.000
CYANIDE	0.090	0.040	0.000	0.000	0.000	0.010
COD	7250.000	5600.000	690.000	252.000	2800.000	520.000
CHROMIUM	0.020	0.230	0.050	0.190	0.770	0.000
COPPER	1.040	6.400	1.130	5.320	0.430	0.560
IRON	3.000	46.000	3.600	28.000	2.900	2.950
MERCURY	0.000	0.000	0.000	0.000	0.000	0.000
MANGANESE	0.140	3.000	0.090	1.350	0.250	0.080
AMMONIA	5.000	0.000	0.000	56.000	0.000	0.000
NICKEL	0.230	3.500	0.170	0.890	0.120	0.250
OIL & GREASE	1550.000	46.000	934.000	725.000	2593.000	10.000
LEAD	0.000	0.230	0.090	2.900	0.050	0.000
PHENOL	0.490	0.600	0.010	0.000	0.000	0.020
ANTIMONY	0.000	0.000	0.000	0.000	0.000	0.000
SELENIUM	0.000	0.000	0.080	0.000	0.040	0.000
THALLIUM	0.000	0.000	0.000	0.000	0.000	0.000
TOR	110.000	644.000	31.700	264.000	570.000	39.400
TSS	520.000	1440.000	338.000	233.000	2684.000	41.000
ZINC	1.900	4.300	0.410	6.560	3.000	0.380

TYPICAL IN-PORT FLEET BY SHIP TYPE

AND

DISRTIBUTION OF BILGE WATER GENERATION

	DISPLACEME TONS FULL	NO. SHIPS IN-PORT	TOTAL DISPLACEMENT	DISTRIBUTION FACTOR
AIRCRAFT CARRIER (NUCLEAR) (CVN)	89600	1	89600	0.066
AIRCRAFT CARRIER CONV. (CV)	82000	2	164000	0.122
CRUISER (CG)	9600	4	38400	0.028
CRUISER (NUCLEAR) (CGN)	11100	2	22200	0.016
DESTROYER (DD & DDG)	9200	10	92000	0.068
AMPHIB ASSAULT	39300	11	432300	0.321
ASSUMED AUX. SUPPORT (AD, AO, AS, MSC)	37300	13	484900	0.360
FRIGATES (FFG)	3605	7	25235	0.019
SUBMARINES (SSN)	6927	14	96978	0.072
			TOTAL	1348635

TYPICAL BILGE WATER DETERMINATION  
WEIGHTED BY SHIP DISTRIBUTION 1

	AVERAGE BILGE WATER CONCENTRATION WT. BY SHIP DISTRIBUTION (mg/l) 1	POUNDS OF CONTAMINANT DISCHARGED PER DAY 2	POUNDS PER YEAR
ARSENIC	0.0006	0.00	0.09
BOD	46.6944	17.13	6254.26
BARIUM	0.0079	0.00	1.06
CADMIUM	0.0040	0.00	0.54
CYANIDE	0.0031	0.00	0.42
COD	396.0608	145.34	53048.55
CHROMIUM	0.0386	0.01	5.17
COPPER	0.2178	0.08	29.17
IRON	1.2931	0.47	173.20
MERCURY	0.0000	0.00	0.00
MANGANESE	0.0758	0.03	10.15
AMMONIA	0.7260	0.27	97.24
NICKEL	0.0819	0.03	10.97
OIL & GREASE	155.4983	57.06	20827.51
LEAD	0.0370	0.01	4.96
PHENOL	0.0211	0.01	2.83
ANTIMONY	0.0000	0.00	0.00
SELENIUM	0.0017	0.00	0.23
THALLIUM	0.0000	0.00	0.00
TOC	40.7632	14.96	5459.84
TSS	151.5724	55.62	20301.66
ZINC	0.3224	0.12	43.18

1 Data was not available for all types of ships. Therefore, CVN & CN, CGN & CG, DD & FF & FFG, LST & AQ, each was assumed to have similar bilge water characteristics.

2 Each ship's data was multiplied by its distribution factor then all the data for each contaminant was averaged.

3 1b/d = 8.34 x mg/L x 0.044 MGD

**Appendix 2**  
**Calculation of Net Non-Tidal Velocity**  
**and Characteristic Cross-Sectional Area**

The information in Appendix 2 was used to calculate the net non-tidal velocity and characteristic cross-sectional area for the estuary. Flow was calculated by multiplying the watershed area by the estimated annual runoff. This had to be done because USGS has no gauges in the Elizabeth River watershed. The value of 15 inches of runoff was taken from a USGS runoff chart. The net non-tidal velocity was calculated by dividing the average annual flow by the cross-sectional area of the estuary at a point.

Appendix 2

Calculation of Net Non-tidal Velocity and  
Characteristic Cross-Sectional Area

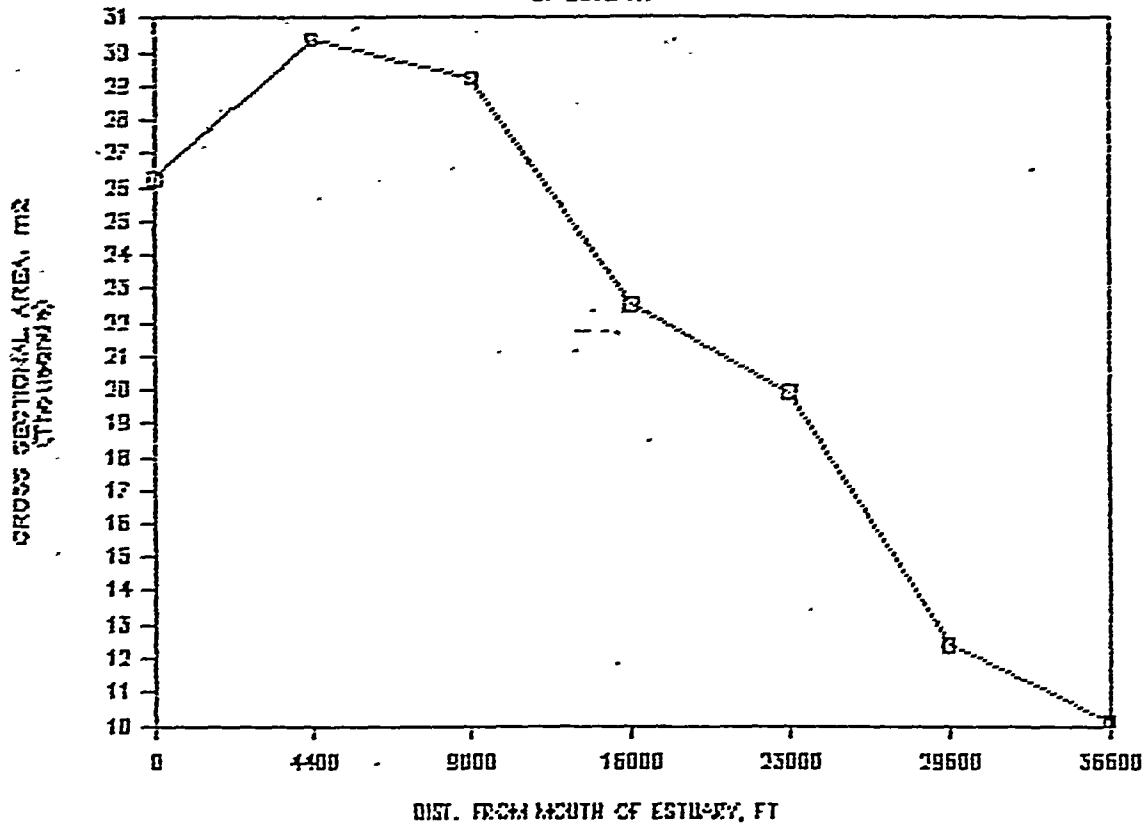
DIST. FROM MOUTH OF ESTUARY	AREA	AREA	AVE ANNUAL VELOCITY
FT	SF	SM	m/d
0	282450	26255	12.49
4400	326835	30381	10.79
9000	314730	29255	11.21
16000	242100	22504	14.57
23000	213955	19879	16.49
29600	133155	12377	26.49
36600	108945	10127	32.37

Characteristic Area = 21540 17.77

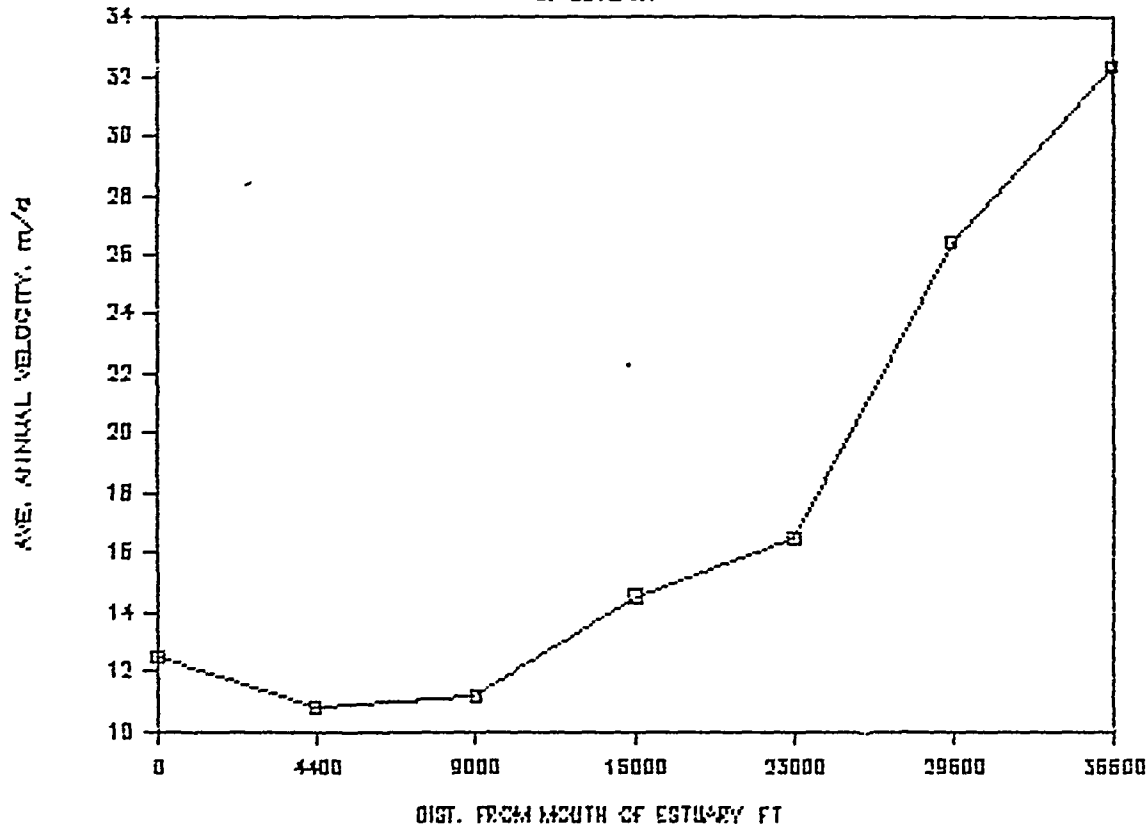
Net Non-tidal Velocity Based on = 15.22 m/d  
Characteristic Area

The Areas were calculated from cross sectional plots  
which were derived from the USGS Norfolk North  
Quadrangle (36076-H3-TB-024 1986)

AREA vs. DISTANCE FROM MOUTH  
OF ESTUARY



AVE. VELOCITY vs. DISTANCE FROM MOUTH  
OF ESTUARY



Appendix 3  
Illustrated Contaminant Profile Calculation

Appendix 3  
 Illustrated Contaminant Profile Calculation

Given:  $U = 15.22$  m/d, assume  $u = 0$   
 $D = 13.8$  m  
 $V_n = 20$  m/d  
 $K_p = 0.1$  L/mg  
 $E = 2.59 \times 10^6$  m<sup>2</sup>/d  
 $S = 15$  mg/L  
 $W_{\text{COPPER}} = 10^{-1.44}$  Kg/d  
 $A = 21540$  m<sup>2</sup>

Solution:

$$f_s = \frac{0.1 \text{ L/mg} \times 15 \text{ mg/L}}{1 + (0.1 \text{ L/mg} \times 15 \text{ mg/L})} = 0.6$$

$$k = 20 \text{ m/d} \times 0.6 / 13.8 \text{ m} = 0.87 \text{ d}^{-1}$$

$$C_o = \frac{10^{-1.44} \text{ Kg/d} \times 10^6 \text{ ug/l/Kg/m}^3}{2 \times 21540 \text{ m}^2 \times (0.87 \text{ d}^{-1} \times 2.59 \times 10^6 \text{ m}^2/\text{d})^{1/2}}$$

$$C_o = 5.6 \times 10^{-4} \text{ ug/L}$$

$$j_1 = j_2 = (0.87 \text{ d}^{-1} / 2.59 \times 10^6 \text{ m}^2/\text{d})^{1/2} = 5.9 \times 10^{-4}$$

$$C = 6.2 \times 10^{-4} \text{ ug/L} \exp [-x j]$$

X m	C ug/L
0	0.0006
400	0.0005
800	0.0004
1200	0.0003

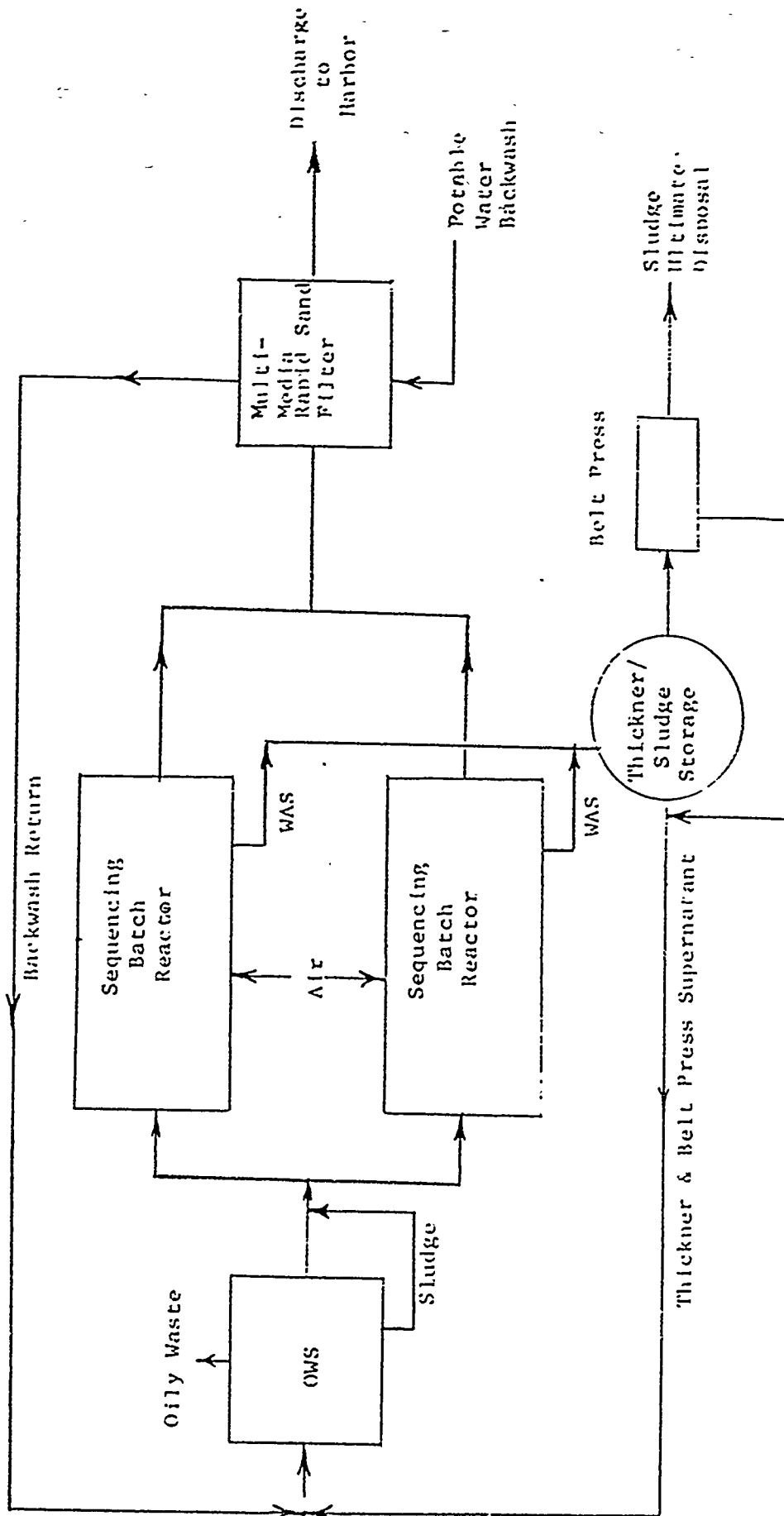
Sensitivity Analysis:

Parameter	% Parameter Change	% Co Change	Sensitivity
$V_n$	100	41	0.41
E	100	28	0.28
S	66	34	0.51
$K_p$	90	115	1.28

Appendix 4  
Sequencing Batch Reactor Flow Diagram

This flow diagram represents one flow scheme for the biological treatment of BW.

Appendix 4



SBR Flow Diagram

Appendix 5  
EPA Treatability Excerpts

Each excerpt comes from the EPA treatability manual and provides information on trace metal removal ranges for different wastewater treatment processes. The treatability manual also lists information on organic chemicals. The metals included in the appendix are present in a typical BW.

Appendix 4

POLLUTANT REMOVABILITY/TREATABILITY WASTEWATER TREATMENT ALTERNATIVE FOR CADMIUM<sup>a,b</sup>

Treatment process <sup>a</sup>	Synthetic wastewater removal range, %		Actual wastewater Average Achievable conc., µg/L		Volume III references, Section numbers
	range, %	conc., µg/L	range, %	conc., µg/L	
Gravity oil separation			NA	69	III.4.1
Gas flotation with chemical addition (calcium chloride, polymer)			79->90	17	III.4.5
Gas flotation with chemical addition (polymer)			0 <sup>d,e</sup>	- <sup>e</sup>	III.4.5
Gas flotation with chemical addition (alum, polymer)			0 <sup>d,e</sup>	- <sup>e</sup>	III.4.5
Filtration			39->99	20	III.4.6
Sedimentation			72->99	210	III.4.2
Sedimentation with chemical addition (lime, polymer)			27-93	<16	III.4.3
Sedimentation with chemical addition (Fe <sup>2+</sup> , lime)			25->50	6	III.4.3
Sedimentation with chemical addition (sulfide)			>50->99	<9	III.4.3
Sedimentation with chemical addition (polymer)			25-50	80	III.4.3
Sedimentation with chemical addition (alum, polymer)			42-61	33	III.4.3
Sedimentation with chemical addition (alum)			44-88	>9	III.4.3
Sedimentation with chemical addition (lime)			60-99	>9	III.4.3
Aerated lagoons			>97	<2	III.5.3
Ultrafiltration			>83->93	<8.3	III.4.7
Ozonation			0 <sup>d,e</sup>	- <sup>e</sup>	III.6.14
Ion exchange			>99 <sup>d</sup>	<10 <sup>d</sup>	III.6.7
Activated sludge			31->99	4	III.5.1
Powdered activated carbon adsorption (with activated sludge)			0 <sup>d,e</sup>	- <sup>e</sup>	III.6.2
Granular activated carbon adsorption			34-95	12	III.6.1
Reverse osmosis			13-50	13	III.6.9

<sup>a</sup> See Volume III for detailed information.

<sup>b</sup> NA - Not available, ND - not detected, BDL - below detection limit.

<sup>c</sup> Average and maximum removals reported.

<sup>d</sup> Only one data point.

<sup>e</sup> Actual data indicate negative removal.

Date: 5/23/80

I.4.5-4

POLLUTANT REMOVABILITY/TREATABILITY WASTEWATER TREATMENT ALTERNATIVE FOR CHROMIUM<sup>a,b</sup>

Treatment process <sup>c</sup>	Synthetic wastewater Removal range, <sup>c</sup> conc., µg/L	Actual wastewater Average Removal range, <sup>c</sup> conc., µg/L	Volume III references, Section numbers
Gravity oil separation		MA	111.4.1
Gas flotation		40-5H	111.4.4
Gas flotation with chemical addition (calcium chloride, polymer)		51-6J	111.4.5
Gas flotation with chemical addition (polymer)		0 <sup>d,e</sup>	111.4.5
Gas flotation with chemical addition (alum, polymer)		19 <sup>d</sup>	111.4.5
Filtration		36-399	111.4.6
Sedimentation		79-399	111.4.2
Filtration, Cr <sup>6+</sup>		0 <sup>e</sup>	111.4.6
Filtration, Cr <sup>3+</sup>		95	111.4.6
Sedimentation with chemical addition (lime, lime)		7 <sup>d</sup>	111.4.1
Sedimentation with chemical addition (lime, polymer)		10-111	111.4.1
Sedimentation with chemical addition (lime, polymer), Cr <sup>6+</sup>		41-82	111.4.3
Sedimentation with chemical addition (Fe <sup>3+</sup> , lime)		355-395	111.4.3
Sedimentation with chemical addition (sulfide)		297-399	111.4.3
Sedimentation with chemical addition (polymer)		396-97	111.4.3
Sedimentation with chemical addition (BaCl <sub>2</sub> )		72-93	111.4.3
Sedimentation with chemical addition (alum, polymer)		69-95	111.4.3
Sedimentation with chemical addition (alum)		69-95	111.4.3
Sedimentation with chemical addition (lime)		49-97	111.4.3
Sedimentation with chemical addition (lime) chromium dissolved		>99 <sup>d</sup>	111.4.3
Tertiary polishing lagoons		>71 <sup>d</sup>	111.5.3
Aerated lagoons		63-99	111.5.3
Trickling filters		0 <sup>d,e</sup>	111.5.2
Ultrafiltration		67 <sup>d</sup>	111.4.7
Ozonation		0 <sup>d,e</sup>	111.6.14
Ion exchange		>99 <sup>d</sup>	111.6.7
Activated sludge		43-99	111.5.1
Powdered activated carbon adsorption (with activated sludge)		87-97	111.6.2
Powdered activated carbon adsorption (with activated sludge), Cr <sup>6+</sup>		41-264	111.6.2
Granular activated carbon adsorption		34-95	111.6.1
Granular activated carbon adsorption Cr <sup>6+</sup>		>33 <sup>d</sup>	111.6.1
Reverse osmosis		44-399	111.6.9
Reverse osmosis Cr <sup>6+</sup>		0 <sup>d,e</sup>	111.6.9
Reverse osmosis Cr <sup>3+</sup>		>99 <sup>d</sup>	111.6.9

<sup>a</sup>See Volume III for detailed information

<sup>b</sup>NA - Not available, ND - not detected, BDL - below detection limit

<sup>c</sup>Average and maximum removals reported.

<sup>d</sup>Only one data point

<sup>e</sup>Actual data indicate negative removal.

Date: 6/23/80

I.4.6-4

Date: 6/23/80

I.4 7-4

67

POLLUTANT REMOVABILITY/TREATABILITY WASTEWATER TREATMENT ALTERNATIVE FOR COPPER<sup>a,b</sup>

Treatment process <sup>a</sup>	Synthetic wastewater		Actual wastewater		Volume III references, Section numbers
	Removal range, conc., µg/L	Average achievable conc., µg/L	Removal range, conc., µg/L	Average achievable conc., µg/L	
Gravity oil separation			NA	100	III.4.1
Gas flotation			69 <sup>d</sup>	5	III.4.4
Gas flotation with chemical addition (calcium chloride, polymer)			78-91	300	III.4.5
Gas flotation with chemical addition (polymer)			42-75	66	III.4.5
Gas flotation with chemical addition (alum, polymer)			19 <sup>d</sup>	660 <sup>d</sup>	III.4.5
Filtration			40->99	200	III.4.6
Sedimentation			66->99	73	III.4.2
Sedimentation with chemical addition (alum, lime)			62-88	36	III.4.3
Sedimentation with chemical addition (lime, polymer)			87->99	56	III.4.3
Sedimentation with chemical addition (Fe <sup>2+</sup> , lime)			72-92	21	III.4.3
Sedimentation with chemical addition (sulfide)			>98->99	260	III.4.3
Sedimentation with chemical addition (polymer)			56->89	140	III.4.3
Sedimentation with chemical addition (BaCl <sub>2</sub> )			>62-73	<25	III.4.3
Sedimentation with chemical addition (alum, polymer)			49-80	6,900	III.4.3
Sedimentation with chemical addition (alum)			>64-81	<37	III.4.3
Sedimentation with chemical addition (lime)			75->99	52	III.4.3
Tertiary polishing lagoons			0 <sup>d,e</sup>	- <sup>e</sup>	III.5.3
Aerated lagoons			49-94	40	III.5.3
Trickling filters			0 <sup>d,e</sup>	- <sup>e</sup>	III.5.2
Ultrafiltration			>73-90	<700	III.4.7
Ozonation			0 <sup>e</sup>	- <sup>e</sup>	III.6.14
Chemical oxidation (chlorination)			14 <sup>d</sup>	320 <sup>d</sup>	III.6.3
Ion exchange			98->99	95	III.6.7
Activated sludge			52->99	43	III.5.1
Powdered activated carbon adsorption (with activated sludge)			52-96	17	III.6.2
Granular activated carbon adsorption			47->85	<66	III.6.1
Reverse osmosis			73->99	1,600	III.6.9

<sup>a</sup> See Volume III for detailed information.  
<sup>b</sup> NA - Not available, ND - not detected, BDL - below detection limit.  
<sup>c</sup> Average and maximum removals reported.  
<sup>d</sup> Only one data point.  
<sup>e</sup> Actual data indicate negative removal.

**POLLUTANT REMOVABILITY/TREATABILITY WASTEWATER TREATMENT ALTERNATIVE FOR NICKEL<sup>a, b</sup>**

Treatment process <sup>a</sup>	Synthetic Wastewater		Actual Wastewater		Volume III reference <sup>c</sup> section numbers
	Removal range, %	Average conc., µg/L	Removal range, %	Average conc., µg/L	
Gravity oil separation	NA		69		111.4.1
Gas flotation	0 <sup>d</sup> , e		- <sup>f</sup>		111.4.4
Gas flotation with chemical addition (calcium chloride, polymer)	65-99		<73		111.4.5
Gas flotation with chemical addition (polymer)	0 <sup>d</sup>		- <sup>f</sup>		111.4.5
Gas flotation with chemical addition (alum, polymer)	41 <sup>d</sup>		270 <sup>d</sup>		111.4.5
Filtration	11-99		64		111.4.6
Sedimentation	59-99		<100		111.4.2
Sedimentation with chemical addition (alum, lime)	0 <sup>d</sup>		<1 <sup>d</sup>		111.4.3
Sedimentation with chemical addition (lime, polymer)	86-96		740		111.4.3
Sedimentation with chemical addition (lime, polymer) N <sub>2</sub> dissolved	99 <sup>d</sup>		2,500 <sup>d</sup>		111.4.3
Sedimentation with chemical addition (Fe <sup>2+</sup> , lime)	34-95		1		111.4.3
Sedimentation with chemical addition (sulfide)	88-96		860		111.4.3
Sedimentation with chemical addition (polymer)	35 <sup>d</sup>		41 <sup>d</sup>		111.4.3
Sedimentation with chemical addition (alum, polymer)	35-97		17,000		111.4.3
Sedimentation with chemical addition (alum)	27-56		<36		111.4.3
Sedimentation with chemical addition (lime)	40-99		540		111.4.3
Sedimentation with chemical addition (lime) N <sub>2</sub> dissolved	99 <sup>d</sup>		20 <sup>d</sup>		111.4.3
Acidated lagoons	17-50		34		111.5.3
Ultrafiltration	32 <sup>d</sup>		<500		111.4.7
Ozonation	0 <sup>d</sup>		- <sup>f</sup>		111.6.14
Ion exchange	>99		<10		111.6.7
Activated sludge	29-92		70		111.5.1
Powdered activated carbon adsorption (with activated sludge)	19-58		<14		111.6.2
Granular activated carbon adsorption	17-48		110		111.6.1
Reverse osmosis	36-98		66		111.6.9

<sup>a</sup> See Volume III for detailed information.

<sup>b</sup> NA - Not available, ND - not detected, BDL - below detection limit.

<sup>c</sup> Average and maximum removals reported.

<sup>d</sup> Only one data point.

<sup>e</sup> Actual data indicate negative removal.

Date: 6/23/80

I.4.11-4

POLLUTANT REMOVABILITY/TREATABILITY WASTEWATER TREATMENT ALTERNATIVE FOR ZINC<sup>a,b</sup>

Treatment process <sup>a</sup>	Synthetic wastewater		Actual wastewater		Volume III reference, Section number <sup>a</sup>
	Removal range, %	Average achievable conc., µg/l.	Removal range, %	Average achievable conc., µg/l.	
Gravity oil separation			NA	390	III.4.1
Gas flotation			11-22	27,000	III.4.4
Gas flotation with chemical addition (calcium chloride, polymer)			>95->99	150	III.4.5
Gas flotation with chemical addition (polymer)			>30->60	120	III.4.5
Gas flotation with chemical addition (alum, polymer) <sup>c</sup>			10 <sup>d</sup>	2,300 <sup>d</sup>	III.4.5
Filtration			39->99	940	III.4.6
Sedimentation			71->99	2,600	III.4.2
Sedimentation with chemical addition (alum, lime)			55->99	3,400	III.4.3
Sedimentation with chemical addition (lime, polymer)			84->99	410	III.4.3
Sedimentation with chemical addition (Fe <sup>2+</sup> , lime)			>79->97	12	III.4.3
Sedimentation with chemical addition (sulfide)			>98->99	140	III.4.3
Sedimentation with chemical addition (polymer)			04-97	2,400	III.4.3
Sedimentation with chemical addition (BaCl <sub>2</sub> )			65-110	30	III.4.3
Sedimentation with chemical addition (alum, polymer)			69-03	660	III.4.3
Sedimentation with chemical addition (alum)			69-03	3,800	III.4.3
Sedimentation with chemical addition (lime)			77->99	640	III.4.3
Aerated lagoons			55->99	180	III.5.3
Ultrafiltration			>78-98	8,600	III.4.7
Ozonation			32-96	260	III.6.14
Ion exchange			97 <sup>d</sup>	400 <sup>d</sup>	III.6.7
Activated sludge			35-92	200	III.5.1
Powdered activated carbon adsorption			0 <sup>d,e</sup>	- <sup>e</sup>	III.6.2
Powdered activated carbon adsorption (with activated sludge)			50-98	110	III.6.2
Granular activated carbon adsorption			40->99	440	III.6.1
Reverse osmosis			03->99	530	III.6.9

<sup>a</sup>See Volume III for detailed information.

<sup>b</sup>NA - Not available, ND - not detected, BDL - below detection limit.

<sup>c</sup>Average and maximum removals reported.

<sup>d</sup>Only one data point.

<sup>e</sup>Actual data indicate negative removal.

Date: 6/23/80

I.4.15-4

Appendix 5  
Sequencing Batch Reactor Operation Pattern

Appendix 5  
SBR Operation Pattern

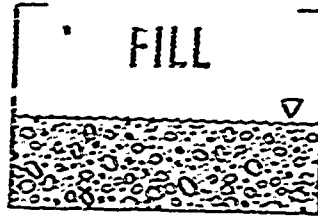
PERCENT OF:  
MAX VOLUME \ CYCLE TIME

INFLUENT

PURPOSE \ OPERATION

60  
to  
100

50

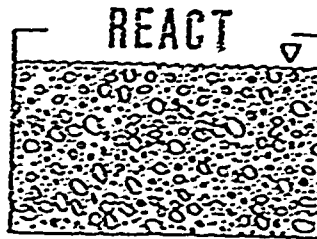


ADD  
SUBSTRATE

AIR  
ON / OFF

100

10

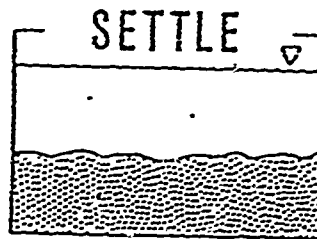


REACTION  
TIME

AIR  
ON / CYCLE

100

10

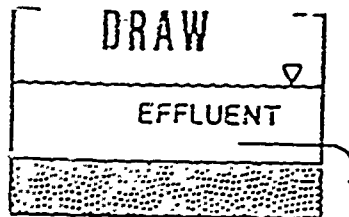


CLARIFY

AIR  
OFF

100  
to  
65

10

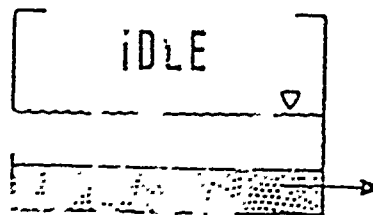


REMOVE  
EFFLUENT

AIR  
OFF

65  
to  
60

20



WASTE  
SLUDGE

AIR  
ON / OFF