MISCELLANEOUS PAPER EL-87-9

DISPOSAL ALTERNATIVES FOR
[illegible]
FROM INDIANA HARBOR, INDIANA

[illegible]

by

Environmental Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631

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Final Report

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19. ABSTRACT (*Continue on reverse if necessary and identify by block number*)

Indiana Harbor and Canal are part of a small, highly industrialized watershed in northwestern Indiana. The Grand Calumet River discharges into Lake Michigan via the Indiana Harbor and Canal. These waterways have a history of water quality problems and have been identified by the International Joint Commission on the Great Lakes as a major area of con- [illegible]

The purpose of this study was to evaluate alternative methods for dredging and dis- [illegible]

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18. SUBJECT TERMS (Continued).

Capping	Dredged material disposal
Confined disposal	Dredging
Contaminants	Indiana Harbor

[redacted]

19. ABSTRACT (Continued).

[redacted]

Three disposal alternatives (contained aquatic disposal (CAD) and two confined disposal alternatives) were identified for the PCB-contaminated sediments and evaluated to determine [redacted]

routinely applied laboratory testing protocol to predict leachate quality from dredged [redacted]

tives and management techniques that were evaluated included confined disposal with appropriate restrictions and capping of contaminated sediments after controlled placement in the aquatic environment.

The feasible disposal alternatives identified for the PCB-contaminated sediments included CAD, in-lake CDF disposal, and upland confined disposal. With appropriate dredging equipment, disposal site designs, and contaminant control measures, any of the three disposal methods could be used to provide environmentally sound disposal of the PCB-contaminated Indiana Harbor sediments.

PREFACE

[redacted]

The Chicago District Project Manager for the studies was Mr. Shamel Abou-El-Seoud.

The studies were conducted by researchers of the WES Environmental Laboratory (EL), Hydraulics Laboratory (HL), and Coastal Engineering Research Center (CERC). The main text (Parts I-VI) is included in Volume I. Appendixes A-J are presented in this volume. Appendixes A, B, and C were written [redacted] Messrs. Thomas G. Sturgis and Issac Smith, Jr., EL. Appendix G was written by [redacted] [redacted] Engineering Division, EL. This work was coordinated with other dredging studies by Dr. Robert M. Engler, Manager, Environmental Effects of Dredging Programs, EL.

The work was conducted under the general supervision of Dr. John Harrison, Chief, EL.

COL Dwayne G. Lee, CE, was Commander and Director of WES, and Dr. Robert W. Whalin was Technical Director.

Environmental Laboratory. 1987. "Disposal Alternatives for PCB-Contaminated Sediments from Indiana Harbor, Indiana, Vol II:

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
gallons	3.785412	cubic decimetres
horsepower (550 foot-pounds (force) per second)	745.6999	watts
[illegible]	[illegible]	[illegible]
knots (international)	0.5144444	metres per second
miles (US statute)	1.609347	kilometres
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.4535924	kilograms
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible] metre
square inches	6.4516	square centimetres
yards	0.9144	metres

[illegible]

DISPOSAL ALTERNATIVES FOR PCB-CONTAMINATED SEDIMENTS FROM INDIANA HARBOR, INDIANA

APPENDIX A: SEDIMENTATION AND FILTRATION

Settling Test Results

1. A flocculent settling test and a 15-day initial storage test were performed on a 100-g/ℓ suspension of the composited Indiana Harbor sediment. The *suspension was not sieved or hydraulically separated to remove the sand prior* to the tests. The sediment was about 35 percent sand as shown in Figure A-1.

2. The procedure used in the flocculent test was to dilute the composited sediment having an initial solids concentration of about 740 g/ℓ with tap [redacted] barrel and then pumped into a 7-ft tall, 8-in.-diam acrylic column to a depth [redacted] settling test, was performed in conjunction with the flocculent settling as a continuation of that test. In this test the height of the interface after forming between material that had settled from the slurry and the supernatant [redacted]

Sedimentation Analysis

4. The following evaluation of sedimentation design was made using procedures given in Palermo, Montgomery, Poindexter (1978) and Palermo

Table A1

Solids Concentrations* During Flocculent Settling Test

Time hr	Surface Height, ft	Sample Locations: Height Above Bottom of Settling Column, ft									
		6.0	5.65	5.35	4.65	4.0	3.35	2.65	2.0	1.5	1.0
0.0	6.255	Initial Solids Concentration = 100 g/ℓ									
1.0	6.220	14.70	-	67.4	78.00	78.50	88.00	94.20	96.10	106.0	110.3
2.0	6.185	10.60	-	10.70	70.40	80.90	84.80	91.30	96.8	100.9	113.6
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12.0	6.110	4.40	-	4.30	4.20	4.20	4.80	4.30	197.3	216.5	231.4
24.0	6.070	4.60	-	3.30	3.30	3.30	3.40	3.40	190.0	231.9	-
48.2	6.010	1.60	-	2.50	2.50	2.50	2.50	2.50	22.90	249.0	-
96.0	5.930	-	1.70	1.80	1.90	1.80	2.00	1.90	1.90	254.7	-
167.5	5.856	-	1.20	1.40	1.50	1.50	1.60	1.60	1.60	47.7	-
263.5	5.730	-	0.82	1.10	1.30	1.40	1.40	1.40	1.40	6.80	-
335.0	5.648	-	-	0.91	1.20	1.30	1.30	1.30	1.30	1.50	-

* In grams per litre.

Table A2

15-Day Compression Settling Test Results*

[redacted]	[redacted]	Solids Concentration Below Interface [redacted]
0.0	–	–
1.0	–	–
2.0	–	–
2.5	–	–
3.0	–	–
4.0	3.79	163
5.0	3.32	185
5.5	3.05	202
6.3	2.80	220
12.0	2.40	255
24.0	2.242	271
26.0	2.203	276
27.5	2.192	277
29.0	2.180	278
48.2	2.070	290
72.0	1.965	306
96.0	1.910	310
119.5	1.830	324
144.2	1.790	331
167.5	1.765	336
191.0	1.710	347
263.5	1.655	358
287.0	1.640	362
311.5	1.630	364
335.0	1.618	366
359.0	1.605	369

[redacted]

Figur Engineering ties edime

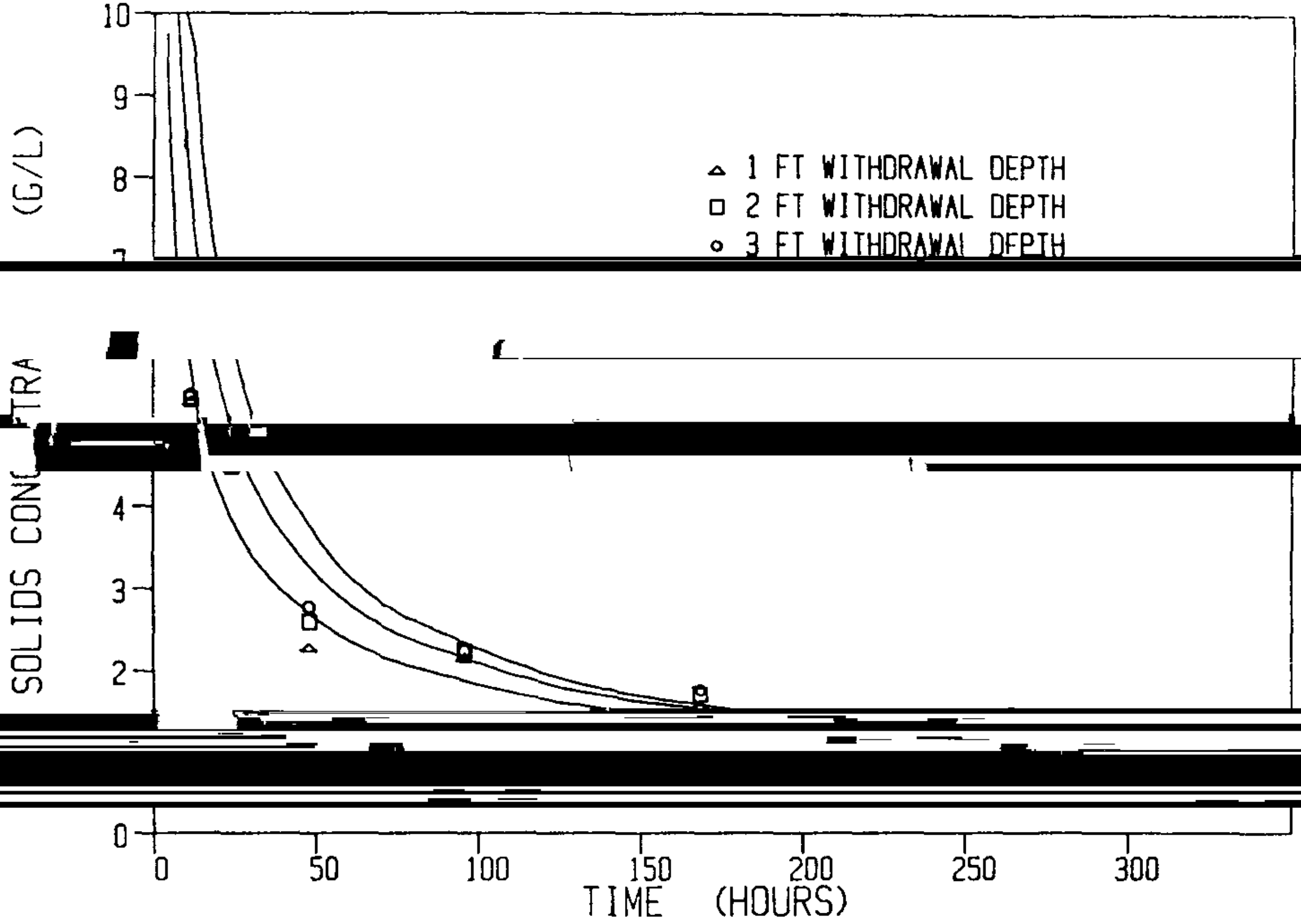

Figure A2. Flocculent settling test results

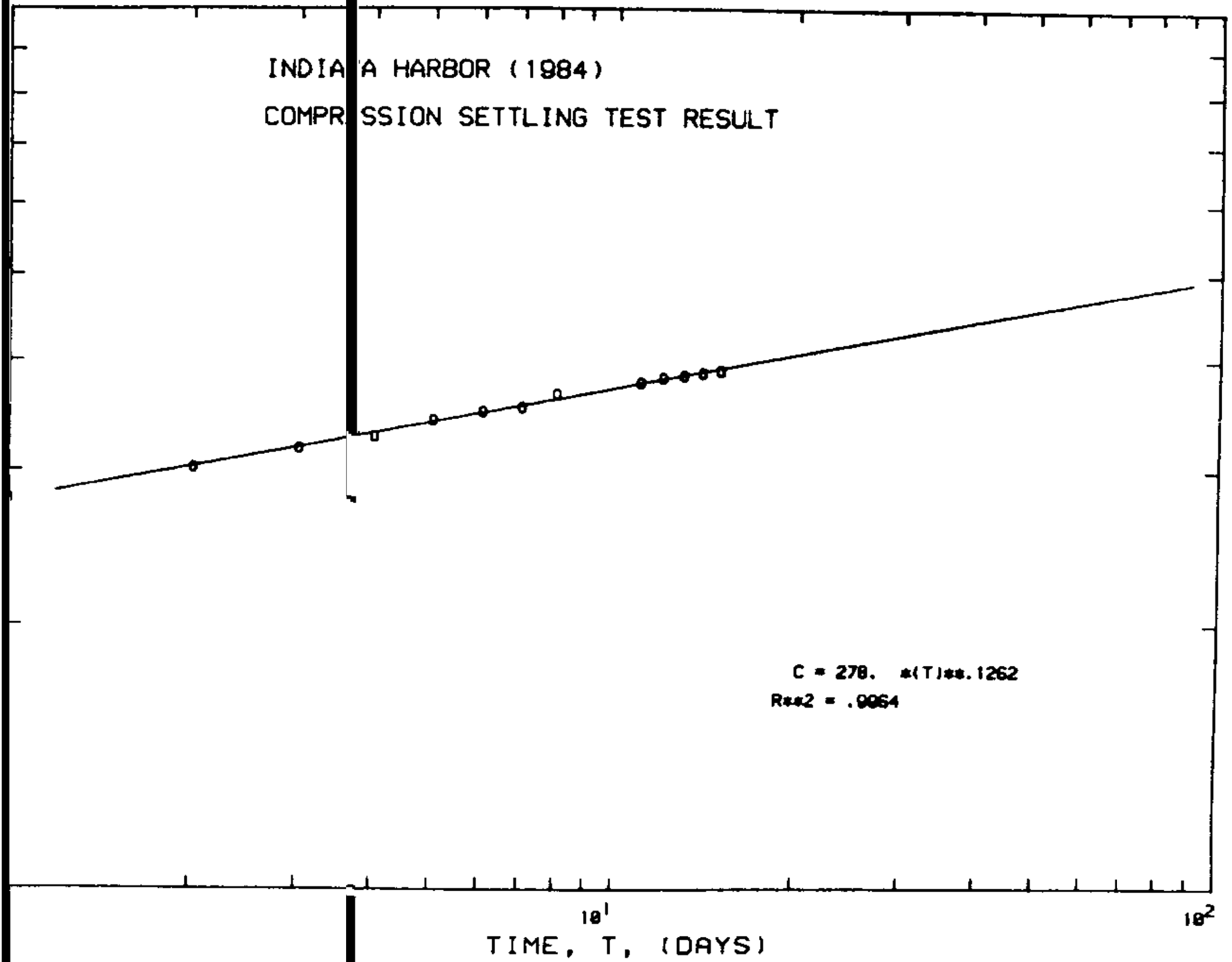

Figure A3. Compression settling test results

[redacted]
for the disposal of the PCB-contaminated sediments to an in-lake CDF of a
[redacted]

Flow rate

5. For the disposal of mechanically dredged materials, the flow rate will be roughly equal to the production rate, which is assumed for this analysis to be 200,000 cu yd per 2 month project duration (U.S. Army Engineer Dis-
[redacted]
dredge.

In situ concentration

6. The in situ void ratio is:

$$e_i = \frac{wG_s}{S_D}$$

$$= \frac{(88\%)(2.69)}{100\%} \qquad \text{(A1)}$$

$$= 2.37$$

where

e_i = in-situ void ratio of sediment
w = water content of sediment, percent
G_s = specific gravity of sediment solids
S_D = degree of saturation, percent

[redacted]

[redacted]

probably be greater than 600 g/ℓ and the concentration of suspended solids in [illegible]

to deposit the material. The conditions resulting from mechanical placement [illegible]

contaminant release would occur.

Initial storage requirements

[illegible] material obtained from the 15-day settling test using a design time of 30 days (one half of the project duration of 2 months) is 280 g/ℓ based on the settling [illegible]

material. At the end of each disposal operation for 200,000 cu yd of sediment, [illegible]

$$V_f = V_i \ (C_i/C_f) + V_{sd}$$

[illegible]

$$+ \ (0.33) \ (200{,}000 \text{ cu yd})$$

$$= 347{,}000 \text{ cu yd or } 215 \text{ acre-ft}$$

where

V_f = volume of new lift at end of each disposal operation, cu yd

V_i = volume of in-situ sediment to be dredged, cu yd

C_f = concentration of newly settled material at end of each disposal operation, g/ℓ

V_{sd} = volume of newly settled sand at end of each disposal operation, cu [illegible]

13. The average dike height above lake bottom of the proposed in-lake CDF will be about 35 ft (US Army Engineer District, Chicago 1986). The height of settled material in the CDF prior to placement of the final lift is unknown [illegible]

based on storage cannot be determined. If the previously deposited material consolidated to the in-situ concentration, the minimum volume required for storage would be the sum of the volume of sediment previously dredged (1,200,000 cu yd) and the volume for new storage (347,000 cu yd), totaling 1,550,000 cu yd or 965 acre-ft. Allowing a minimum of 3 ft of freeboard and 2 ft of ponding, the maximum height for storage is about 30 ft. Therefore, the minimum area required for storage is 32 acres (965 acre-ft/30 ft). Addi-

[redacted]

storage volume required for new lift of 200,000 cu yd of sediment would be

[redacted]

The resulting area required for storage would be only about 1.5 acres smaller than for hydraulic disposal.

Required area for effective zone settling

[redacted]

$$S_{d(max)} = C_i V_{si}$$

$$= (9.36 \text{ lb/cu ft})\ (0.30 \text{ ft/hr}) \qquad \text{(A5)}$$

$$= 2.8 \text{ lb/sq ft-hr}$$

where

$S_{d(max)}$ = maximum solids loading rate

[redacted]

[redacted]

greater than $S_{d(max)}$, the design loading rate is 2.8 lb/sq ft-hr. Therefore, the required surface area for zone settling is

$$A = \frac{Q_i \ C_i}{S_d}$$

$$= \underline{(3690 \text{ cu ft/hr})\ (9.36 \text{ lb/cu ft})\ (800 \text{ g/ℓ})} \qquad \text{(A6)}$$

[redacted]

where

A = surface area

Q_i = discharge rate

[redacted]

$$A_d = (\text{HEF})(A)$$

$$= 2.25\ (1.5 \text{ acres}) \qquad \text{(A7)}$$

$$= 3.4 \text{ acres}$$

where

[redacted]

Required area and detention for flocculent settling

[redacted]

ment Station 1980). A flocculent settling test was performed on a 63-g/ℓ slurry of fines in 1980 (US Army Engineer Waterways Experiment Station 1980) and on a 100-g/ℓ slurry that was about 35-percent sand in December 1984. In the first test a 6-hr detention resulted in an effluent having 250 mg/ℓ

[redacted]

solids to less than 2 g/ℓ and after 336 hr 1.2 g/ℓ of solids still remained suspended. The two tests show significantly different results, illustrating

[redacted]

culent settling test. Since basins are not perfectly hydraulically efficient

[redacted]

$$T = (HEF)T_d$$

$$= (2.25)(96\ \text{hr}) \qquad \text{(A8)}$$

$$= 216\ \text{hr or 9 days}$$

[redacted]

$$V = Q T$$

[redacted]

$$= 4{,}250{,}000\ \text{cu ft or 97.6 acre-ft}$$

where

V_{pd} = volume of ponded supernatant

Q_i = influent flow rate

[redacted]

$$A_{pd} = V_{pd}/H_{pd}$$

$$= (97.6 \text{ acre-ft})/(2 \text{ ft}) \qquad (A10)$$

$$= 48.8 \text{ acres}$$

where

A_{pd} = ponded surface area
H_{pd} = ponded depth

[redacted]

Supernatant suspended solids concentration

18. Comparisons of the areas required for storage, zone settling and flocculent settling show that storage controls the size of the minimum surface area for all three alternatives if zone settling occurs as expected. Therefore, the required surface area should be about 35 to 40 acres assuming a dike height of 35 ft and effective consolidation. Consequently, the ponded volume will be greater than the volume required to achieve a supernatant having 2 g/ℓ

[redacted]

detention time will contain about 1.3 g/ℓ of suspended solids for hydraulic transfer from scows and about 2.1 g/ℓ for hydraulic dredging. If zone

[redacted]

solids. Laboratory tests were not performed specifically for the prediction of suspended solids concentration of the supernatant following settling for the mechanical disposal. The supernatant quality for this alternative can only be estimated using the flocculent settling tests results and field measurements as a guide. Based on those results and the expected resuspension

[redacted]

19. To prevent resuspension at the weir between the primary and secondary areas, the weir should be designed for a weir loading rate of 0.08 cfs/ft. Therefore, weir lengths of 13 ft (1.03 cfs/0.08 cfs/ft) and 35 ft are required for mechanical dredging and hydraulic dredging, respectively. The 35-ft weir should be specified for both cases to provide for flexibility in future disposal operations.

Sedimentation Summary

20. The proposed in-lake CDF is sufficient to store the volume of dredged material to be disposed. The effluent quality of the supernatant and the loading on the filter dikes are highly dependent on the dredging and disposal methods. The suspended solids loading on the filter dikes can be as high as 2.1 g/ℓ for hydraulic dredging, 1.3 g/ℓ for hydraulic transfer of mechanically [redacted]

Filtration Analysis

Background

21. The filter system consists of a pervious dike enclosing the complete CDF and a pervious cross dike separating the primary and secondary settling areas. The cross-section of the dike is shown in Figure 30 (Volume I). The [redacted] cient of permeability of the sand ranges from 1.5 × 10 cm/sec to 13.6×10^{-5} cm/sec. The effective particle size D_{10} of the sand deposits is [redacted]

Filter coefficients

22. Krizek et al. (1976) developed the following relationship to estimate the filter coefficient for sands and gravels:

$$\gamma = 0.40\ D_{10}^{-1.84} \tag{A11}$$

where

γ = filter coefficient, m^{-1}

D_{10} = effective particle size, mm

For the lake sands the filter coefficient would be

$$\begin{aligned}\gamma &= (0.40)\ (0.20)^{-1.84} \\ &= 7.7\ m^{-1} \text{ or } 2.4\ ft^{-1}\end{aligned} \tag{A12}$$

[redacted]

effective size of 0.5 mm, yielded a filter coefficient of:

$$\gamma = \frac{\ln\ (C_o/C)}{L}$$

[redacted]

$$= 3.0\ m^{-1} \text{ or } 0.92\ ft^{-1}$$

where

[redacted]

C = suspended solids concentration of the filtrate

[redacted]

sand instead of uniformly throughout the bed. This appears to have happened

[redacted]

$$= 15{,}000{,}000 \text{ cu ft or } 570{,}000 \text{ cu yd}$$

or about 41 percent of the total in situ sediment volume or about 15 percent of the total inflow.

[redacted]

minimize the clogging potential. Mechanical placement of material along the dike will also seal the dike and reduce the area for filtering. A settling and filtering aid will probably be required to dispose and filter the entire

[redacted]

$$C = (C_o)\, e^{-\gamma L}$$

$$= (1100 \text{ mg}/\ell)\, e^{-(2.4)\ (10)} \qquad \text{(A17)}$$

[redacted]

Sands having an effective size less than 0.4 mm would, in effect, capture all of the suspended solids using this described filter design.

Maximum discharge rate

29. The laboratory permeability of the lake sand ranges from 1.5×10^{-5} to 13.6×10^{-5} cm/sec but, as discussed previously, the field

[redacted]

$$Q = \frac{KA\Delta h}{L}$$

$$= \frac{(1 \times 10^{-3} \text{ cm/sec})(250{,}000 \text{ sq ft})(8 \text{ ft})}{(30.48 \text{ cm/ft})(10 \text{ ft})} \qquad \text{(A18)}$$

$$= 7 \text{ cfs}$$

where

Q = rate of seepage

K = coefficient of permeability

A = surface area of sand filter

Δh = height of ponded water in CDF above the lake water level

L = thickness of sand filter

The surface area of the sand will decrease to about 60,000 sq ft at the end of the disposal operation. The permeability will also decrease as clogging [redacted] that clogging can be prevented. Even without clogging, the seepage rate at [redacted]

APPENDIX B: EFFLUENT QUALITY

1. A modified elutriate test was performed on a 100-g/ℓ suspension of the composited Indiana Harbor sediment. The procedures used in the test are fully described in the Environmental Effects of Dredging Technical Note EEDP-04-2, "Interim Guidance for Predicting Quality of Effluent Discharged from Confined [redacted]

The results of these analyses are presented in Table B1. The site water was collected on December 10, 1984 in the Indiana Harbor Canal near the northwest corner of the railroad bridge at Canal Street. This water was used in the [redacted]

2. The effluent quality is a function of the disposal alternative used. [redacted] in Table B4. These estimates assume that the water in the in-lake CDF prior to disposal has no contaminants, the quantity of water available for dilution is the minimum to maintain one foot of ponding, the effluent following filtration contains 0.5 mg/ℓ suspended solids, and the concentration of dissolved contaminants does not change while passing through the filter dikes. Signifi- [redacted] (PCBs) onto the filter material is expected and, therefore, the estimates are [redacted] water available for dilution may be as much as four times as large as assumed in calculating the effluent quality in the following sections.

Hydraulic Transfer from Scows

3. The sediment in the modified elutriate test was diluted to 100 g/ℓ since the sediment is expected to be diluted to 100 g/ℓ during the transfer [redacted]

several times and, unlike the clean water used for dilution in the modified elutriate test, the CDF dilution water may accumulate contaminants each time

[redacted]

tion, then additional contaminants may not partition into the water, and the

[redacted]

will be multiplied by the number of uses as dilution water to generate a con-

[redacted]

Total Volume of Sediment = 200,000 cu yd $(e_o/(1 + e_o)$

Total Volume of In Situ Pore Water = (2.37/3.37) 200,000 cu yd
= 141,000 cu yd

Total Volume of In Situ Solids = 200,000 - 141,000 = 59,000 cu yd

Total Volume of Available Dilution Water (assuming 1 ft of ponding at end of disposal) = 347,000 cu yd (initial storage volume)
+ 56,000 cu yd (ponded volume)

[redacted]

= 1,600,000 cu yd

Required Dilution Water = 1,600,000 - 200,000 = 1,400,000 cu yd

Ratio of Dilution Water to Pore Water in Modified Elutriate Test = 1,400,000/141,000 = 9.93

Ratio of Dilution Water to Pore Water in Field = 403,000/141,000 = 2.86

Therefore, the dilution water will be used

[redacted]

2.86

Consequently, the dissolved contaminant concentrations predicted by the modi- [redacted]

Hydraulic Disposal by Matchbox or Cutterhead Dredge

[redacted]

4. The modified elutriate test predicts the release of contaminants to the supernatant water following hydraulic dredging (generally by a cutterhead [redacted] culent or zone settling and a significant quantity of supernatant is quickly [redacted] dilution of pore water, and mechanical means. Hydraulic disposal by a matchbox dredge is expected to produce a slurry that has a solids concentration that is similar to that used in the modified elutriate test. The slurry is expected to settle by flocculent or zone settling as the slurry does in the modified elutriate test. The modified elutriate test best represents the effluent [redacted] from an in-lake CDF during hydraulic dredging.

[redacted]

Total Volume of Influent = (800 g/ℓ)/(150 g/ℓ) 200,000 cu yd
= 1,070,000 cu yd

Total Volume at End of Disposal = 347,000 cu yd

Total Volume of Supernatant Produced During Disposal
= 1,070,000 - 347,000 = 720,000 cu yd

Total Volume of Dilution Water in CDF = 403,000 cu yd

Available Dilution = 720,000 cu yd/(720,000 + 403,000) cu yd
= 0.64

[redacted]

Mechanical Dredging and Disposal

5. Dredging and disposal by mechanical methods is expected to sig- [redacted] mixing and turbulence of pumping, resuspension, and volume of carrier water should be much smaller. Consequently, water released from the dredged material by resuspension and compression settling may have appreciably lower concentrations of contaminants than obtained in the modified elutriate test. This difference is evident from the initial leaching data which had contaminant [redacted] quality of the water released by compression settling. The quality of water [redacted] contaminant release will be computed to be the sum of these two parts, and this quantity will be reduced by the dilution available in the in-lake CDF.

[redacted]

Total Volume at End of Disposal = (800 g/ℓ)/(615 g/ℓ) 200,000 cu yd
= 260,000 cu yd

Total Volume of Water Released by Compression Settling During
Disposal = 267,000 − 260,000 = 7,000 cu yd

Total Volume of Water for Resuspension (assuming 1 ft of ponding at end of disposal) = 56,000 (volume of ponding) + 260,000 cu yd

= 316,000 cu yd

[redacted]

= 53 cu yd

Total Volume of Influent Water Released by Resuspension =

[redacted]

[redacted]

[redacted]

Table B1

Chemical Characterization of Indiana Harbor Site Water and Bulk Sediment

Constituent	Constituent Concentration of Sample*	
	Site Water	Bulk Sediment
Arsenic	<0.005 ppm	36.8 ppm
Cadmium	0.0007 ppm	22.2 ppm
Chromium	0.004 ppm	514 ppm
Copper	0.005 ppm	266 ppm
Lead	<0.001 ppm	933 ppm
Mercury	0.0020 ppm	0.262 ppm
Nickel	0.008 ppm	120 ppm
Zinc	<0.03 ppm	3,785 ppm
Iron	<0.03 ppm	182,000 ppm
Manganese	0.042 ppm	2,085 ppm
[illegible]	[illegible]	[illegible]
D-BHC	<0.00001 ppm	<0.02 ppm
Chlordane	<0.0002 ppm	<0.02 ppm
PPDDD	<0.00001 ppm	<0.02 ppm
PPDDE	<0.00001 ppm	<0.02 ppm
PPDDT	<0.00001 ppm	<0.02 ppm
Dieldrin	<0.00001 ppm	<0.0002 ppm
A-Endosulfan	<0.00001 ppm	<0.0002 ppm
[illegible]	[illegible]	[illegible]
Endrin aldehyde	<0.00001 ppm	<0.0002 ppm
Heptachlor	<0.00001 ppm	<0.02 ppm

(Continued)

Table B1 (Concluded)

Constituent	Constituent Concentration of Sample	
	Site Water	Bulk Sediment
Heptachlor epoxide	<0.00 001 ppm	<0.0002 ppm
PCB-1016	<0.0002 ppm	<0.2 ppm
PCB-1221	<0.0002 ppm	<0.2 ppm
PCB-1232	<0.0002 ppm	<0.2 ppm
PCB-1242	<0.0002 ppm	<0.2 ppm
PCB-1248	0.0003 ppm	29.4 ppm
PCB-1254	<0.0002 ppm	<0.2 ppm
PCB-1260	<0.0002 ppm	<0.2 ppm
Toxaphene	<0.0002 ppm	<0.2 ppm
Naphthalene	<0.01 ppm	2050 ppm
Acenaphthylene	<0.01 ppm	22 ppm
Acenaphthene	<0.01 ppm	110 ppm
Fluorene	<0.01 ppm	83 ppm
Phenanthrene	<0.01 ppm	210 ppm
Anthracene	<0.01 ppm	64 ppm
Fluoranthene	<0.01 ppm	175 ppm
Pyrene	<0.01 ppm	145 ppm
Chrysene	<0.01 ppm	98 ppm
Benzo(a)anthracene	<0.01 ppm	110 ppm
Benzo(b)fluoranthene	<0.01 ppm	165 ppm
Benzo(k)fluoranthene	<0.01 ppm	165 ppm
Benzo(a)pyrene	<0.01 ppm	115 ppm
Indeno(1 2 3-c d)pyrene	<0.025 ppm	60 ppm
Dibenzo(a h)anthracene	<0.025 ppm	<10 ppm
Benzo(g h i)perylene	<0.025 ppm	42 ppm
Total organic carbon	4.6 ppm	48,258 ppm
Phenol	<0.01 ppm	4.02 ppm
Dissolved solids	342 ppm	
Suspended solids	<4 ppm	

Table B2 (Continued)

Constituent	Constituent Concentration of Modified Elutriate Test Samples	
	Unfiltered Water	Filtered Water
[redacted]	[redacted]	[redacted]
PCB-1221	<0.0002 ppm	<0.0002 ppm
PCB-1232	<0.0002 ppm	<0.0002 ppm
[redacted]	[redacted]	[redacted]
PCB-1248	31.5 ± 16.4 ppm	0.0034 ± 0.0017 ppm
[redacted]	[redacted]	[redacted]
Toxaphene	<0.0002 ppm	<0.0002 ppm
Naphthalene	4.2 ± 1.4 ppm	<0.01 ppm
Acenaphthylene	0.086 ± 0.047 ppm	<0.01 ppm
Acenaphthene	0.39 ± 0.22 ppm	<0.01 ppm
[redacted]	[redacted]	[redacted]
Fluoranthene	0.59 ± 0.35 ppm	<0.01 ppm
Pyrene	0.54 ± 0.30 ppm	<0.01 ppm
Chrysene	0.34 ± 0.20 ppm	<0.01 ppm
Benzo(a)anthracene	0.24 ± 0.17 ppm	<0.01 ppm
Benzo(b)fluoranthene	0.43 ± 0.28 ppm	<0.01 ppm
[redacted]	[redacted]	[redacted]
Benzo(a)pyrene	0.26 ± 0.19 ppm	<0.01 ppm
[redacted]	[redacted]	[redacted]
Benzo(g h i)perylene	0.08 ± 0.14 ppm	<0.025 ppm
Total organic carbon	1073 ± 607 ppm	44.5 ± 3.7 ppm
Phenol	0.070 ± 0.015 ppm	0.037 ± 0.004 ppm
[redacted]	[redacted]	[redacted]

Table B2 (Concluded)

Constituent	Constituent Concentration of Modified Elutriate Test Samples	
	Unfiltered Water	Filtered Water
pH	7.59	
Dissolved oxygen	1.3 ± 0.1 ppm	

(Sheet 3 of 3)

Table B3

	Water	Maximum	Harbor	Michigan
Chromium	0.05	2.2-9.9	-	0.050
Copper	1.0	0.012-0.043	-	-
Lead	0.05	0.074-0.400	-	0.050
Mercury	0.002	0.0017	0.0005	0.00005
Nickel	-	1.1-3.1	-	-
Zinc	5.0	0.18-0.57	-	-
Iron	0.3	-	0.300	0.150
Manganese	0.05	-	-	-
Total phosphorus	-	-	0.1	0.03
NH3-N	-	-	1.5	-
Aldrin	-	-	-	-
A-BHC	-	-	-	-
G-BHC	-	-	-	-
D-BHC	-	-	-	-
Chlordane	-	-	-	-
PPDDD	-	-	-	-
PPDDE	-	-	-	-
PPDDT	-	-	-	-
Dieldrin	-	-	-	-
A-Endosulfan	-	-	-	-
B-Endosulfan	-	-	-	-
Endrin	-	-	-	-
Endrin aldehyde	-	-	-	-
Heptachlor	-	-	-	-
Heptachlor epoxide	[illegible]	[illegible]	[illegible]	[illegible]

Table B3 (Concluded)

Constituent	Standards	Criteria	WQ Standard	WQ Standard
PCB-1016	–	–	–	–
PCB-1221	–	–	–	–
PCB-1232	–	–	–	–
PCB-1242	–	–	–	–
PCB-1248	–	0.014	0.000001	0.000001
PCB-1254	–	–	–	–
PCB-1260	–	–	–	–
Toxaphene	–	–	–	–
Naphthalene	–	–	–	–
Acenaphthylene	–	–	–	–
Acenaphthene	–	–	–	–
Fluorene	–	–	–	–
Phenanthrene	–	–	–	–
Anthracene	–	–	–	–
Fluoranthene	–	–	–	–
Pyrene	–	–	–	–
Chrysene	–	–	–	–
Benzo(a)anthracene	–	–	–	–
Benzo(b)fluoranthene	–	–	–	–
Benzo(k)fluoranthene	–	–	–	–
Benzo(a)pyrene	–	–	–	–
Indeno(1 2 3-c d)pyrene	–	–	–	–
Dibenzo(a h)anthracene	–	–	–	–
Benzo(g h i)perylene	–	–	–	–
Total organic carbon	–	–	–	–
Phenol	–	–	0.01	0.001
Dissolved solids	–	–	500	172
Suspended solids	–	–	–	–

Table B4

[redacted]

	Hydraulic	Matchbox	Mechanical
[redacted]			
Chromium	0.122	0.022	0.0013
Copper	0.122	0.022	0.001
Lead	0.224	0.041	0.052
Mercury	<0.0028	<0.0005	<0.0001
Nickel	0.112	0.020	0.0007
[redacted]			
[redacted]			
G-BHC	<0.00004	<0.000006	<0.000001
D-BHC	<0.00004	<0.000006	<0.000001
Chlordane	<0.0007	<0.00013	<0.00001
PPDDD	<0.00004	<0.000006	<0.000001
PPDDE	<0.00004	<0.000006	<0.000001
PPDDT	<0.00004	<0.000006	<0.000001
Dieldrin	<0.00004	<0.000006	<0.000001
[redacted]			

(Continued)

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* Assuming that the water in the CDF has no contaminants prior to disposal, [redacted] the new lift of material plus the ponded volume for a 1-ft ponding depth, that the effluent following filtration contains 0.5 mg/ℓ suspended solids, and that the concentration of dissolved contaminants does not change while passing [redacted]

[redacted]

	Estimated Constituent Concentrations, ppm*		
Constituent	Hydraulic Transfer	Matchbox Dredge	Mechanical Disposal
Endrin	<0.00004	<0.000006	<0.000001
Endrin aldehyde	<0.00004	<0.000006	<0.000001
Heptachlor	<0.00004	<0.000006	<0.000001
Heptachlor epoxide	0.00014	0.00003	<0.000001
PCB-1016	<0.0007	<0.00013	<0.00001
PCB-1221	<0.0007	<0.00013	<0.00001
PCB-1232	<0.0007	<0.00013	<0.00001
PCB-1242	<0.0007	<0.00013	0.00001
PCB-1248	0.0238	0.0051	<0.00001
PCB-1254	<0.0007	<0.00013	<0.00001
PCB-1260	<0.0007	<0.00013	<0.00001
Toxaphene	<0.0007	<0.00013	<0.00001
Naphthalene	<0.04	<0.007	<0.0001
Acenaphthylene	<0.04	<0.007	<0.0001
Acenaphthene	<0.04	<0.007	0.0003
[redacted]	[redacted]	[redacted]	[redacted]
Anthracene	<0.04	<0.007	<0.0001
Fluoranthene	<0.04	<0.007	0.0004
Pyrene	<0.04	<0.007	0.0004
Chrysene	<0.04	<0.007	0.0002
Benzo(a)anthracene	<0.04	<0.007	0.0002
Benzo(b)fluoranthene	<0.04	<0.007	<0.0002
Benzo(a)pyrene	<0.04	<0.007	<0.0001
Indeno(1 2 3-c d)pyrene	<0.04	<0.007	<0.0001
Dibenzo(a h)anthracene	<0.09	<0.016	<0.0005
Benzo(g h i)perylene	<0.09	<0.016	<0.0001
Total organic carbon	156	28.6	1.
Phenol	0.130	0.024	0.0008
Dissolved solids	-	-	-
Suspended solids	0.5	0.5	0.5
[redacted]	[redacted]	[redacted]	[redacted]

Conclusions

6. In general, the contaminant concentrations in the effluent from an in-lake CDF during hydraulic transfer from scows are about 5 to 6 times as [redacted] ical disposal. Considering the discharge volume, the quantities of contami- [redacted] the mechanical disposal alternative.

7. The maximum quantity of PCBs expected to be released from the pro- [redacted] magnitude less) since PCBs are very hydrophobic and are adsorbed very easily.

[redacted] ably total organic carbon for the hydraulic transfer from scows alternative [redacted] alternative barely exceed the water quality standards without considering a mixing zone.

1. Laboratory settling and filtering tests were performed in 1980 on sediments from Indiana Harbor. Descriptions and results of these tests were reported in US Army Engineer Waterways Experiment Station (1980).* Results of those tests are excerpted from the report and presented in this appendix.

2. A flocculent settling test was run on a 63-g/ℓ suspension and the results are shown in Figure C1. Zone settling tests were run on seven slurries [redacted] The results of this test are plotted in Figure C3.

3. Several filtering tests were performed on supernatant from sedimentation of 190 g/ℓ. The supernatant had a solids concentration of 1.49 g/ℓ. A [redacted]

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* See References at the end of the main text (Vol 1).

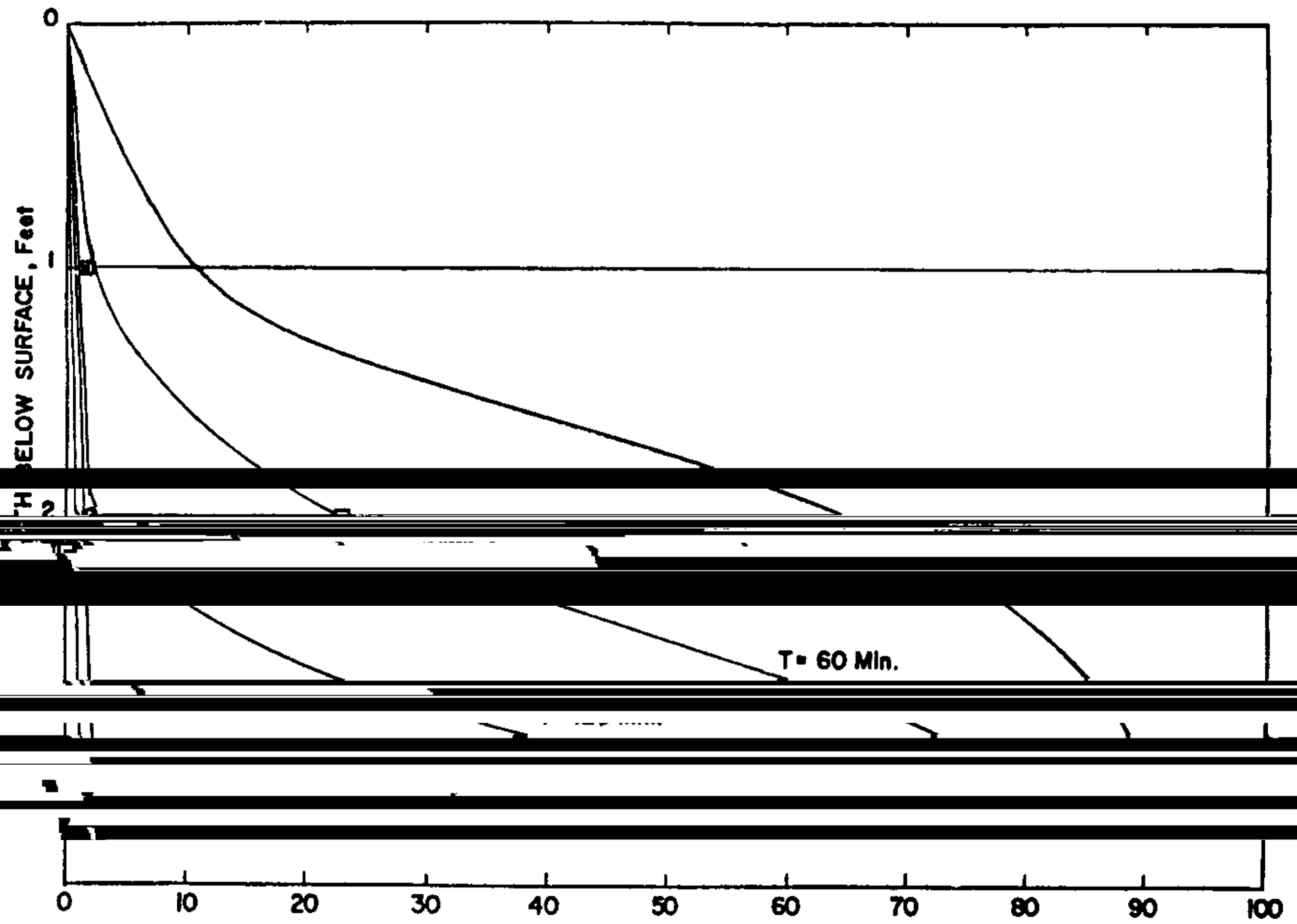

Figure C1. Solids [illegible]

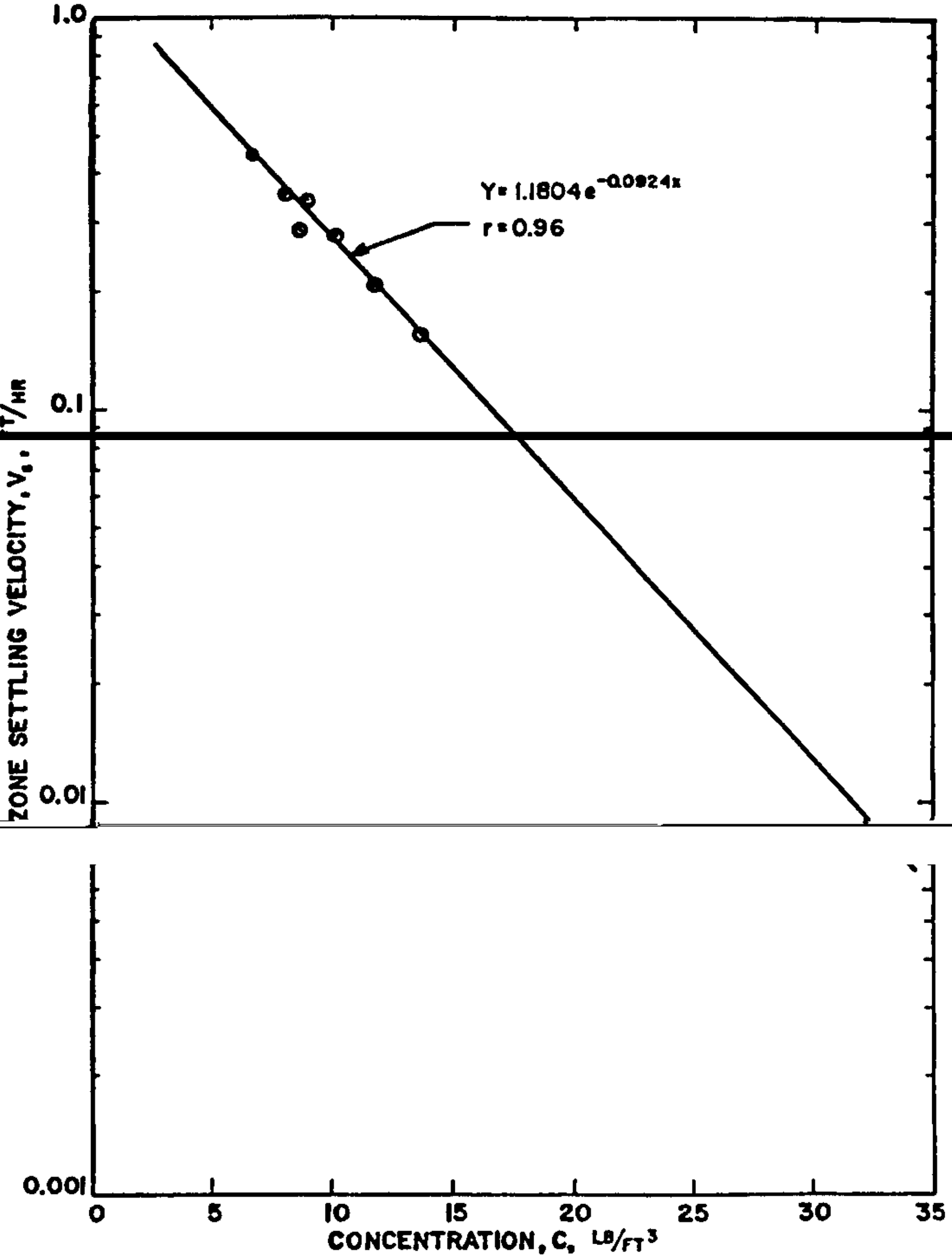

Figure C2. Zone settling velocity versus concentration

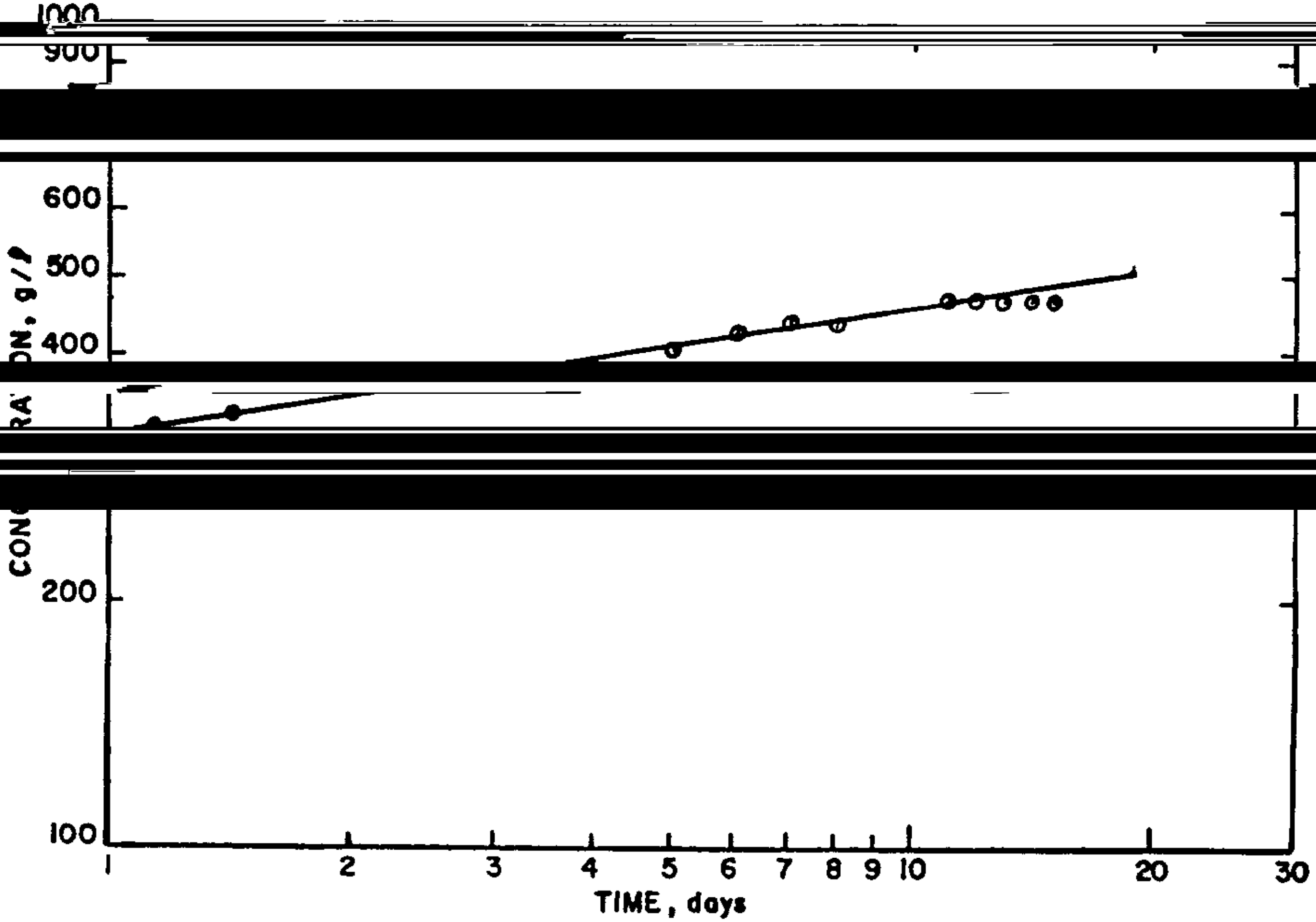

Figure C3. Solids concentration versus time

Table C1

Summary of Laboratory Filter Tests

Test Run	Filter Media	Filter Depth cm	[illegible] Concentration** mg/ℓ	[illegible] Head cm	Initial Discharge ℓ/min	Total Volume of Throughput ℓ	Length of Test before Plugging mins
[illegible]	[illegible] sand	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sand II	Fine sand	120	1490	220	0.68	37.9	115
Carbon	Calgon Filtrasorb 400	120	1490	157	0.49	60.6	105
Sand-Carbon	Fine sand Filtrasorb 400	240	1490	179	0.42	53.0	--

[illegible]

Table C2

Suspended Solids Analysis of Filter Samples

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Carbon	0.022	0.035	--	0.029	98.1
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Table C3

PCB* Analysis of Filter Samples

Sample	Aroclor 1242	Aroclor 1248	Aroclor 1254	Aroclor 1260	Total PCB	Removal Efficiency
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Supernatant	8.8**	0.03*	2.8	0.03	11	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Carbon	0.73	0.03	0.63	0.03	1.4	87.3
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

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* PCB = Polychlorinated biphenyls.

** Typographical correction from the original report.

Table C4

Additional Chemical Analyses of Filter Samples

	Parameter							
Sample Identification	[illegible] mg/ℓ	Efficiency %	[illegible] mg/ℓ	Efficiency %	[illegible] mg/ℓ	Efficiency %	[illegible] mg/ℓ	Efficiency %
Supernatant	46.3		5.57		0.033		15*	
Sand I	39.6	14.5	0.565	89.8	0.033	0	5,850*	99.7
Sand II	76.4	--	0.815	85.4	0.038	--	5	99.9
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Sand-Carbon	26.9	41.9	0.800	85.6	0.010	--	10	99.8

[illegible]

Table C5

Metal Analyses of Filter Samples

Sample Identification	As mg/ℓ	Cd mg/ℓ	Cr mg/ℓ	Cu mg/ℓ	Pb mg/ℓ	Mn mg/ℓ	Ni mg/ℓ	Zn mg/ℓ	Hg mg/ℓ
Supernatant									
Total	0.19	0.0412	0.989	0.350	1.110	1.30	0.113	7.77	0.0022
Filtered	<0.010	<0.0001	0.002	0.004	<0.001	0.122	0.018	<0.050	<0.0002
Sand I									
[redacted]									
Carbon									
Total	0.017	0.0034	0.091	0.057	0.114	0.076	0.012	1.01	0.0006
Filtered	0.018	0.0002	<0.001	0.004	<0.001	0.046	0.006	0.329	<0.0002
Sand-Carbon									
Total	0.022	0.0008	0.026	0.196	0.176	0.026	0.012	0.657	<0.0002
Filtered	0.026	0.0004	<0.001	0.014	<0.001	0.016	0.006	0.232	<0.0002
Blank									
Total	<0.010	0.0006	<0.001	<0.001	<0.001	<0.001	<0.003	<0.050	
Interim Drinking Water Standard	0.05	0.01	0.05*	1.0	0.05	0.05	--	5.0	0.002

[redacted]

Table C6

Percentage Removal Efficiencies for Total Metals

Sample Identification	As	Cd	Cr	Cu	Pb	Mn	Ni	[illegible]	Hg
Sand I	--	89	90	73	99	87	88	[illegible]	--
Sand II	--	76	84	40	76	86	81	[illegible]	91
Carbon	10	92	91	84	90	94	95	[illegible]	73
Sand-Carbon	--	98	97	44	84	99	95	[illegible]	--

APPENDIX D: PLANT AND ANIMAL BIOASSAY PROCEDURES AND DATA

Plant Bioassay

1. Confined disposal is one of the disposal alternatives for contaminated dredged material. A potential problem resulting from confinement of contaminated dredged material is that of plant uptake of contaminants from the dredged material and subsequent mobilization into the ecosystem. A plant bio- [redacted]

Methods and materials

2. Sediment preparation. Enough sediment for the upland portion of the [redacted] turned daily to facilitate drying. The air-drying process was conducted for about 4 weeks in the greenhouse to minimize airborne contamination of the [redacted] chemical and physical analyses.

3. Greenhouse procedures. The plant bioassay was conducted using the WES plant bioassay procedure. This method was reported by Folsom and Lee (1981).* A schematic diagram of the Experimental Unit (EU) is illustrated in [redacted] (ODW)) to be tested was placed into the inner container of the EU (Figure D1). [redacted]

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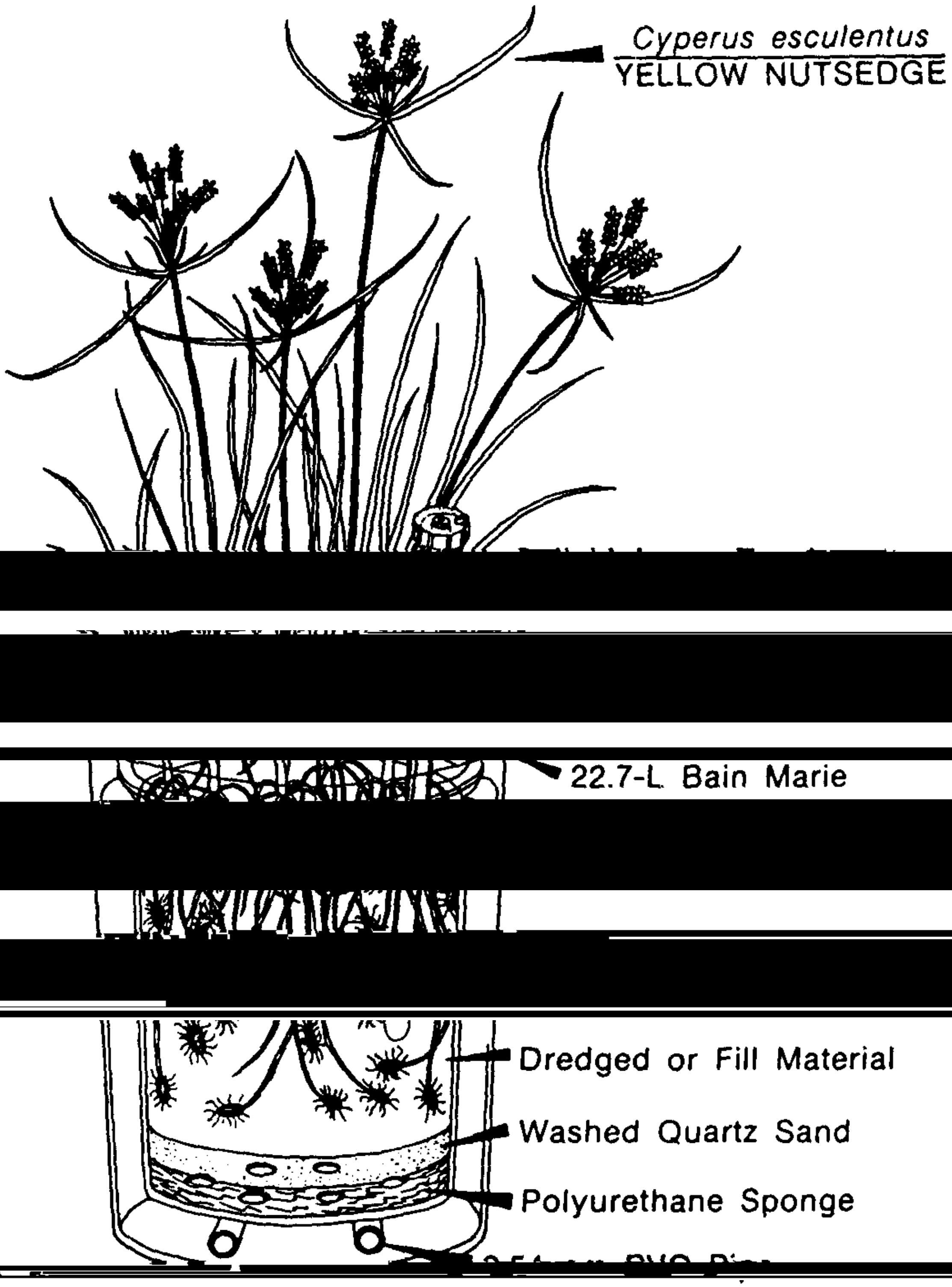
* See References at the end of the main text (Vol I).



[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Figure D1. Plant bioassay experimental unit

[redacted]

polyurethane sponge overlaid with a 2.54-cm layer of washed quartz sand was placed on the sponge. The sand and sponge acted as a filter to keep the sediment from draining out the bottom of the inner container through the small

[redacted]

out of the sediment. After the sediment had been placed into the container, a

[redacted]

4. Three sprouted *Cyperus esculentus* tubers were planted in four replicates of the flooded sediment and four replicates of the air-dried sediment (to reflect submerged and upland conditions, respectively) and allowed to grow

[redacted]

tensiometer was greater than 0.050 MPa, deionized RO water was used to fill the outer container up to the level of the sediment sample in the inner container. When the tensiometer reading was less than 0.03 MPa, the water was siphoned out of the outer container. The tensiometers were monitored daily

[redacted]

adsorbed particulates. The leaves were placed in a second plastic tray filled

[redacted]

allow chemical analysis for either metals or organics. Therefore, a composite sample was made by combining the plant tissue from all four replicates to give enough tissue for subsequent analyses.

6. Laboratory procedures. Ten grams of sediment (dry basis) was weighed [redacted] with a magnetic stirrer. After 45 min., the pH of the suspension was determined using a glass and reference calomel electrode on a Beckman Model SS-3 pH meter (Beckman Instrument Co., Inc., Irving, California). Calcium carbonate [redacted] The CEC was determined using the ammonium saturation method of Schollenberger and Simon (1945). The EC was determined on extracts of saturated pastes from sediments using the method of Rhoades (1982). The conductivity meter used was a Model Number 31 YSI (Yellow Springs Instrument Company, Yellow Springs, Ohio). Total and DTPA-extractable metals were determined on both the flooded and air-dried sediments using the procedures of Folsom, Lee, and Bates (1981). Sediments were also analyzed for PCB, PAH, and pesticides using standard EPA procedures (USEPA 1982).

7. The plant tissue digestion was accomplished by the following procedure. Two grams of oven-dried plant tissue was placed into a 100-ml micro- [redacted] almost dry. Five millilitres of red fuming nitric acid was added, and then the solution was again heated until almost dry. The mixture was allowed to cool to room temperature and diluted with 30 ml of 1.2 N hydrochloric acid (HCl). The solution was quantitatively transferred with 1.2 N HCl and filtered through Whatman No. 42 paper in a long-stem funnel into a 50-ml volumetric flask. The filtered solution was diluted to volume with 1.2 N HCl and [redacted] cury, nickel, chromium, and lead. Plant tissue analysis for PCB, PAH, and pesticides was performed according to USEPA (1982).

Results and discussion

8. Selected physical and chemical parameters of the Indiana Harbor sediment are listed in Table D1. The data presented in Table D1 indicate that the [redacted] in the air-dried sediment compared with the original flooded sediment (56.7 percent compared to 18.7 percent, respectively) and could explain the decrease in percent clay size particles. An increase in both inorganic and [redacted]

Table D1

Selected Chemical and Physical Characteristics of Indiana Harbor [redacted]

Sediments Placed Under Two Different Environmental Conditions,

Original-Flooded (Reduced) and Air-Dried Upland (Oxidized)

Characteristics	Sediment Flooded	Sediment Upland
Percent sand	72.5a*	75.0a
Percent silt	20.0a	22.5a
Percent clay	7.5a	2.5b
CEC, meq/100g	3.08b	8.78a
pH	7.40a	7.50a
Electrical conductivity, S/m**	0.367a	0.390a
Percent organic matter	56.7b	18.7a

[redacted]

** S/m = Siemans per metre = 0.1 χ mmhos per centimetre.

Table D2

Concentration of Organic Contaminants in Indiana Harbor Sediment

	Concentration, µg/g (ODW)*	
[redacted]	[redacted]	[redacted]
Aldrin	4.800a	4.600a
A-BHC	<0.155a	<0.200a
B-BHC	<0.155a	<0.200a
G-BHC	<0.155a	<0.200a
D-BHC	<0.155a	<0.200a
[redacted]	[redacted]	[redacted]
A-endosulfan	<0.02a	<0.02a
B-endosulfan	<0.02a	<0.02a
Endosulfan sulfate	<0.02a	<0.02a
Endrin	<0.02a	<0.02a
Endrin aldehyde	<0.02a	<0.02a
Heptachlor	<0.02a	<0.02a
Heptachlor epoxide	<0.02a	<0.02a
PCB-1016	<1.55a	<2.00a
PCB-1221	<1.55a	<2.00a
PCB-1232	<1.55a	<2.00a
PCB-1242	<1.55a	<2.00a
PCB-1248	62.3a	66.3a
PCB-1254	<1.50a	<2.00a
[redacted]	[redacted]	[redacted]
Toxaphene	<1.50a	<2.00a
Naphthalene	693a	123a
Acenaphthylene	13.9a	5.00b
Acenaphthylene	81.5a	39.3b
Fluorene	72.5a	42.8b
Phenanthrene	225a	188a
Anthracene	62.8a	38.0a
Fluoranthene	175a	143a
Pyrene	150a	120a
Chrysene	99.3a	76.5a
[redacted]	[redacted]	[redacted]
Benzo(a) pyrene	136a	111a
Benzo(g h i)perylene	45.3a	41.0a

[redacted]

[redacted]

10. There were measurable quantities of aldrin; PCB-1248, and all of the [redacted]

sediments.

11. Total and DTPA extractable heavy metals are listed in Tables D3 and Table D4, respectively. Total quantities of some of the metals are quite

Table D3

Total Heavy Metal Content of Sediment from Indiana Harbor

Metal	Concentration, μg/g Flooded	Concentration, μg/g Upland
Zn	4550a*	4270a
Cd	28.1a	27.2a
Cu	322a	316a
Fe**	135a	134a
Mn	2219a	2288a
As	22.9a	23.7a

[redacted]

[redacted]

** Fe concentration is milligrams per gram.

Table D4

[redacted]

Zn	270a	1300a
Cd	0.245a	8.86b
Cu	<0.005a	0.154a
Fe	259a	442a
Mn	18.3a	41.9a
As	0.083a	0.091a
Hg	<0.001a	<0.001a
Ni	19.0a	19.1a
Cr	0.118a	0.314b
Pb	3.14a	26.9b

---

* Mean of four replicates. Means followed by the same letter in a row are not significantly different at P = 0.05 level of probability using Duncan's New Multiple Range Test.

[redacted]

available form. Cadmium and lead are the major metals that would be mobilized

[redacted]

12. Plant growth (Figure D2) on the flooded Indiana Harbor sediments was greater than that on the upland sediment. This difference is also reflected in a greater yield on the flooded IN sediments compared to that of the upland sediments (Table D5).

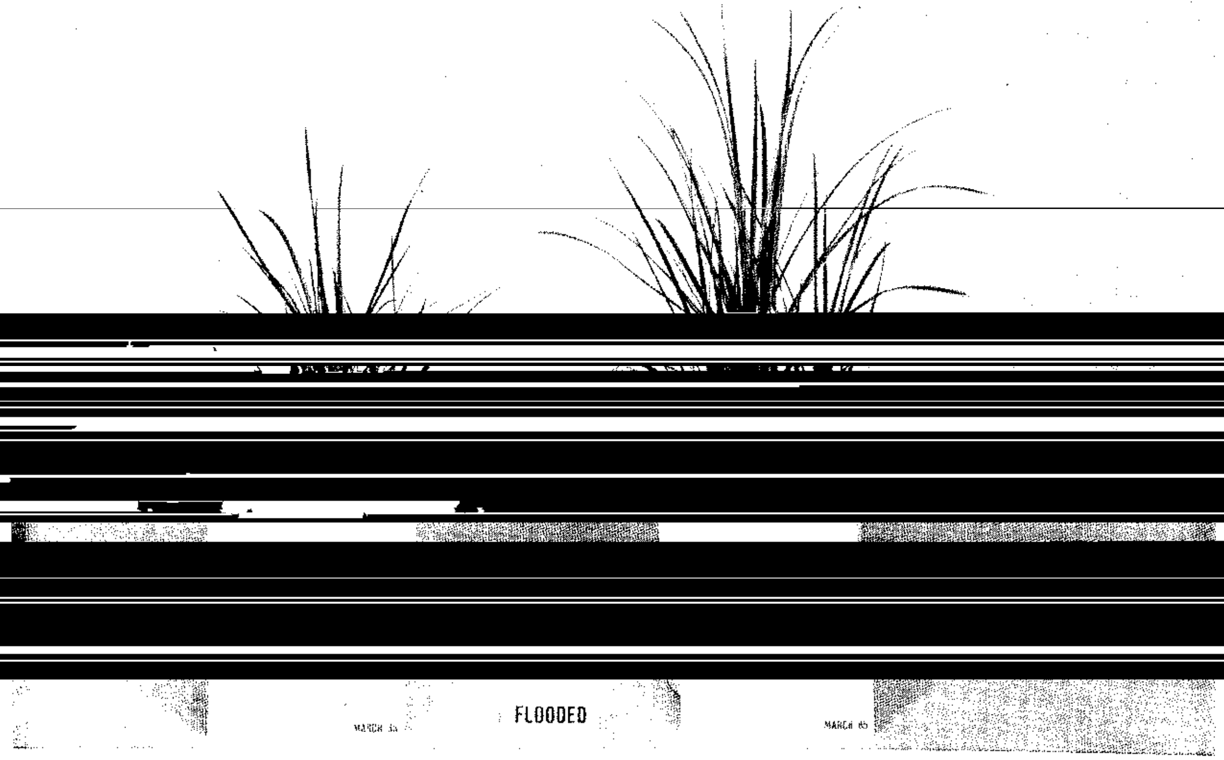
Table D5

Yield (g, ODW) of C. esculentus Grown in Sediments from Indiana Harbor and the WES Reference Soil

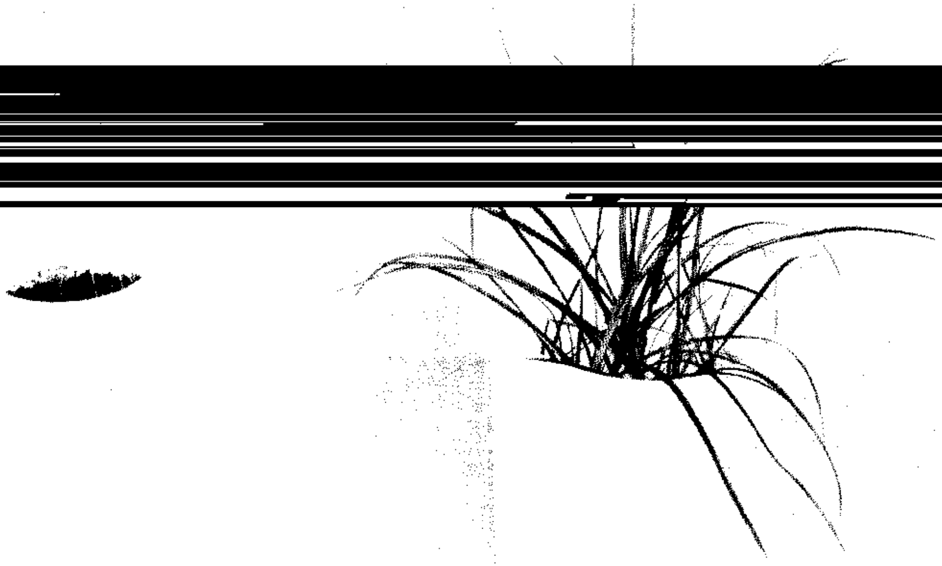
Indiana Harbor		WES Reference	
Flooded	Upland	Flooded	Upland
1.82b*	0.034a	5.38d	3.74c

---

* Mean of four replicates. Means followed by the same letter in a row are not significantly different at P = 0.05 level of probability using Duncan's New Multiple Range Test.



FLOODED



C. esculentus
INDIANA HARBOR

C. esculentus
WESREF

UPLAND

[illegible]

Table D6

Concentration of Organic Contaminants in

[redacted]

Naphthalene	<2	<2
Acenaphthylene	<2	<2
Acenaphthene	<2	<2
Fluorene	<2	<2
Phenanthrene	<2	<2
Anthracene	<2	<2
Fluoranthene	<2	<2
Pyrene	<2	<2
Chrysene	<2	<2
Benzo(a)anthracene	<2	<2
Benzo(b)fluoranthene	<2	<2
Benzo(k)fluoranthene	<2	<2
Indeno-1,2,3-c d)pyrene	<2	<2
Dibenzo(a h)anthracene	<2	<2
Benzo(g h i)perylene	<2	<2

* Mean of four replicates.

16. Heavy metal content of plants grown on the upland sediment was gener-

[redacted]

Bates 1981; Folsom and Lee 1981). Plant cadmium and lead were quite high in the plants grown on the upland sediments (14.5 and 47.0 μg/g, respectively). The cadmium value is above the World Health Organization (WHO) allowable range of 0.5 - 2.0 μg/g Cd (World Health Organization 1972) and should be cause for

[redacted]

total plant uptake (concentration times yield) is considered (Table D8) it is apparent that the stunted plant growth resulted in higher tissue contents of

[redacted]

vated tissue contents of the metals cadmium and lead could present potential adverse food chain impacts.

Table D7

Heavy Metal Content of Cyperus esculentus Grown in Sediment from Indiana Harbor

	Concentration, μg/g	
Metal	Flooded*	Upland**
Zn	34.9*	128
Cd	0.095	14.5
Fe	138	226
Mn	38.4	453
As	<0.025	<0.025
Hg	<0.005	<0.005
Ni	0.549	0.167
Cr	2.43	14.5

[redacted]

* Mean of four replicates.
** Composite of four replicates.

Table D-8

[redacted]

	Total Uptake, μg/pot	
Metal	Flooded*	Upland**
Zn	61.5	2.38
Cd	0.198	0.009
Cu	2.64	0.237
Fe	245	4.18
Mn	69.9	8.38
As	--	--
Hg	--	--
Ni	1.03	0.003
Cr	3.71	0.268
Pb	2.75	0.869

* Mean of four replicates.
** Composite of four replicates.

[illegible] tially low available nitrogen and phosphorus, as well as very low concentrations of unknown organics that may limit plant growth. Air drying of the original flooded sediments resulted in reduced levels of OM and two of the [illegible]

18. Plant growth on the flooded Indiana Harbor sediment was greater than that on the upland sediment. However, heavy metal content of plants grown on the upland sediment was generally greater than that of plants grown on the flooded sediment and is consistent with the behavior of metal uptake found in [illegible] to nutrient limitations or inhibition of root function by organic compounds and/or heavy metals, especially Cu. Organic contaminants were not found in [illegible]

Animal Bioassay

19. Dredged or fill material placed in an upland or in-lake confined disposal facility (CDF) eventually may become a wildlife habitat and resting area for migratory birds. This situation has occurred in many confined disposal facilities around the Great Lakes, such as Times Beach, Buffalo, N.Y., where a prolific wildlife habitat has developed on contaminated dredged material. It is, therefore, important to note that processes such as weathering, leaching, and mobilization of some compounds may result in a material, that, after a period of time, is quite unlike the original sediment. The upland animal bioassay addresses both the immediate response of animals to a newly dredged sed- [illegible] material at some indefinite time in the future.

20. The upland animal bioassay procedures applied are those developed by Edwards (1983) to evaluate the effects of new chemicals for the European Economic Commission (EEC) and the Organization for European Common Development [illegible]

[redacted]

worms followed by acute toxicity indicated that bioaccumulation testing for

[redacted]

aging and drying under upland disposal conditions including: ashing in a muf-

[redacted]

shade for 6 months. After each aging process, the resulting material was completely air dried, ground with a mortar and pestle, and re-wet to field capacity before adding earthworms. Five worms were added to 50-g triplicate subsamples of each material, and survival was recorded.

[redacted]

cylinder were covered with 340-μ mesh Nitex bolting cloth (Wildco), which was

[redacted]

23. Each bioassay container received 30 g of earthworms (counted and

[redacted]

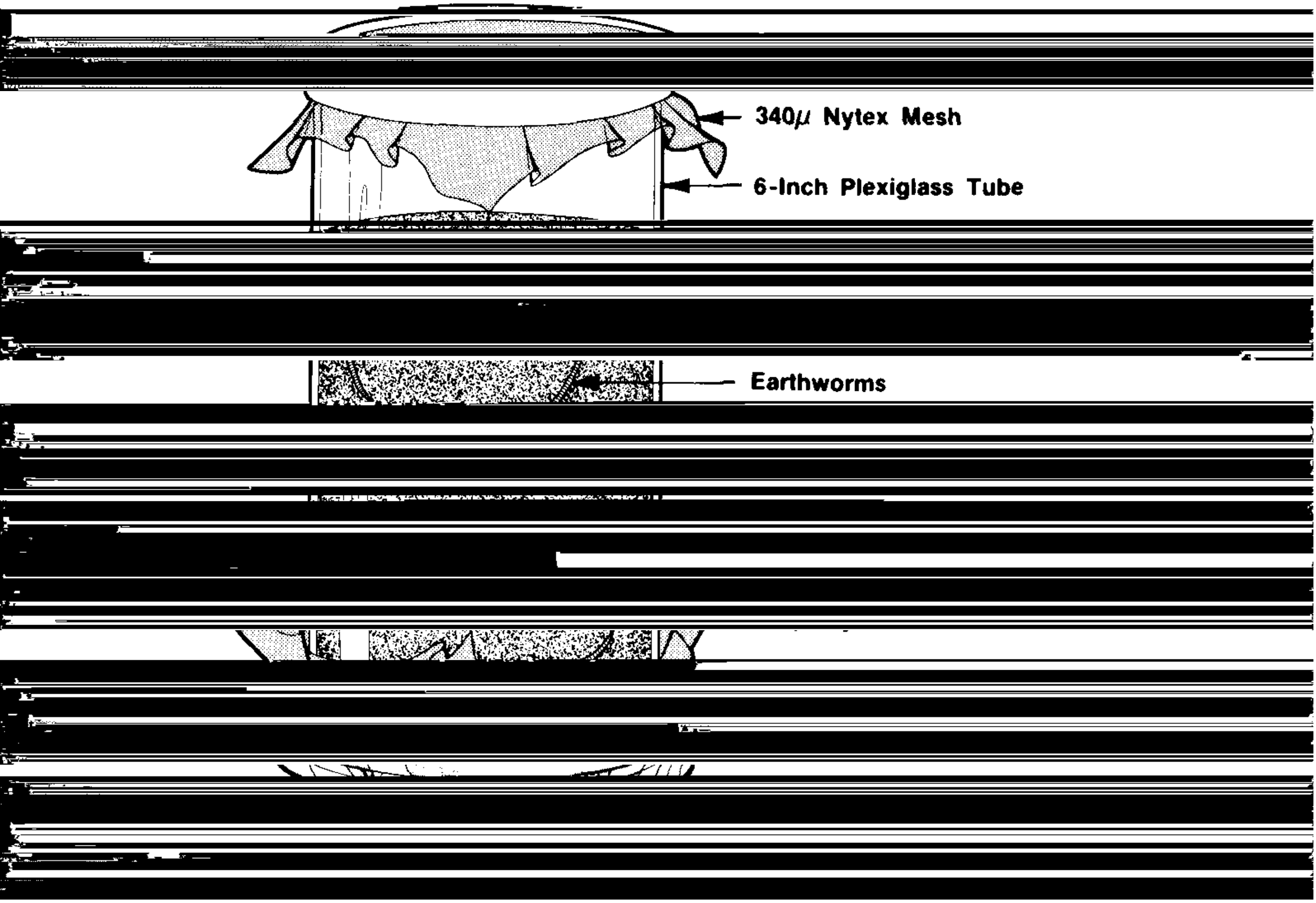


Figure D3. Test cyclinders

growth medium, rinsed with RO water, and placed on paper towels to remove excess water. Then the worms were weighed and placed on the test sediment. The test was conducted in a temperature-controlled chamber at 15°C with con-

[redacted]

transparency of the Plexiglas, the worms were forced to stay within the sub-

[redacted]

[redacted]

[redacted]

metals using atomic absorption spectroscopy following appropriate USEPA sample

[redacted]

Model 2100 Heated Graphite Atomizer and a Perkin Elmer Model 5000 Atomic

[redacted]

[redacted]

[redacted]

[redacted]

jected to capillary gas chromatography.

Results and discussion

26. The Indiana Harbor sediment, in its original reduced state, was extremely toxic to the worms. No burrowing occurred, and the worms were dead

or moribund in less than 24 hr. Immediate burrowing of the worms into the manure controls indicated that neither handling nor the physical condition of

[redacted]

100 percent survival for more than 28 days. At this point, a 28-day earthworm bioassay was initiated to evaluate contaminant bioaccumulation from this "aged"

[redacted]

results of the earthworm bioassay on the sediment that was aged for 6 months

[redacted]

concentrations of organic compounds present in the original Indiana Harbor sediment but had relatively little effect on the metals (Table D9). The concentration of the total PCBs (sum of congeners) in the aged sediment decreased by over 80 percent of the original sediment concentration (Table D10). The most dramatic effect of the aging process was on the PAHs, particularly naphthalene, which dropped to about 2 percent of its original concentration (Table D11). The total of all 16 PAHs analyzed dropped an entire order of magnitude, largely as the result of the loss of naphthalene (see discussion of volatilization in Appendix G).

[redacted]

29. The concentrations of arsenic, cadmium, copper, lead, and nickel increased significantly in earthworm tissues during the 28-day exposure period.

[redacted]

[redacted]

Metal Concentrations* in Indiana Harbor Sediments and Bioassay Earthworms

Metal	Original Sediment	Aged** Sediment	Initial Earthworms †	Bioassay Earthworms ††	CF‡
Arsenic	29.5	25.962 +/- 1.587	1.582 +/- 0.072a	2.808 +/- 0.369b	0.11
Cadmium	20.0	19.094 +/- 2.519	6.082 +/- 0.468a	9.037 +/- 0.823b	0.47
Chromium	650.0	506.729 +/- 36.102	0.000 +/- 0.000a	3.892 +/- 2.822a	0.01
Copper	282.0	237.888 +/- 7.128	11.302 +/- 0.389a	23.112 +/- 3.022b	0.10
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Mercury	0.530	0.522 +/- 0.904	0.059 +/- 0.103a	0.000 +/- 0.000a	0.00
Nickel	137.0	111.860 +/- 1.401	1.302 +/- 0.295a	3.225 +/- 0.829b	0.03
Zinc	4125.0	3767.454 +/- 114.381	118.426 +/- 5.693a	149.956 +/- 19.096a	0.04

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* Mean of three replicates +/- standard deviation expressed as μg/g (=ppm) dry weight. Means in a row followed by the same letter are not significantly different according to Duncan's New Multiple Range procedure at alpha = 0.05.

** 6-month aging.

[redacted]

†† Time = 28 days.

‡ Concentration factor (ratio of concentration in worms to that in the aged sediment).

Table D10

PCB Concentrations* in Indiana Harbor Sediments and Bioassay Earthworms

Chlorobiphenyls	Original Sediment	Aged** Sediment	Initial Earthworms†	Bioassay Earthworms††
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
2,2',5,5'-Tetra	35.0	<0.010 +/- 0.000	<0.015 +/- 0.013a	<0.008 +/- 0.002a
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
2,2',3,4,4',5,5'-Hepta	1.85	1.660 +/- 1.449	<0.008 +/- 0.000a	0.104 +/- 0.047b
Sum	137.35	15.11		

[redacted]

‡ The analysis of variance indicated that uptake could be considered marginally significant:probability > F = 0.0754.

Table D11

PAH Concentrations* in Indiana Harbor Sediments and Bioassay Earthworms

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Naphthalene	2033.333 +/- 57.735a	46.267 +/- 1.258b	d	d
Acenaphthylene	21.667 +/- 0.577	d	d	d
Acenaphthene	105.333 +/- 8.083	d	d	d
Fluorene	78.333 +/- 8.145a	4.287 +/- 0.731b	d	d
Phenanthrene	206.667 +/- 11.547a	14.267 +/- 3.650b	d	d
Anthracene	63.333 +/- 1.528a	74.033 +/- 6.269b	d	35.264 +/- 16.37
Fluoranthene	160.000 +/- 10.000a	36.933 +/- 5.659b	d	d
Pyrene	[illegible]	[illegible]	[illegible]	[illegible]
Chrysene	93.667 +/- 4.041a	23.300 +/- 3.724b	d	12.218 +/- 5.92
Benzo(a)anthracene	102.000 +/- 13.856a	21.633 +/- 2.363b	d	d
Benzo( )fluoranthene†	156.667 +/- 15.275a	41.700 +/- 19.213b	d	20.915 +/- 10.49
Benzo(a)pyrene	105.667 +/- 16.921a	33.900 +/- 10.789b	d	18.420 +/- 5.90
Indeno(1,2,3-c,d)pyrene	57.000 +/- 10.440a	18.513 +/- 12.491b	d	9.295 +/- 2.78
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[redacted] centration factors (ratios of metal concentrations in bioassay worms to those [redacted]

30. The uptake of PCBs by earthworms was significant during the 28-day exposure period. The earthworms accumulated PCB concentrations that were about 25 percent of those in the aged sediments (Table D10). Of the 15 PCB [redacted] 0.0754) in one additional tetrachlorinated congener. Other congeners were [redacted]

31. The bioaccumulation of PAHs by earthworms was significant only for five of the 16 compounds analyzed (pyrene, benzo[b]fluoranthene + benzo[k]fluoranthene, benzo[a]pyrene, and indeno[1,2,3-c,d]pyrene). The remaining PAHs were near or below the detection limits in the worms, except chrysene, which also showed marginally significant ($p > F = 0.0701$) bioaccumulation. All PAHs which bioaccumulated significantly were present in the tissues in concentrations about 50 percent of those found in the aged sediments; these PAHs apparently were the least labile of those in the original sediments.

Conclusions

32. Very little is known about bioaccumulation and effects of chemicals on earthworms, except for some pesticides and metals. The initial toxicity of [redacted] thalene. The presence of the metals probably did not contribute significantly to the observed worm mortality, as the concentrations of metals in both the sediments and earthworms were generally below the levels demonstrated to be toxic or to inhibit growth and reproduction of earthworms (Neuhauser et al. 1984; Malecki, Neuhauser, and Loehr 1982; Hartenstein, Neuhauser, and Narahara [redacted]

[redacted] by earthworms (Neuhauser et al. 1984). The presence of substantial concentrations of copper and zinc in the earthworms should be of little concern, as [redacted] mal tissues. Cadmium bioaccumulation may become a potential problem in the food chain, as cadmium is readily mobilized and is known to cause adverse effects at relatively low levels of exposure (Kay, 1985). The effects of PCBs and PAHs on earthworms are essentially unknown. Existing literature indicates [redacted]

33. Of immediate concern in the upland disposal of Indiana Harbor dredged [redacted] organic compounds, the sediments possibly would be colonized by earthworms and other soil-dwelling invertebrates. Bioaccumulation of metals and the less [redacted] earthworm bioassay.

34. The results from the 6-month aging of the Indiana Harbor sediment [redacted] conditions may become habitable and develop into a biologically prolific ecosystem. This has occurred at the Times Beach disposal site at Buffalo, N. Y. (Marquenie, Simmers, and Kay, in preparation) as well as elsewhere in the Great Lakes area. Therefore, upland disposal of Indiana Harbor sediment would require a monitoring and management strategy to address contaminant bioaccumulation as the site became biologically productive. [redacted]

APPENDIX E: QUANTIFICATION OF SURFACE RUNOFF WATER QUALITY

Introduction

[redacted] on several factors including the chemical form of the contaminants and the type of disposal environment. Dredged material in its original condition is anaerobic with a pH > 7 where many contaminants are closely bound to the particulates and are poorly soluble and not bioavailable. Movement of contam- [redacted] during this time may be very high with suspended solids concentrations ranging [redacted] disposal site, physiochemical changes occur as the wet anaerobic material dries and oxidizes. The extent to which changes occur may significantly affect the surface runoff water quality, particularly the dissolved portion. As the sediment dries and oxidizes, it becomes more resistant to erosion with suspended solids decreasing to 10 to 1,000 mg/ℓ. Total concentrations of con- [redacted] If high levels of sulfides are present in the sediment, then oxidation may cause the pH to lower to <4.0 where contaminants such as heavy metals become very soluble in surface runoff.

2. The US Army Engineer Waterways Experiment Station (WES) Rainfall Simulator-Lysimeter System has proven to be very effective in predicting surface runoff water quality from Corps of Engineers project sites such as confined upland dredged material disposal sites. The WES System is a rotating [redacted]

[redacted]
placed in an upland environment. The air-dried and oven-dried tests deter-
[redacted]
in predicting the availability of of several heavy metals in plants (Lee, Folsom, and Bates 1983). The peroxide test was originally developed as a test for quickly oxidizing pyrite in acid mine spoils to determine potential soil acidity and lime requirements (Barnhisel 1976).

Materials and Methods

Rainfall Simulator-Lysimeter System

[redacted]
brought to the WES, and placed in three lysimeters measuring 4.57 by 1.22 m. Each lysimeter was loaded with nine 200-ℓ barrels of sediment to a depth of 33.02 cm. Standing water on the sediment was allowed to drain out of the lysimeters. The following day each lysimeter was subjected to a 30-min storm event at a 6.5-cm/hr application rate. Initial sediment moisture was 55 to 67 percent (60-65 percent solids) and pH was 7.9. Runoff rates were measured
[redacted]
tered and unfiltered heavy metals, PCBs, PAHs, and pesticides.

6. The lysimeters were then moved outside the greenhouse and covered with semitransparent tops which allowed air movement over the surface of the sediment. Surface moisture and pH were monitored during the drying period. After 6 months of drying and oxidation, storm events were conducted on the three lysimeters. The depth of the sediment decreased to 22.9 cm, the sediment
[redacted]

Simplified laboratory tests

[redacted]

Such simple screening tests could be performed at most Corps of Engineers field laboratories.

8. The laboratory tests were divided into two categories: those for

[redacted]

these laboratory tests, three sediment-to-water ratios were selected:

a. 1:10 or 100,000 ppm SS (250 g to 2,500 ml reverse osmosis (RO) water).
b. 1:100 or 10,000 ppm SS (25 g to 2,500 ml RO water).

[redacted]

9. Sufficient dry weight equivalents of wet sediment to match the ratios above were placed into 4-ℓ glass jars and filled with RO water. Sediment and water were well mixed and divided into two portions: one for unfiltered contaminant analysis and one for filtered analysis. Samples were analyzed for

[redacted]

10. Because of the physicochemical changes that occur when dredged mate-

[redacted]

inexpensive. A number of procedures were therefore screened in this study and

[redacted]

a. Oven drying to 5 percent.

b. Oven drying to 5 percent + peroxide.

c. Air drying to 5 percent.

d. Air drying to 5 percent + 14 days aging.

e. Air drying to 5 percent + 28 days aging.

f. Air drying to 5 percent + peroxide.

g. DTPA extract.

[redacted]

a. 1:100 or 10,000 ppm SS (25 g to 2,500 ml RO water).

[redacted]

c. 1:10,000 or 100 ppm SS (0.25 g to 2,500 ml RO water).

The purpose of the different lengths of drying time was to determine if sediment could be sufficiently dried and oxidized in a reasonable period of time to predict surface runoff water quality. The DTPA extract has been success-

[redacted]

might require months or years to completely oxidize, thereby making normal pH and lime requirement tests impractical for mine spoils. The peroxide test

[redacted]

short period what might require months by natural processes.

[redacted]

with RO water to attain the appropriate sediment-to-water ratios and divided

[redacted]

12. Air-dried tests were conducted by placing wet sediment in drying [redacted] that even after reaching 5-percent moisture, additional time was required to completely oxidize the sediment. After 14 and 28 days, sediment was ground up and mixed with RO water as before.

13. [redacted] RO water to 1ℓ and adjusted to pH of 7.3 using HCl or NaOH as needed:

DTPA Solution
1.099 g/ℓ $CaCl_2$ (0.01 M)
14.919 g/ℓ triethanolamine (0.1 M)
1.967 g/ℓ DTPA (0.0005 M)

[redacted] (1976). For this procedure a pretest was used to determine the total amount of peroxide required to completely oxidize all the sediment. For the pretest, [redacted] another 10 ml was added. This was continued until visible reactions did not occur when additional peroxide was added. This estimated the approximate amount of peroxide required to completely oxidize the sediment. The appropriate amounts of sediment for each sediment-to-water ratio were then mixed with [redacted] unfiltered and filtered contaminants.

[redacted]

Results

Rainfall Simulator-Lysimeter System

15. Results of the lysimeter test for wet, anaerobic sediment showed high concentrations of contaminants in the unfiltered samples (Table E1). At this stage contaminants were bound up tightly in the SS and, therefore, poorly soluble. The sediment was anaerobic with a high pH in the sediment and in the [redacted]

16. Organic compounds were highest in the unfiltered samples indicating [redacted] metals were also mostly in the unfiltered samples. Relatively high concentra- [redacted] below detectable limits. The US Environmental Protection Agency Maximum Cri- [redacted]

17. Significant physicochemical changes occurred in the Indiana Harbor [redacted] 5 percent, and the sediment pH decreased to 6.3. The sediment in the lysim- [redacted] decreased by several orders of magnitude. The effects of the physicochemical changes on the filtered concentrations were varied depending on the [redacted]

18. Sediment concentrations of organic compounds decreased significantly [redacted]

Table E1

Surface Runoff Water Quality During Early, Wet, Anaerobic Stage

[redacted]	[redacted]	[redacted]	[redacted]
pH	7.64	7.66	N*
[redacted]	[redacted]	[redacted]	[redacted]
DDE	< 0.00001	0.00004	N
PCB-1248	0.051	0.0015	0.014
PAH_s	18.03	0.148	N
Naphthalene	6.91	0.115	N
Acenaphthylene	0.212	< 0.005	N
Acenaphthene	0.857	0.0131	N
Fluorene	0.780	0.010	N
Phenanthrene	1.67	0.0097	N
Anthracene	0.494	< 0.005	N
Fluoranthene	1.57	< 0.005	N
Pyrene	1.35	< 0.005	N
Chrysene	0.843	< 0.005	N
Benzo(a) anthracene	0.787	< 0.005	N
Benzo(b) [redacted]	1.12	< 0.005	N
[redacted] pyrene	[redacted]	[redacted]	[redacted]
Benzo(g h i) perylene	0.124	< 0.005	N
Heavy metals			
[redacted]	[redacted]	[redacted]	[redacted]
Manganese	9.04	0.0170	N
Chromium	4.06	0.056	2.2-9.9
Lead	6.80	0.0670**	0.074-0.400
Iron	627	1.39	N
Mercury	0.0037	< 0.0002	0.0017
Arsenic	0.232	< 0.005	0.440

---

* N No values available.

** Concentrations equal or exceed USEPA Maximum Water Quality Criteria.

Table E2

Surface Runoff Water Quality During Dry, Oxidized Stage

[redacted]

[redacted]	[redacted]	[redacted]	[redacted]
pH	6.3	6.3	N*
conductivity (S/m)	4.9	N	N
SS	56	N	N
[redacted]	[redacted]	[redacted]	[redacted]
Acenaphthylene	< 0.005	< 0.005	N
Acenaphthene	< 0.005	< 0.005	N
Fluorene	< 0.005	< 0.005	N
Phenanthrene	0.0069 A	0.0056 A	N
Anthracene	< 0.005	< 0.005	N
Fluoranthene	0.0067	< 0.005	N
Pyrene	0.0061	< 0.005	N
Chrysene	< 0.005	< 0.005	N
Benzo (a) anthracene	< 0.005	< 0.005	N
Benzo (b) fluoranthene	< 0.005	< 0.005	N
Indeno-1,2,3_C D pyrene	< 0.005	< 0.005	N
Benzo (g h i) perylene	< 0.005	< 0.005	N
Heavy metals			
Cadmium	0.0011 A	0.0026 A**	0.0015-0.0024
Copper	0.054 A	0.072 A**	0.012-0.043
Chromium	0.027 A	0.0043 B	0.021
Nickel	0.038 A	0.046 A	1.1-3.1
Zinc	0.34 A	0.53 A**	0.180-0.570
Manganese	0.28 A	0.40 A	N
Lead	0.032 A	0.008 A	0.074-0.400
[redacted]	[redacted]	[redacted]	[redacted]
Arsenic	< 0.005	< 0.005	0.440

---

* N No values available

** Concentrations equal or exceed USEPA Maximum Water Quality Criteria.

[redacted]

[redacted] nificantly. Most of the organic compounds were below detectable limits even [redacted] centrations of Cadmium, Copper, Nickel, Zinc, Manganese, and Lead were not significantly different from the unfiltered concentrations, indicating that [redacted] oxidation but was still significantly lower than the unfiltered concentra- [redacted]

Simplified laboratory tests

20. Wet, anaerobic sediment. Laboratory test results were very promising and should provide the basis for an effective simplified predictive test that can be conducted by other Corps laboratories. Results for a dilution of 1:10 [redacted] from the lysimeter tests were between dilutions 1:100 and 1:1,000 (Table E3).

[redacted] by a dilution 1:100; however, lysimeter results for PAHs were slightly higher. Replicate 1 of the lysimeter test was an order of magnitude higher than the other two replicates causing the average concentration to be excessively high. [redacted]

Table E3

Wet, Anaerobic Sediment Laboratory Test Results, Unfiltered

Parameter	Runoff Conc.	1:100	1:1000
SS	6,600	10,000	1,000
PCB-1248	0.096	1.14	0.066
Naphthalene	6.91	9.0	0.65
Acenaphthylene	0.212	0.11	0.006
Acenaphthene	0.857	0.54	0.049
Fluorene	0.780	0.48	0.040
Phenanthrene	1.67	1.30	0.070
Anthracene	0.494	0.42	0.027
Fluoranthene	1.57	0.84	0.076
Pyrene	1.35	0.83	0.075
Chrysene	0.843	0.39	0.043
Benzo(a) anthracene	0.787	0.38	0.047
Benzo(b) fluoranthene	1.12	< 0.3	0.072
Benzo(k) fluoranthene	1.12	< 0.3	0.072
Indeno-1,2,3_C D pyrene	0.195	< 0.3	< 0.005
Dibenzo (a h) anthracene	< 0.010	< 0.30	< 0.005
Benzo(g h i) perylene	0.124	< 0.30	0.012
Heavy metals			
Cadmium	0.154B	0.2793A	0.0282C
Copper	1.70A	2.456A	0.272B

Different tests with the same letter are not significantly different

[redacted]

because of the much lower concentrations in the samples (Table E4). In many cases concentrations were at or near detection limits where precision is more difficult. In general the laboratory tests gave a good indication of the contaminant concentrations that will occur in surface runoff from the lysimeters. A dilution of 1:100 gave the best results but generally slightly under-

[redacted]

tion of 1:100 and 1:1,000. Concentrations of PCB-1248 from the lysimeter were

[redacted]

23. Dry, oxidized sediment. Except for naphthalene, all organic compound concentrations were at or below detection limits so that comparison of labo-

[redacted]

laboratory tests did indicate that the PAHs would be lost from the sediment

[redacted]

PCB-1248 to be below detection limits. Comparisons for the dry, oxidized

[redacted]

24. Unfiltered concentrations of heavy metals were dependent only on the

[redacted]

the oven-dried and the oven-dried + peroxide laboratory tests. No significant

[redacted]

the total concentration of metals in the sediment. These results were to be

[redacted]

Table E4

Wet, Anaerobic Sediment Laboratory Tests, Filtered Contaminants

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PCB-1248	0.0016 B	0.011 A	0.0037 B	0.0025 B
PAH				
Naphthalene	0.115 B	2.8 A	0.39 B	0.11 B
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Anthracene	< 0.005	0.013	0.006	< 0.005
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Benzo(a) anthracene	< 0.005	0.006	< 0.005	0.007
Benzo(b) fluoranthene	< 0.005	< 0.005	< 0.005	< 0.005
Benzo(k) fluoranthene	< 0.005	< 0.005	< 0.005	< 0.005
Indeno-1,2,3_C D pyrene	< 0.005	< 0.005	< 0.005	< 0.005
[illegible] anthracene	[illegible]	[illegible]	[illegible]	[illegible]
Benzo(g h i) perylene	< 0.005	< 0.005	< 0.005	< 0.005
Heavy metals				
Cadmium	0.0021 AB	0.0070 A	0.0009 B	0.0039 AB
Copper	0.0237 B	0.0647 A	0.0063 B	0.006 B
Chromium	0.0567 B	0.211 A	0.019 B	0.009 B
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table E5

Dry, Oxidized Sediment Laboratory Tests, Unfiltered Concentrations*

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
SS	56	10,000	1,000	100
[redacted]				
Cu	0.0011	1.86	0.278	0.0031
Cr	0.027	3.85	0.447	0.0490
Ni	0.038	0.899	0.165	0.042
Zn	0.34	33.1	3.77	1.44
[redacted]				
[redacted]		OVEN DRIED + PEROXIDE		
Cd	0.0011B	0.531A	0.106B	0.0035B
Cu	0.054B	6.40A	0.383B	0.042B
Cr	0.027C	12.7A	0.717B	0.093BC
Ni	0.038C	2.47A	0.332B	0.033C
Zn	0.443B	103A	6.01B	1.34B

---

* Different tests with the same letter are not significantly different at P = 0.05.

25. Significant differences did occur between the different laboratory tests when filtered metal concentrations are considered (Table E6). Even the highest sediment-to-water ratio for the air-dried + 28 days underestimated the concentrations of Cadmium, Copper, Zinc, and Nickel measured from the lysimeter. Concentrations of these metals appeared to increase slightly as the aging period was increased. However, even the longest drying period of the air-dried + 28 days was insufficient to completely oxidize the sediment. [redacted] would be impractical for a quick, standardized laboratory test. The oven-dried + peroxide, the air-dried + peroxide, and the DTPA tests were all significantly better at predicting the filtered metal concentrations determined from the lysimeter. The oven-dried + peroxide was better than the air-dried + peroxide, but this was probably the result of variations in sediment concentrations and not from differences in the tests. The peroxide tests increased the solubility of Cadmium, Copper, Nickel, and Zinc but did not increase the solubility of Chromium, which was similar to the lysimeter tests. The peroxide tests slightly underestimated the metal concentrations in surface runoff, but the tests did show the increased solubility of the heavy metals and volatilization of the organic compounds. The DTPA test results were highly variable but they did indicate potential for use in predicting surface runoff water quality from dry, oxidized dredged material. Refinements of the [redacted]

26. Based on the results of this study, the surface runoff from Indiana [redacted] environmental impacts. During the early, wet, anaerobic stages, contaminants [redacted] period were low compared with the unfiltered concentrations but were still of concern when compared with the USEPA Maximum Criteria for the Protection of Aquatic Life. Results of the lysimeter tests represented the worst possible case that could occur during the wet, anaerobic stage. Control measures during this period should concentrate on control of the SS in the surface

Table E6

Dry, Oxidized Sediment Laboratory Tests, Filtered Concentrations*

[illegible]

		Oven Dried		
Cd	0.0026 A	0.0007 A	0.0004 A	0.0005 A
Cu	0.072 A	0.006 B	0.004 B	0.004 B
Cr	0.0043 AB	0.013 A	0.007 AB	0.003 B
Ni	0.046 A	0.031 AB	0.006 B	0.012 B
Zn	0.53 A	0.127B	< 0.030 B	< 0.030 B
		Oven Dried + Peroxide		
Cd	0.0026B	0.0067A	0.0021B	0.0018B
Cu	0.072B	0.212A	0.037C	0.023D
Cr	0.0043C	0.258A	0.120B	0.018C
Ni	0.046B	0.114A	0.017C	0.006C
Zn	0.53C	1.27A	0.714B	0.278D

Heavy Metal	Lysimeter Concentration mg/ℓ	Metal Concentration (mg/ℓ) at Indicated Ratio		
		1:100	1:1,000	1:10,000
		DTPA Extract		
Cd	0.0026	0.0287	< 0.010	< 0.010
Cu	0.072 A	0.036 A	0.513 A	0.014 A
Cr	0.0043 B	0.054 A	0.032 AB	0.014 B
Ni	0.046 B	0.283 A	0.046 B	0.193 AB
Zn	0.53 B	5.65 A	1.56 AB	0.244 B

[redacted]

27. After the sediment dried and oxidized, the surface runoff water quality constituents of concern changed. Organic compounds were not a problem during this stage since most of the compounds had been lost from the sediment due to volatilization into the atmosphere or adsorption to soil particles. Some naphthalene was present in both the filtered and unfiltered samples but the total PAHs were low. No PCBs were detectable in runoff from the dry,

[redacted]

These metals were present in mostly soluble forms, which are more difficult to control. Chromium also increased in solubility but not to the extent of the other metals. Filtered concentrations of Cadmium, Copper, Zinc, and Lead were high enough to be of concern as they were greater than or equal to the USEPA

[redacted]

28. Based on the results of the laboratory tests from this study, an extraction procedure does exist that can estimate the physicochemical changes that occur in a dredged material when it dries and oxidizes. The extraction procedures utilized peroxide to quickly oxidize a sediment which would require at least 6 months by natural means or a DTPA extract. Filtered concentrations from wet, anaerobic dredged material were estimated using the simple water--sediment dilution method. Filtered contaminant concentrations from the dry, oxidized sediment required the use of hydrogen peroxide. Further refinement and testing will greatly improve the accuracy and reliability of this

vegetating

procedure. Additional verification on several different types of dredged material is required to determine the most effective test as well as to establish the reliability of these tests before one can be widely used as a [illegible]

water and estuarine dredged material, including dredged material with a wide [illegible]

APPENDIX F: EVALUATION OF THE EFFECTIVENESS OF CAPPING IN ISOLATING CONTAMINATED INDIANA HARBOR DREDGED MATERIAL: BIOLOGICAL AND CHEMICAL ASPECTS

Introduction

1. Capping is a physical process in which a contaminated dredged material [redacted] ing it harmless. Capping has been utilized by the New England Division and New York District in open-water disposal sites. These field studies have shown that capping is technically feasible and that the caps are stable under normal tidal and wave conditions (O'Conner and O'Conner 1982, Science Applications, Inc. (SAI) 1982). However, the efficiency of capping in isolating contaminants in dredged material from overlying water and from pelagic and benthic biota is unknown (O'Conner and O'Conner 1982). In the New York Bight, a mussel bioaccumulation study at the capping site indicated low body burdens that [redacted] Island Sound, mussels were also suspended in the water column at the sand- and [redacted] time, but these changes were thought to be unrelated to the caps because differences in spatial concentration were not detected (Morton and Kemp 1980). Based on these and other field study results, bioaccumulation of contaminants by test organisms in the water column can result from sources other than dredged material. Therefore, determining the ability of caps to isolate contaminated dredged material from the water column has proven to be a difficult question to answer in the field (Morton and Kemp 1980; O'Conner and O'Conner 1982).

2. Analyses performed on sediments from within two specific reaches in Indiana Harbor indicate that the sediments are contaminated with polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), various metals, and [redacted] tection of freshwater aquatic life. Capping contaminated dredged material with clean dredged material within Indiana Harbor or Lake Michigan may be an

alternative to other disposal methods, such as confined land disposal. How- [illegible]

3. The purpose of this study was to identify the minimum thickness of a Lake Michigan sediment that will inhibit sediment-water interactions between [illegible] and aquatic biota. Data developed from this work will be used in evaluating the suitability of the confined aquatic disposal concept for Indiana Harbor and, if appropriate, in preparing the preliminary design of the site.

Approach

4. The effectiveness of capping in chemically [illegible] Experiment Station (WES). The approach used to conduct the present study is the result of this research, and the following procedures were followed.

5. An initial analyses of the contaminated dredged material and the cap material was performed to determine which chemical contaminants were most appropriate to monitor in the studies. The information obtained from this procedure was used to select several key parameters that were monitored in the large-scale reactor studies described below.

6. [illegible] In these units, capping effectiveness is determined by following changes in dissolved oxygen and selected inorganic chemical species in the water column [illegible] this approach is as follows. Most contaminated dredged material exerts an oxygen demand on the overlying water column that exceeds the oxygen demands [illegible]

dredged material, the cap sediment must be thick enough to prevent the migration of oxygen-demanding materials into the overlying water column. If these materials are able to diffuse through the cap layer, their presence in the water column will cause a dissolved oxygen depletion rate that exceeds that of the cap material alone. In like manner, once the layer of cap material is [redacted] applicable to ammonium-nitrogen and orthophosphate-phosphorus. These two con- [redacted] [redacted] [redacted] tested using large-scale (250-ℓ) reactor units. The rationale for these tests is based on the fact that organisms tend to accumulate contaminated materials to which they are exposed. Thus, if contaminants are moving into the surface layer of the cap material, the biota living on the surface will be exposed to the contaminants and will accumulate them in their tissues. If the contaminants are moving through the cap material and into the water column, then organisms living in the water column will be exposed to the contaminants and are likely to accumulate these materials in their tissues. Analysis of the tissues of these organisms for key contaminants will then reveal if the contaminants have moved through the cap material and into the overlying water column and aquatic biota.

Methods and Materials

Sediment acquisition

[redacted]

operation. At each of two locations in Indiana Harbor, a sediment in the navigation channel was obtained using a clamshell dredge and placed into a total of forty 208-ℓ steel barrels. Five 208-ℓ barrels of Lake Michigan sed- [redacted]

Upon arrival at WES, contents of the 40 barrels of Indiana Harbor sediment and the 5 barrels of Lake Michigan sediment were separately composited and mixed, then returned to the barrels for storage.

[redacted]

constituents was determined in 22.6-ℓ, cylindrical, Plexiglas leaching col- [redacted]

for 3 days by slowly bubbling air through the water column. This procedure ensured that the dissolved oxygen concentration for all units was relatively uniform (±0.5 mg/ℓ) at the start of the experiment. At the end of 3 days, the aeration apparatus was removed and a 4 cm layer of mineral oil was added to seal the surface of the water column from the atmosphere. Water samples were [redacted]

Standard Methods (American Public Health Association (APHA) 1980).

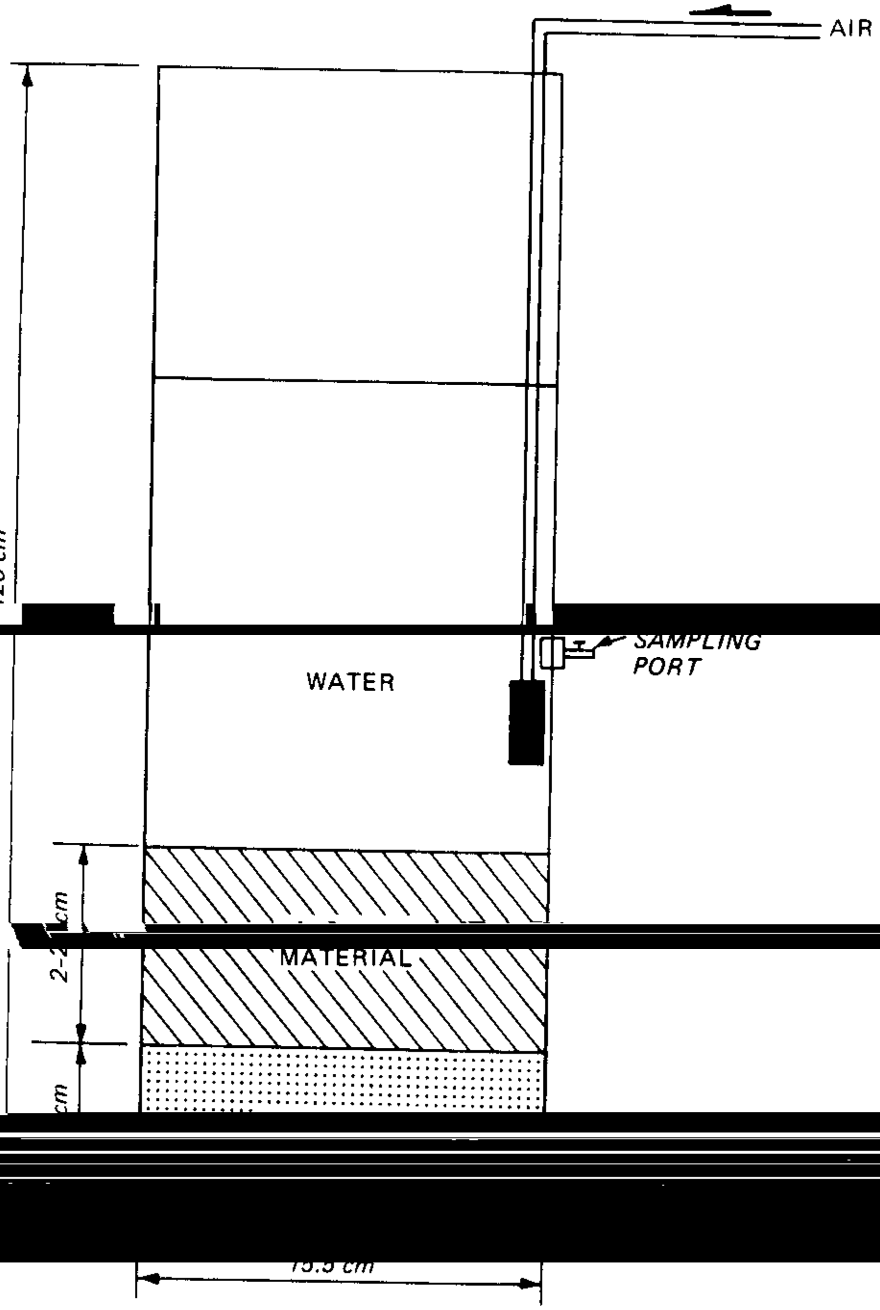

Figure F1. Small-scale reactor unit

[redacted]

phosphorus, relatively mobile compounds that are released under anaerobic

[redacted]

acidification with concentrated HCl to pH 2, followed by immediate freezing and storage at -4°C. Ammonium-nitrogen and orthophosphate-phosphorus were determined using a Technicon Autoanalyzer II, in accordance with procedures recommended by Ballinger (1979).

Large-scale reactor unit experiments

13. Laboratory studies to assess the effectiveness of the cap in isolat-

[redacted]

ports with Plexiglas, removal of the mixing pump from the system, and provision for constant aeration of the water column. With the exception of the control units, to which only Lake Michigan sediment was added, enough Indiana Harbor

[redacted]

each of the three treatments (Table F1). Sixty litres of aged tap water were then added as gently as possible to each reactor unit and allowed to equilibrate with aeration for 14 days. A 14-day equilibration time was selected to

[redacted]

50 percent of the overlying water column was replaced every 36 hr (Sprague 1969). The water column in each reactor unit was continuously aerated to ensure a well-mixed aerobic water column.

14. The results of previous capping studies have demonstrated the importance of using at least two organisms to assess capping effectiveness in preventing movements of contaminants into the biota (see Brannon, et al., 1985,

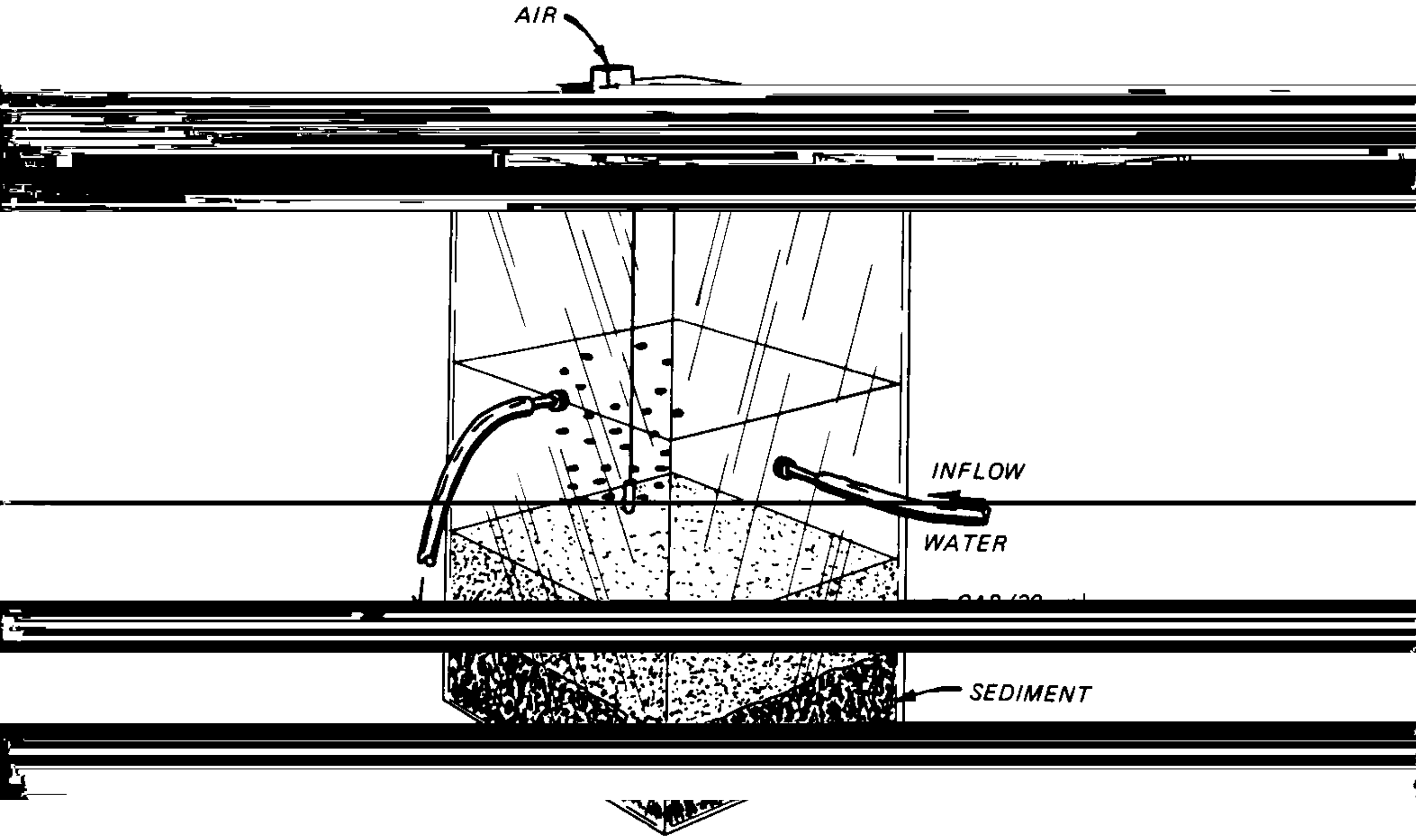

Figure F2. Large-scale reactor unit

Table F1

Experimental Design for Large-scale Reactor Column Experiments

Treatment	Reaction Chamber Replicate Designation
[redacted]	[redacted]
Indiana Harbor Sediment only	IH-1 IH-3 IH-5
Indiana Harbor sediment with 30 cm Lake Michigan sediment cap	IH-7 IH-8 IH-9

1986). Normally, one organism is selected that is representative of the benthic surface community. The second organism is often a variety of mussel that [redacted]

(*Anondonta grandis*) and yellow perch fingerlings (*Perca flavescens*) were selected, in consultation with the Chicago District, as bioassay organisms to determine if contaminants were moving through the cap and into the water column, while the red swamp crayfish (*Procambarus clarkii*) was used to assess the effect of capping on contaminant bioaccumulation in benthic organisms and to provide a source of bioturbation. Clams were obtained by scuba divers from the Detroit District from a freshwater lake in the Detroit area. Yellow perch fingerlings were supplied by the U.S. Fish and Wildlife Service Laboratory at LaCrosse, Wis. Crayfish were provided by the Center for Wetland Resources, [redacted]

through operation in the reactor units. A square basket, open on the top, having dimensions of 45 cm on a side, a height of 45 cm, and a mesh size of 2.5 sq mm was then suspended in the water column 5 cm above the sediment surface of each reactor unit. Fifty of the perch fingerlings were added to each basket. A second cylindrical basket containing 30 clams was suspended 5 cm [redacted]

ples of these populations were removed from the holding tanks for initial [redacted] reaction chamber; this was then added to the chamber as a slurry. Fifteen clams were removed from each reactor unit at 10- and 40-day intervals and [redacted] fish samples.

17. Samples of the aged tap water (inflow water) and water in the reactor [redacted] Samples to be used for PCB and PAH analyses were placed in 3.8-ℓ glass jars which had been hexane washed and dried at 105°C for 24 hr. Samples for metal analyses were filtered through 0.45-μm pore size membrane filters. The first [redacted] groups: total monochlorobiphenyls through total decachlorobiphenyls. Isomer [redacted]

19. Sixteen compounds comprising the family of compounds collectively referred to as polyaromatic hydrocarbons (Table F2) were also determined in water, sediment, and tissue samples. Samples were extracted overnight with a Soxhlet using benzene:methanol. The aromatic hydrocarbon fraction was then [redacted] equipped with a flame ionization detector. Individual compounds were quanti- [redacted] describe by Ballinger (1979).

20. Total organic carbon (TOC) in sediment samples was determined by dry [redacted] using the method of Patrick (1958).

Table F2

Polyaromatic Hydrocarbon Compounds Determined in [illegible]

[illegible]	[illegible]
Two-ring compounds	Napthalene
Three-ring compounds	Acenaphthalene
	[illegible]
	Phenanthrene
	Anthracene
	Fluorene
	Fluoranthene
Four-ring compounds	Pyrene
	Chrysene
	Benzo(a)anthracene
Five-ring compounds	Benzo(a)pyrene
	Benzo(b)fluoranthene
	Benzo(k)fluoranthene
	Dibenzo(a,h)anthracene
[illegible]	[illegible]
	Benzo(g,h,i)perylene

Statistical analysis of results

[redacted] tiple range test to determine differences between means. Statements of significance made in the text refer to the 5-percent level ($p < 0.05$) or less.

Results

Sediment characterization

22. Sediment from Indiana Harbor had higher concentrations of metals and pesticides than did the Lake Michigan cap material (Table F3). For example, the arsenic concentration in Indiana Harbor sediment was nearly triple that in [redacted]

[redacted] than did the cap material (Table F3). The only PAH compound present in detectable quantity in Lake Michigan sediment was naphthalene, and the level of this compound in Indiana Harbor sediment was more than three orders of magnitude [redacted]

not detected in Lake Michigan sediment (Table F3). By contrast, Lake Michigan sediment contained a trace amount of PCB-1254, a compound not found in the material from Indiana Harbor. Indiana Harbor sediment also contained substantial quantities of total organic carbon, oil and grease, and a small amount of phenol (Table F3); these were either not present or present in much smaller [redacted]

[redacted]

ana Harbor sediment from the water column. The Lake Michigan sediment as [redacted]

Table F3

Comparative Chemical Composition of Indiana Harbor and Lake Michigan Sediments

Parameter	Concentration in Sediment, mg/kg dry weight Indiana Harbor	 Lake Michigan
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
Chromium	650.0	4.4
Lead	879.0	11.9
Mercury	0.5	BD*
Zinc	4125.0	54.1
Pesticides		
Aldrin	2.55	0.0006
Polyaromatic Hydrocarbons		
Acenapthene	96	BD
Acenapthylene	22	BD
Anthracene	62	BD
[illegible]	[illegible]	[illegible]
Benzo(a)pyrene	87	BD
Benzo(g,h,i)perylene	35	BD
Chrysene	92	BD
Fluoranthene	150	BD
[illegible]	[illegible]	[illegible]
Indeno(1,2,3-c,d)pyrene	50	BD
Naphthalene	2000	0.46
Phenanthrene	200	BD
Pyrene	140	BD
Polychlorinated biphenyls		
PCB-1248	7.39	BD
PCB-1254	BD	0.013
Total carbon	2.28% of [illegible]	1.83% of [illegible]
[illegible]	[illegible]	[illegible]
Oil and grease	3.9% of sediment weight	1.71% of sediment weight
Phenol	3	BD

* BD = below detection.

Table F4

Selected Physical Characteristics of Indiana Harbor Sediment

Constituent	Concentration
[illegible]	
Sand	72.5
Silt	20.0
Clay	7.5
Percent moisture	50-80
Specific gravity of solids	2.50-2.54
Hydraulic conductivity, cm/sec	10-8

Chicago District indicated that the Lake Michigan material supplied may have had a higher gravel content than is typical of most sediment from this lake. [illegible]

[illegible] expected to be a problem in the open-water environment because of mixing and reaeration. Previous studies have shown that dissolved oxygen depletion can be used as one of several possible tracers for determining how effectively a cap can isolate an underlying dredged material, such as Indiana Harbor, that exerts a high oxygen demand (Brannon, et al. 1985, 1986). [illegible] the water overlying the cap material is summarized in Figure F3. Oxygen depletion rates were computed by performing linear regression analyses of net uptake [illegible] surface versus time. Rates plotted are the means of three replicates and represent values greater than baseline (i.e., oxygen demand of cap alone). As [illegible] uncapped Indiana Harbor sediment. As the unsieved cap thickness was increased [illegible] Lake Michigan cap with respect to decrease of oxygen depletion rate with depth.

28. Nutrient release rates. Ammonium-nitrogen-release rates to the overlying water, derived in the same manner as oxygen depletion rates, are presented in Figure F4 as a function of the thickness of cap material used. The [illegible] nitrogen release rates then decreased linearly until a cap depth of 23 cm was [illegible] observed with uncapped Indiana Harbor sediment, then decreased linearly to a cap thickness of 30 cm.

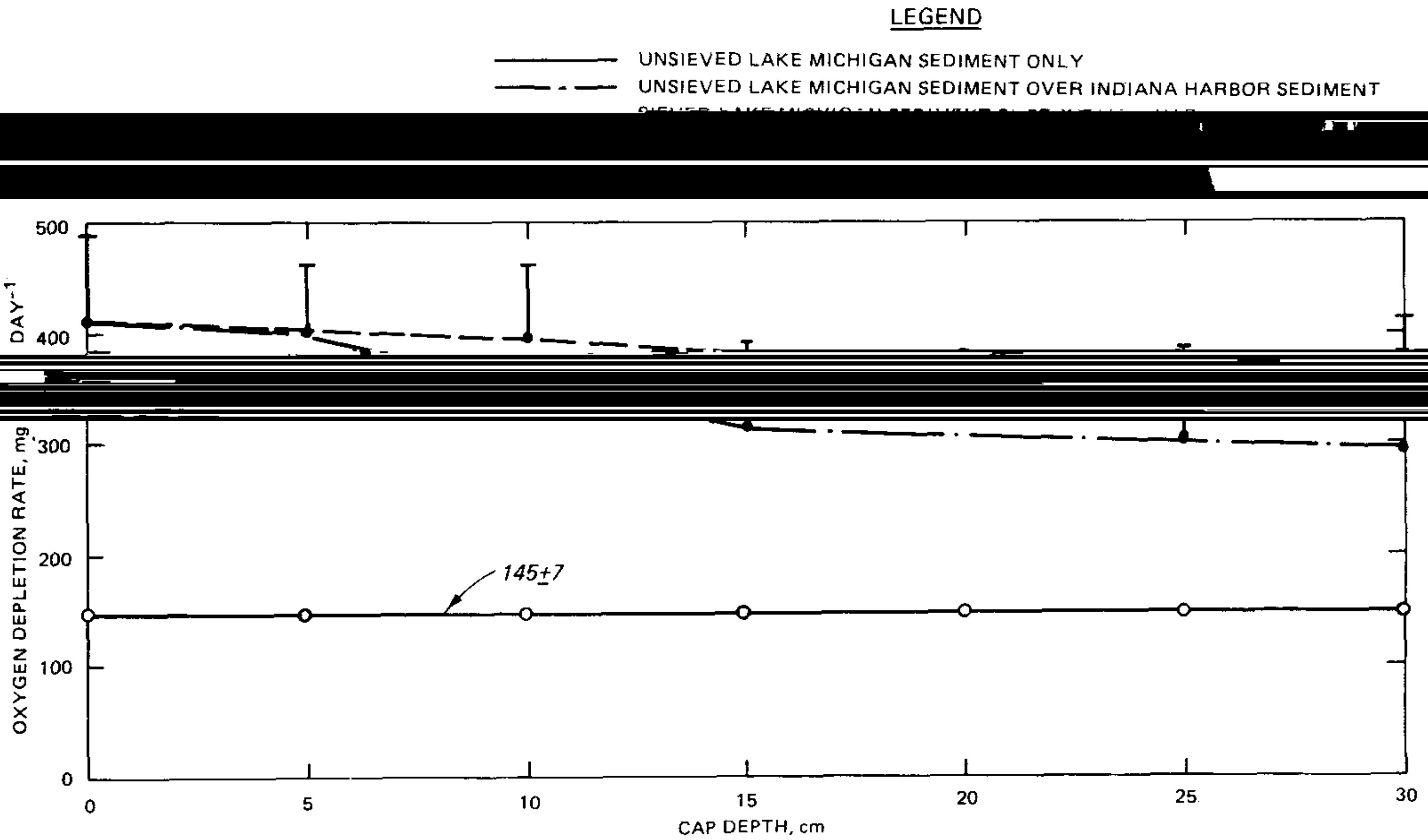

Figure F3. Dissolved oxygen depletion rates

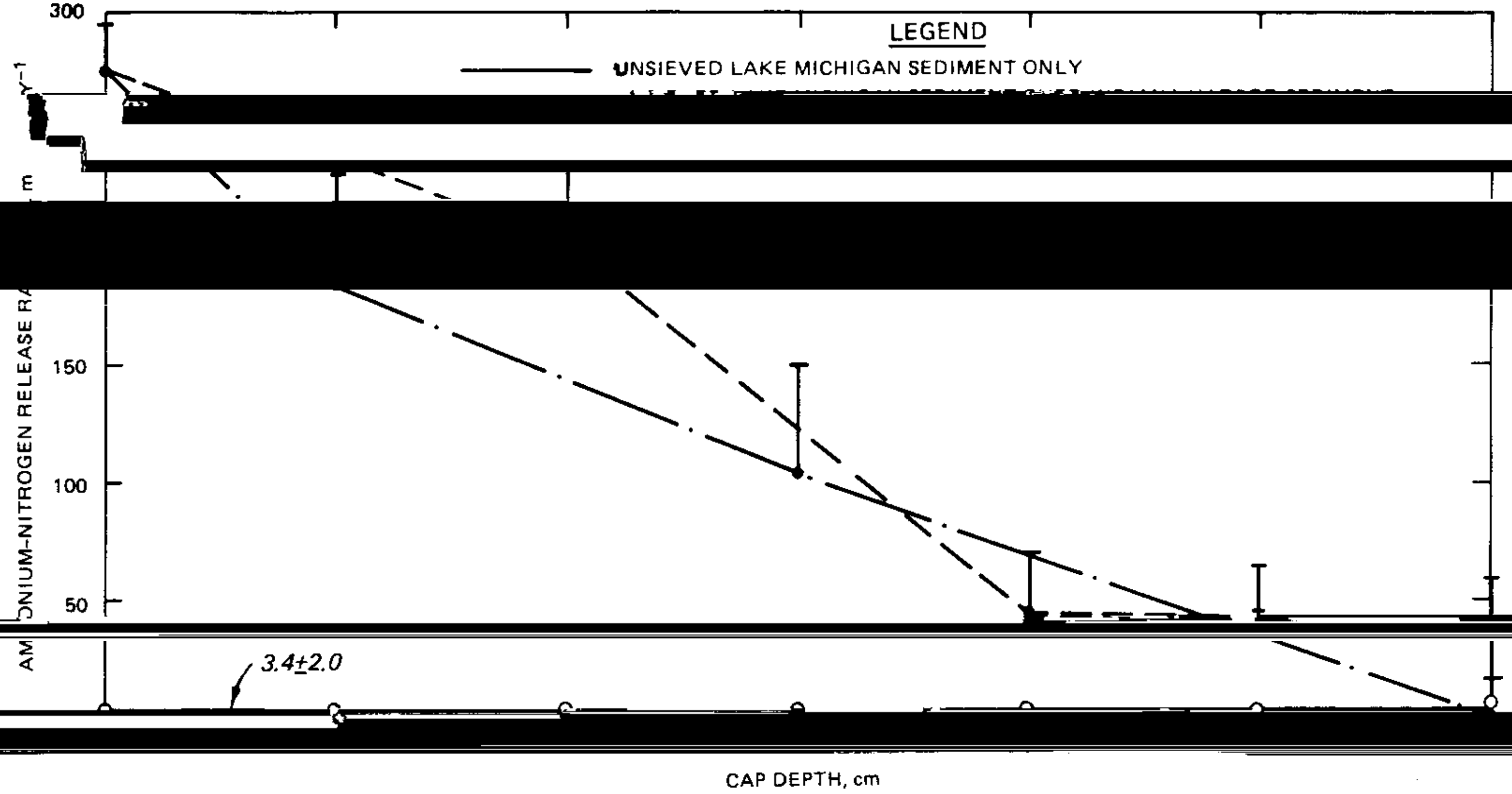

Figure F4. Ammonium-nitrogen release rates

29. There was no significant difference between unsieved and sieved Lake Michigan cap in orthophosphate-phosphorus release rates. Orthophosphate-

[redacted]

respectively (Figure F5).

30. These results demonstrated that the thickness of the Lake Michigan cap, rather than the texture of the sediment, exerted a considerable influence

[redacted]

ness of at least 30 cm appears to be necessary to completely seal Indiana Harbor sediment from the overlying water column with respect to releases of

[redacted]

ments: contaminant release and uptake

[redacted]

cap to isolate Indiana Harbor sediment over a 40-day period. The animals did not suffer excessive mortality in reactor units containing either Lake Michigan sediment only or Indiana Harbor sediment capped with 30 cm of Lake Michigan sediment; 95 percent or more of the animals added initially to the reactor

[redacted]

addition, large numbers of clams were killed in the Indiana Harbor sediment

[redacted]

[redacted]

observation is purely visual. No direct analysis was made of the suspended

[redacted]

tions in the control (Lake Michigan sediment only) unit water columns (Table 5).

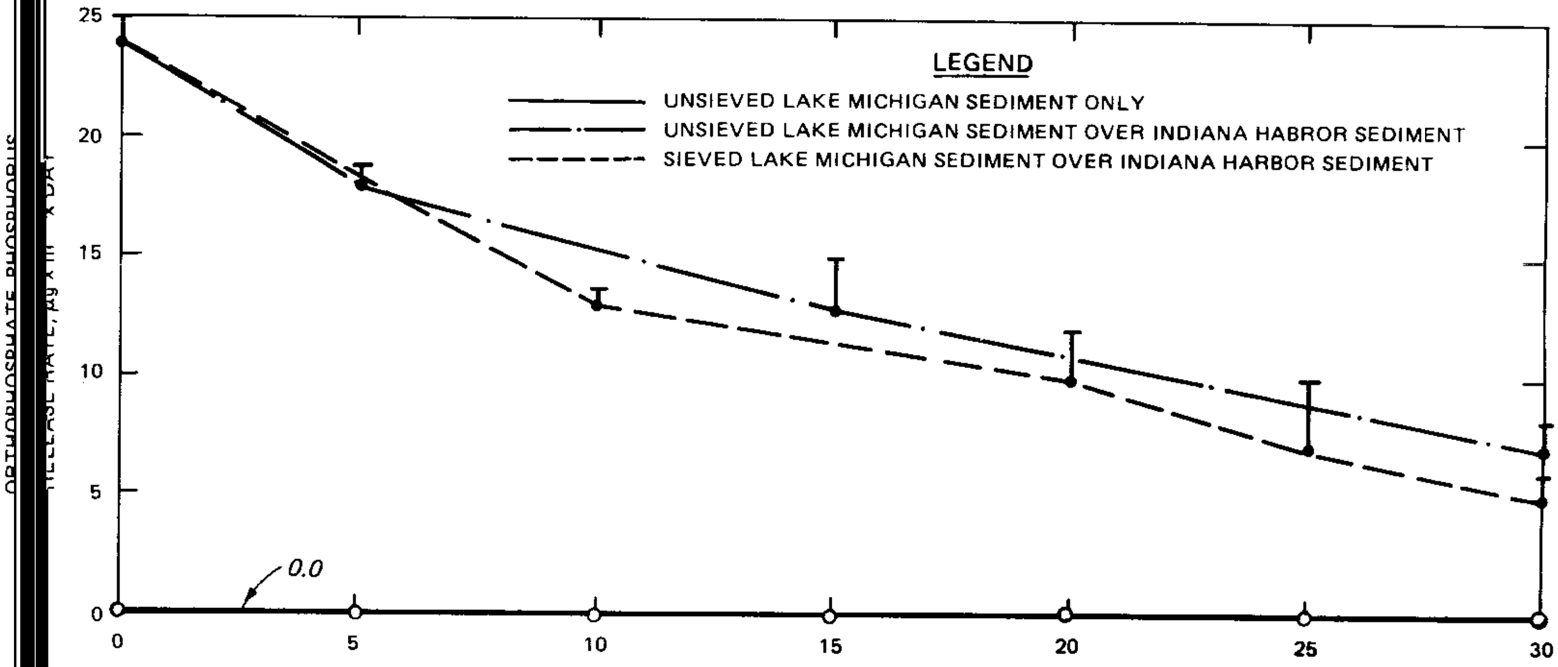

Figure F5. Orthophosphate-phosphorus release rates

Table F5

Heavy Metal Concentrations in the Inflow Water

[redacted]

Treatment	Metal					
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Lake Michigan sediment only (control)	<0.005	0.0002 (0.0001)	<0.001	0.003 (0.003)	<0.0008	<0.030
Indiana Harbor sediment only	<0.005	0.0002 (0.0001)	<0.001	0.003 (0.001)	<0.0008	<0.030
[redacted] with cap	<0.005	0.0001 (0)	<0.003	0.003 (0)	<0.0008	<0.030

---

* Number in parentheses is the standard error of the mean for the value given above it.

** Only one sample taken.

[redacted] column were composited to obtain lower detection limits by increasing the vol- [redacted] of the various treatments are summarized in Table F6. Data for the Lake Michigan sediment caps were below detection limits (1 ng/ℓ). There was no apparent enhancement of water column PAH concentrations compared with the inflow or control in any of the treatments, except for the uncapped Indiana Harbor sediment. This treatment demonstrated elevated concentrations of two-, three-, [redacted] used to obtain detection of these compounds in the water (see footnote to Table F6), no significance can be attached to the levels of these compounds in the water over Indiana Harbor sediment as compared with the other treatments.

34. Water column PCBs. Samples analyzed for the presence of PCB isomer groups in the water column revealed the presence of very low, but detectable, [redacted] inflow water appears to have been in the trichlorobiphenyl and tetrachlorobiphenyl isomer groups. For the three treatments, this is also true for the [redacted] There were significantly higher levels of trichlorobiphenyl and tetrachlorobiphenyls in the Indiana Harbor sediment with cap treatments as compared with [redacted] presented in any of the tables. [redacted] Harbor sediment only treatment where all the crayfish died. Heavy metal con- [redacted]

Table F6

Water Column PAH and Phenol Concentrations (μg/ℓ) in the Inflow Water and Following 40 Days of Incubation in Each of the Treatments*

[redacted]

Class of Compound	Water	Lake Michigan (Control)	Sediment Only	Indiana Harbor Cap
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Three-Ring Compounds	<0.001	<0.001	0.088	<0.001
Four-Ring Compounds	0.005	<0.001	0.058	0.006
Five-Ring Compounds	<0.001	<0.001	0.100	<0.001
Six-Ring Compounds	<0.001	<0.001	<0.001	<0.001
Total PAHs	0.005	<0.001	0.253	0.006

[redacted]

* Values given were obtained by compositing the replicates of each treatment and then concentrating to increase the detectability of the compounds. Since there was only one value for the replicates, there are no associated error terms.

[redacted]

Table F7

Water Column PCB Concentrations (μg/ℓ) in the Inflow Water and Following 40 Days of Incubation in Each of the Treatments*

	[illegible]							
Treatment	1	2	3	4	5	6	7	PCBs
Lake Michigan Sediment Only (Control)	<0.5	0.03	0.01	0.08	<0.01	<0.01	0.01	0.13
		(0.02)	(0.01)	(0.03)			(0)	(0.03)
Indiana Harbor Sediment Only	<0.5	<0.01	<0.01	0.11	0.003	0.01	0.01	0.14
				(0.01)	(0.003)	(0)	(0)	(0.01)
Indiana Harbor Sediment with Cap	<0.5	0.04	0.04	0.19	<0.01	0.003	0.01	0.29
		(0.01)	(0)	(0.03)		(0)	(0)	(0.03)

* Number in parentheses is the standard error of the mean for the value given above it.

** 1 = Monochlorobiphenyl
2 = Dichlorobiphenyl
3 = Trichlorobiphenyl
4 = Tetrachlorobiphenyl
5 = Pentachlorobiphenyl
6 = Hexachlorobiphenyl
[illegible]

Table F8

Heavy Metal Concentrations in Crayfish Tissue (μg/g wet weight) With No Treatment and Following 40 Days of Incubation in Each of the Treatments*

Treatment	Metal					
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted] (Control)	0.075	0.047	0.416	0.200	<0.0081	18.5
	(0.004)	(0.009)	(0.049)	(0.030)		(0.1)
Indiana Harbor sediment only	NO CRAYFISH SURVIVED THIS TREATMENT					
Indiana Harbor sediment with cap	0.117**	0.013	0.335	0.177	<0.0037	20.5
	(0.007)	(0.004)	(0.013)	(0.012)		(1.8)

[redacted]

** Significantly different from the control.

[redacted] (controls) following 40 days of exposure. The only exception was arsenic; in this case, arsenic concentration in the Indiana Harbor with cap treatment significantly exceeded the level of the Lake Michigan sediment only sample.

36. Crayfish PAHs and phenol. Data for PAHs and phenol are presented in Table F9. There was no significant difference between the mean values for any [redacted]

37. Crayfish PCBs. Data for PCBs are presented in Table F10. Because [redacted] There were minimal accumulations of PCBs in the control and none in the sediment plus cap treatments; PCB levels in these two treatments did not differ [redacted]

[redacted] sented in Table F11. Enough clams in the Indiana Harbor sediment only treatment survived through 10 days to obtain the numbers necessary for chemical [redacted] remaining for analysis; no replicates were available for comparison. There was no significant difference in the levels of metals accumulated by clams in any of the three treatments at 10 days. The trend at 40 days suggests larger accumulations of metals in the Indiana Harbor sediment only treatment than in [redacted]

39. Clam PAHs and phenol. After 10 days of incubation, clam tissue in the Indiana Harbor sediment treatment acquired higher concentrations of three- [redacted] (Table F12). Both the Indiana Harbor only and the capped treatments had significantly less accumulation of phenol than the control. At 40 days, there

Table F9

PAH and Phenol Concentrations in Crayfish Tissue (μg/g wet weight) With No Treatment and Following 40 Days of Incubation in Each of the Treatments*

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Two-ring compounds	0	0.026 (0.008)	N O N	0.039 (0.018)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Four-ring compounds	0	0.016 (0.006)	S U R	0.028 (0.021)
Five-ring compounds	0	0.121 (0.083)	V I V E D	0.094 (0.005)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Phenol	0.565	0.356 (0.130)		0.678 (0.208)

---

* Number in parenthesis is the standard error of the mean for the value given above it.

Table F11

[redacted]

Treatment (If Appropriate)	Metal					
	As	Cd	Cr	Pb	Hg	Zn
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Lake Michigan sediment only (control)						
10 days	0.133	0.224	0.168	0.120	<0.0010	10.2
	(0.011)	(0.018)	(0.033)	(0.021)		(1.2)
40 days	0.077	0.145	0.144	0.103	<0.0012	7.8
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Indiana Harbor sediment only						
10 days	0.128	0.145	0.156	0.113	<0.0010	8.4
	(0.024)	(0.022)	(0.018)	(0.014)		(1.2)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Indiana Harbor sediment with cap						
10 days	0.134	0.189	0.191	0.133	<0.0015	10.0
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

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* Number in parentheses is the standard error of the mean for the number [redacted]

** Only clams from IH-5 survived for 40 days in numbers large enough to permit [redacted]

Table F12

PAH and Phenol Concentrations in Clam Tissue (μg/g wet weight)

[redacted]

	Treatment 10 days			
Class of Compound	None	Lake Michigan Sediment Only (Control)	Indiana Harbor Sediment Only	Indiana Harbor Sediment With Cap
Two-ring compounds	0	0.024	0.033	0.045
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
		(0.117)	(0.238)	(0.274)
Six-ring compounds	0	0.020 (0.020)	0.139 (0.112)	0
Total PAHs	0.236	0.418 (0.088)	2.660** (0.830)	0.572 (0.234)
Phenol	0	0.062 (0.032)	0**	0**

(Continued)

[redacted]

above it.

** Significantly different from the control.

Table F12 (Concluded)

Class of Compound	Treatment 40 days None	Lake Michigan Sediment Only (Control)	Indiana Harbor Sediment Only	Indiana Harbor Sediment With Cap
Two-ring compounds	0	0.005 (0.003)	0.011†	0.010 (0.004)
Three-ring compounds	0.042	0.060 (0.020)	0.405	0.020 (0.007)
Four-ring compounds	0.020	0.060 (0.050)	1.500	0.006 (0.002)
Five-ring compounds	0.174	0.060 (0.017)	2.190	0.065 (0.027)
Six-ring compounds	0	0	0.694	0
Total PAHs	0.236	0.515 (0.304)	4.800	0.102 (0.019)
Phenol	0	0	0.057	0

[redacted]

associated error term.

was no significant difference between the control and the capped treatments

Table F13 Michigan

PCB Concentration in Clam Tissue (µg/g wet weight)

[redacted]

	PCB Isomer Group (Number of Chlorine Atoms/Group)**							Total
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted] sediment only (control)								
10 days	<0.5	0	<0.01	<0.01	<0.01	<0.01	<0.01	<0.5
40 days	<0.5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.5
Indiana Harbor sediment only								
10 Days†	<0.5	0.04 (.01)	0.04 (0)	0.14 (.02)	0.06 (0)	0.06 (0)	<0.01	0.34 (.04)
40 Days††	<0.5	0.03 (0)	0.06 (0)	0.26 (.02)	0.12 (0)	0.14 (0)	<0.01	0.62
Indiana Harbor sediment with cap								
10 days	<0.5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.5
40 days	<0.5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.5

---

* Number in parentheses is the standard error of the mean for the value given above it.

† Samples from IH-1 were lost during analytical laboratory processing.

†† Only clams from IH-1 and IH-5 survived in numbers large enough to analyze.

** 1 = Monochlorobiphenyl
2 = Dichlorobiphenyl
3 = Trichlorobiphenyl
4 = Tetrachlorobiphenyl

[redacted]

[redacted] only treatment for analysis of any of the metals; the few fish that remained were saved for analyses for PAHs, phenols, and PCBs.

42. Fish PAHs and phenol. When compared with the time 0 values, fish [redacted] late large amounts of two-, three-, four-, and five-ringed compounds and total PAHs (Table F15). Sufficient fish for chemical analyses survived in only one [redacted] fact that the capped treatment showed significantly less accumulation of four-ringed compounds than the control while demonstrating a significantly greater accumulation of five-ringed compounds. There was no significant difference in the total PAH levels accumulated, nor in the amount of phenol in these treatments.

43. Fish PCBs. Data on PCB isomer group levels in fish tissue for the various treatments are shown in Table F16. As was true for the PAHs and phe- [redacted] primarily from isomers with two chlorine substituents and secondarily from isomers with from three to six chlorine substituents, the latter isomers being approximately equally distributed in all fish in the control and capped sediment treatments.

Discussion

44. Results of this study demonstrated that capping can isolate contami- [redacted] isms. This conclusion is based on observations on the death of the animals in [redacted]

45. There was a large amount of variability associated with the bioaccu- [redacted] *Nereis virens*, *Mercenaria mercenaria*, and *Palaemonetes pugio*. It is highly probable that much of the variability observed represents differences in

Table F14

Heavy Metal Concentrations in Fish Tissue (µg/g wet weight) With No Treatment and Following 40 Days of Incubation in Each of the Treatments*

[redacted]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Lake Michigan sediment only	[redacted]					
Indiana Harbor sediment only	NOT ENOUGH FISH SURVIVED THIS TREATMENT TO PERMIT [redacted]					
[redacted] sediment with cap	0.086 (0.034)	0.017 (0.003)	0.678 (0.186)	0.117 (0.061)	<0.0190	36.1 (1.6)
[redacted]						

* Number in parenthesis is the standard error of the mean for the value given above it.

Table F15

PAH and PHENOL Concentrations in Fish Tissue (μg/g wet weight) With No Treatment and Following 40 Days of Incubation in Each of the Treatments*

		Treatment		
Class of Compound	None	Lake Michigan Sediment Only (Control)	Indiana Harbor Sediment Only **	Indiana Harbor Sediment With Cap
Two-ring compounds	0	0.031 (0.017)	0.101	0.066 (0.059)
Three-ring compounds	0	0.280 (0.101)	2.310	0.240 (0.121)
Four-ring compounds	0	0.272 (0.015)	0.355	0.158† (0.018)
Five-ring compounds	0	0	0.170	0.054† (0.034)
Six-ring compounds	0	0	0	0
Total PAH	0	0.583 (0.268)	2.929	0.515 (0.367)
Phenol	0	0	0	0

---

* Number in parentheses is the standard error of the mean for the val [illegible]

the values given have no associated error terms.

[illegible]

Table F16

[redacted]

Treatment	PCB Isomer Group (Number of Chlorine Atoms/Group)** 1	2	3	4	5	6	7	Total PCBs
None	<0.5	0.02	0.02	0.04	0.03	<0.01	<0.01	0.11
Lake Michigan sediment only (control)	<0.5	0.17	0.05	0.05	0.04	0.03	<0.01	0.35
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Indiana Harbor sediment only†	<0.5	0.02	0.03	0.13	0.04	0.04	<0.01	0.25
Indiana Harbor sediment with [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

* Number in parentheses is the standard error of the mean for the value

[redacted]

4 = Tetrachlorobiphenyl
5 = Pentachlorobiphenyl
6 = Hexachlorobiphenyl
7 = Heptachlorobiphenyl

† Only fish from IH-1 survived in numbers large enough for analysis.

exposure conditions caused by crayfish activity among the chambers. For example, the die-off rates of both fish and clams were observed to decrease in the [redacted] control and the Indiana Harbor with cap treatments, bioturbation activity by crayfish at the cap surfaces had a winnowing effect. The finer silt particles [redacted]

[redacted]

Cap effectiveness

46. Clam tissue analysis and water column chemical data showed that the 30-cm cap of Lake Michigan sediment generally served as an effective barrier [redacted]

or may not have been as severe as that normally encountered in the field. Crayfish are among the most severe bioturbators of the sediment surface. How- [redacted] sediments. Among the normal benthic residents of the Great Lakes are *Hexagenia* [redacted] tory, particularly in months other than the late spring. The freshwater benthic macroinvertebrate *Stylodrilus heringianus* also occurs in the Great Lakes [redacted] (Krezoski, Robbins, and White 1984). Another benthic organism found in the Great Lakes is the freshwater oligochaete *Tubifex tubifex*; this organism has

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* Personal communication, R. C. Aller, Department of Geophysical Sciences, University of Chicago).

[redacted]

extent as in marine and estuarine environments, where many examples of the effects of bioturbation have been reported. For example, Rhoads, McCall, and Yingst (1978) reported that polychaetes observed recolonizing a dredged material disposal site in Long Island Sound were *Streblospio benedictii*, *Capitella* [redacted]

1979, Davis 1980). The data of Davis (1980) showed that the largest 1- to 2-year-old *Nephtys* (0.6 g wet weight) burrowed to a depth of approximately [redacted]

greater depths (at least 50 cm) than the smaller polychaete species. In these studies, bioturbation was observed to be much greater than would be expected [redacted]

to capping operations so that the contaminated dredged material truly can be [redacted]

tion, a 5-cm cap appeared to be generally effective in preventing the movement [redacted]

showed that simply isolating organisms (fish) from contact with contaminated sediment with a 1-mm mesh screen significantly reduced PCB body burdens compared with organisms allowed to contact the sediment. In the work reported here, once the crayfish in the reactor units containing Indiana Harbor sediment [redacted] of the water column, and the mortality rates of the fish and clams in the [redacted]

Thickness and relative effectiveness of cap material

[redacted] Brannon, et al. (1985, 1986) found that cap materials with higher proportions of clay and silt were more effective in preventing the movement of contaminants into the overlying water and biota than sand. This enhanced effectiveness [redacted] sand sealed Black Rock sediment with a 54-percent solids content from the [redacted] prevent formation of an effective cap. These authors stressed the importance of closely examining the engineering properties of a dredged material and proposed cap material prior to capping to determine their compatibility. These observations are of particular relevance to the study presented here because our attempts to achieve a 30-cm cap in the large column studies were opposed by the tendency of the Lake Michigan cap material to sink into the underlying [redacted] 1986). The effects that strong compaction have on dissolved oxygen depletion rates and other biological and chemical phenomena are unknown.

[redacted]

project will have to be carefully monitored to ensure that the recommended cap [redacted] the aquatic environment. Morton and Miller (1980) reported that a sand cap was found to be physically more stable than a silt cap--trends apparently [redacted] effectiveness.

Summary and Conclusions

[redacted] ammonium-nitrogen and orthophosphate-phosphorus from Indiana Harbor sediment [redacted] did not significantly alter these results. A 30-cm cap of Lake Michigan sedi- [redacted] was found to be extremely toxic to aquatic life, particularly in the presence of bioturbation. Some of the benthic fauna indigenous to the Great Lakes region have been reported to burrow as deep as 10 to 15 cm. Therefore, it is [redacted]

APPENDIX G: LEACHATE TESTING RESULTS

Introduction

1. Bottom sediments contaminated with organic matter, heavy metals, [illegible] for environmental protection, a prime requirement is information on potential [illegible] protocol capable of predicting, or even approximating, leachate quality from confined dredged material disposal sites. Testing procedures to predict leachate quality are, therefore, needed to fully evaluate the confined disposal alternative for Indiana Harbor dredged material. [illegible] and quantity can be predicted, the potential impacts of CDF disposal of contaminated dredged material can be evaluated, allowing the most cost-effective site design to be utilized.

Objectives and Approach

3. The objectives of this study were twofold. The primary objective was to assess the leaching potential of Indiana Harbor sediment. Since standard [illegible] were not available, a supporting objective was to develop, evaluate, and apply [illegible]

4. The technical approach used in this study was based on recommenda- [redacted] tests with a mass transport equation. Comparison of predicted and observed column effluent quality is the basis for evaluating the processes that govern [redacted]

Materials and Methods

5. Upon arrival at the US Army Engineer Waterways Experiment Sta- [redacted] in a covered enclosure (open to the air) at ambient temperatures. At least once each week the sediment was thoroughly stirred to expose fresh sediment to the air. When necessary, distilled-deionized water was added to the sediment to prevent it from completely drying out. At the end of 6 months the sediment was removed from the aquaria, placed in a 115-ℓ mortar mixer, and thoroughly mixed for 2 hr. The sediment was then refrigerated at 4 °C until used for aerobic leachate testing.

6. Two types of leachate tests were conducted, batch and column tests [redacted] systems. The test procedures and a protocol for integrating the results from the batch and column tests are described below.

Batch testing

7. **Kinetic tests.** In this report kinetic testing refers to a series of [redacted]

Table G1

Experimental Sequence for Determining Appropriate Shaking Times in Indiana Harbor Kinetic Testing

STEP 1	Place sediment in appropriate centrifuge tube (stainless steel or polycarbonate), and sufficient deoxygenated-distilled water to maintain water-to-sediment ratio of 4:1.
STEP 2	Place centrifuge tubes horizontally on shaker and shake at 160 cycles per minute.
[redacted]	[redacted] 96 hr for metals.
[redacted]	[redacted] for organics. Repetition of Step 4 using clean centrifuge tubes is necessary for leachate for organic analyses.
STEP 5	Filter centrifuged, deoiled leachate through 0.45-μm pore size membrane filters for metals and through a Whatman GF/D glass fiber prefilter and a Gelman AE glass fiber filter of 1 μm nominal pore size.
STEP 6	Acidify leachate for organic analysis with HCL and leachate for metals with Ultrex nitric acid. Store leachate for organic analysis in acetone-rinsed glass bottles and leachate for metals analysis in plastic bottles.

Note: The test sequence was carried out twice for metals. The tubes were shaken vertically the first time and horizontally the second time. Centrifuge [redacted]

8. For kinetic testing of metals, triplicate 250-ml polycarbonate cen-

[redacted]

box under a nitrogen atmosphere. Sufficient centrifuge tubes were loaded to allow sampling, in triplicate, at 6 hr, 24 hr, 48 hr, 72 hr, and 96 hr. Samples were placed upright on a mechanical shaker and shaken at 160 cycles per minute for the allotted time. Three tubes were then removed from the shaker

[redacted]

rinsed centrifuge tubes were loaded with sufficient sediment and deoxygenated, distilled-deionized water to obtain a 4:1 water-to-sediment dry weight ratio.

[redacted]

then passed through acetone-rinsed glass wool, and recentrifuged in clean cen-

[redacted]

acidification with 1 ml of concentrated HCl to prevent iron precipitation and scavenging of organic contaminants from solution. Samples were then stored in the dark in acetone-rinsed 2-ℓ glass bottles until analyzed.

10. Liquid-solids ratio testing. Following determination of the shake

[redacted]

continued for 5 days. Fresh deoxygenated, distilled-deionized water was added to each 500-ml centrifuge tube to replace the leachate removed for analysis. [illegible] aerobic sediment leachate was used to challenge anaerobic sediment.

15. [illegible] ferently from metals testing in that the challenge testing of fresh sediment was not conducted concurrently. Twelve centrifuge tubes were loaded with equal amounts of either anaerobic or aerobic sediment and equal amounts of distilled-deionized water to obtain a 4:1 liquid-solids ratio. The tubes were then sealed and shaken horizontally for 24 hr at 160 cycles per minute, then centrifuged and filtered as previously described for the kinetic tests. The only modification consisted of adding the small amount of glass wool used in the prefiltering step to trap oil back to the centrifuge tube prior to addition of fresh distilled [illegible] from the sediment. As discussed later, the oil contains a sizable portion of the organic contaminants associated with Indiana Harbor sediment. These tests were conducted using both anaerobic and aerobic sediment. Tests with anaerobic sediment were conducted in a nitrogen atmosphere. A subsample of filtered leachate was set aside from both the anaerobic and aerobic tests for analysis of total organic carbon. In each case, the leachate was replaced with [illegible] ously described. This cycle was repeated five times.

16. Anaerobic/anaerobic leachate challenge testing for organic contaminants was conducted separately as shown in Table G3, but could not be replicated because of equipment limitations. [illegible] and organic contaminant analysis were obtained by centrifugation of the Indiana Harbor sediment. To obtain samples for metals from anaerobic Indiana [illegible] gen atmosphere. The centrifuge tubes were then centrifuged at 9,000 × g for 30 min, and the supernate filtered in a nitrogen atmosphere through 0.45 [illegible]

Table G3

Test Sequence for Sequential Batch Leaching and Challenge Testing

[redacted]

STEP 1 Load sediment into appropriate centrifuge tubes: 500 ml polycarbonate for metals and 450 ml stainless steel for organic contaminants. Add sufficient water to each tube to bring final water-to-sediment ratio to 4:1. Sufficient stainless steel tubes [redacted]

STEP 3 For half of the leachate, carry through steps 4 and 5 in Table G2, setting aside a small amount of leachate prior to acid- [redacted] for organic contaminants. Carry these centrifuge tubes through steps 2 through 5 in Table G2.

STEP 4 Return to step 2 after replacing leachate removed in the initial [redacted]

[redacted]

pore size membrane filters following passage through acid-washed glass wool to

[redacted]

that all steps in the operation were conducted without a nitrogen atmosphere.

[redacted]

steel centrifuge tubes. For separation of interstitial water from anaerobic Indiana Harbor sediment, six tubes were loaded with sediment, then centrifuged for 30 min at 6,500 × g. The supernate was then passed through acetone-rinsed glass wool, and recentrifuged in clean centrifuge tubes to remove residual

[redacted]

Gelman AE glass fiber filter with a nominal pore size of 1.0 μm. All steps in

[redacted]

Column testing

19. *Loading and operation.* Column leaching tests were conducted in

[redacted]

pressurized operation (Figure G1). The bottom ring divides flow, separating

[redacted]

allow sample collection in a reasonable period.

20. Permeameter tests were run to simulate leaching of anaerobic and aerobic sediment, prepared as previously described. Because of the large leachate volume needed to conduct organic analyses (1 ℓ), separate permeameter tests were run for metals and organic analysis. Each test was run in tripli-

[redacted]

metals, anaerobic organics, aerobic metals, and aerobic organics.

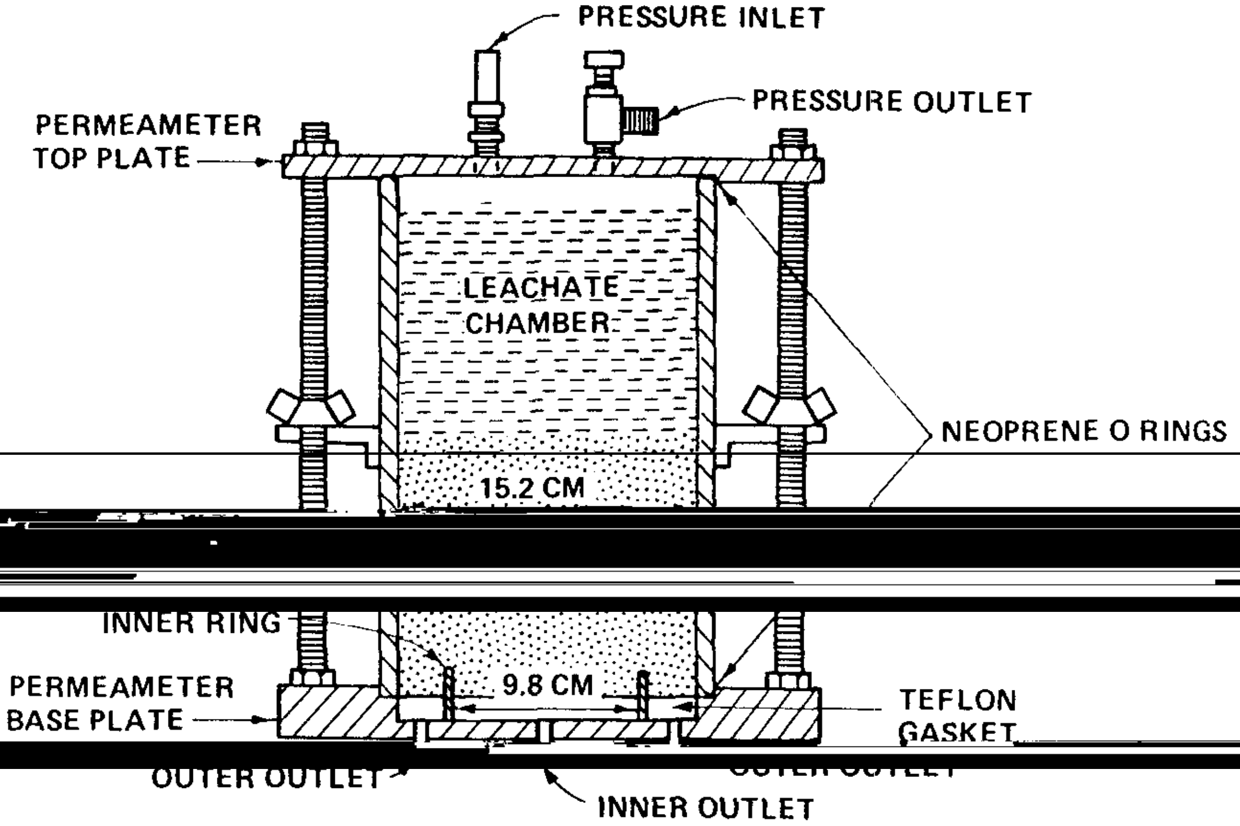


Figure G1. Divided-flow permeameter used for continuous-flow column test

21. Indiana Harbor sediment was loaded into the permeameters in several lifts each having an average thickness of 5 cm, the number of lifts added depended on the target column height. As each lift of water-saturated sediment was added, the permeameter was vigorously agitated on a vibrating table to remove trapped air. The weight and height of each lift was measured and

[redacted]

was placed in the permeameters used for organic testing because the volume of sample required for organic analysis is greater than that required for metals

[redacted]

ing the weight and volume of sediment added to the permeameter, then measuring the weight and volume of a separate sediment sample before and after oven drying at 105 °C; weight loss upon drying was then equated to the volume of water in the permeable voids. The pore volume in each permeameter was then calcu-

[redacted]

the permeameters: the apparatus was sealed and pressurized with either nitro-

[redacted]

permeameters during testing. Leachate from all three permeameter outlets was

[redacted]

23. Flow from the permeameters were regulated by adjusting the operating pressure. The permeability of the sediment decreased for the first week of operation. As permeability decreased, operating pressure was increased until a maximum value of 172 kPa (25 psig) was reached in all permeameters. A daily

[redacted]

determination were obtained from slices made along the vertical axis of the core. Moisture content was determined by oven drying at 105 °C. The ratio of initial moisture content to final moisture content was used to calculate the final porosity of the sediment.

[redacted]

organic contaminants and dissolved organic carbon.

26\. Leachate samples for metals and organic contaminants from anaerobic sediment were filtered in a nitrogen atmosphere using procedures previously [redacted] pH using a combination electrode and a millivolt meter, and for conductivity using a Yellow Springs Instrument Company conductivity meter and cell.

[redacted]

D_p, was determined by operating a separate permeameter using anaerobic sediment and distilled-deionized water containing bromide as a tracer (constant concentration = 1,000 mg/ℓ). Effluent samples were collected periodically, [redacted] that dispersion is small, i.e., $D_p/VL < 0.01$. The term D_p/VL is a dimensionless ratio, termed the dispersion number, that characterizes the amount of [redacted]

Chemical analysis

28\. Leachate and sediment samples were analyzed for concentrations of selected congeners (PCBs) of Aroclor 1248, PAHs, and heavy metals (arsenic, cadmium, chromium, lead, zinc, and mercury). Specific organic contaminants [redacted] Florosil cleanup, and quantification in either a Hewlett Packard 5985A gas chromatograph/mass spectrophotometer equipped with a flame ionization detector

Table G4

Organic Compound Identification Key

No.	Compound	No.	Compound
1.	Napthalene	16.	2,4'-dichlorobiphenyl
2.	Acenaphthalene	17.	2,4,4'-trichlorobiphenyl
3.	Acenapthene	18.	2,3',4',5-tetrachlorobiphenyl
4.	Fluorene	19.	2,2',4,5'-tetrachlorobiphenyl
5.	Phenanthrene	20.	2,2',5,5'-tetrachlorobiphenyl
6.	Anthracene	21.	2,2',4,6-tetrachlorobiphenyl
7.	Fluoranthene	22.	2,2',3',4,5-pentachlorobiphenyl
8.	Pyrene	23.	2,2',4,5,5'-pentachlorobiphenyl
9.	Chrysene	24.	2,2',3,4,5'-pentachlorobiphenyl
[redacted]	[redacted]	[redacted]	[redacted]
14.	Benzo (ghi) perylene	29.	2,2',3,4,4',5,5'-heptachlorobiphenyl
15.	2,4-dichlorobiphenyl	30.	Total arochlor 1248 congeners

(PAHs) or a Hewlett Packard 5880A gas chromatograph equipped with an electron capture detector (PCBs). Concentrations of PAH and Aroclor 1248 congeners in leachate samples following methylene chloride extraction were determined on [redacted] MHC-10 hydride generator. Leachate samples and digested sediment samples were analyzed for cadmium, chromium, and lead using a Perkin-Elmer Model 5000 [redacted] dures (Ballinger 1979).

Theoretical Basis for Leachate Quality Prediction

Design basis for batch and column leaching tests

[redacted]

Grove and Stollenwerk 1984):

[redacted]

where

C = aqueous phase contaminant concentration, mg/ℓ

t = time, sec

ρ = bulk density, kg/ℓ

θ = porosity, dimensionless

q = solid phase contaminant concentration, mg/kg

[redacted]

V = average pore water velocity, cm/sec

[redacted]

The derivation of this equation is based on a balance of mass fluxes into and

[redacted]

nant, the second term represents convective transport (bulk flow). The first term on the left-hand side, sometimes referred to as the accumulation term,

[redacted]

reactive term, represents interphase transfer of contaminant from the sediment

[redacted]

standard procedures have not been developed for quantifying the contaminant source term for dredged material. The primary objective of the laboratory tests performed in this study was to provide an accurate description of the source term for Indiana Harbor sediment.

[redacted]

term. The second step is quantification of the coefficients in the mathemati-

[redacted]

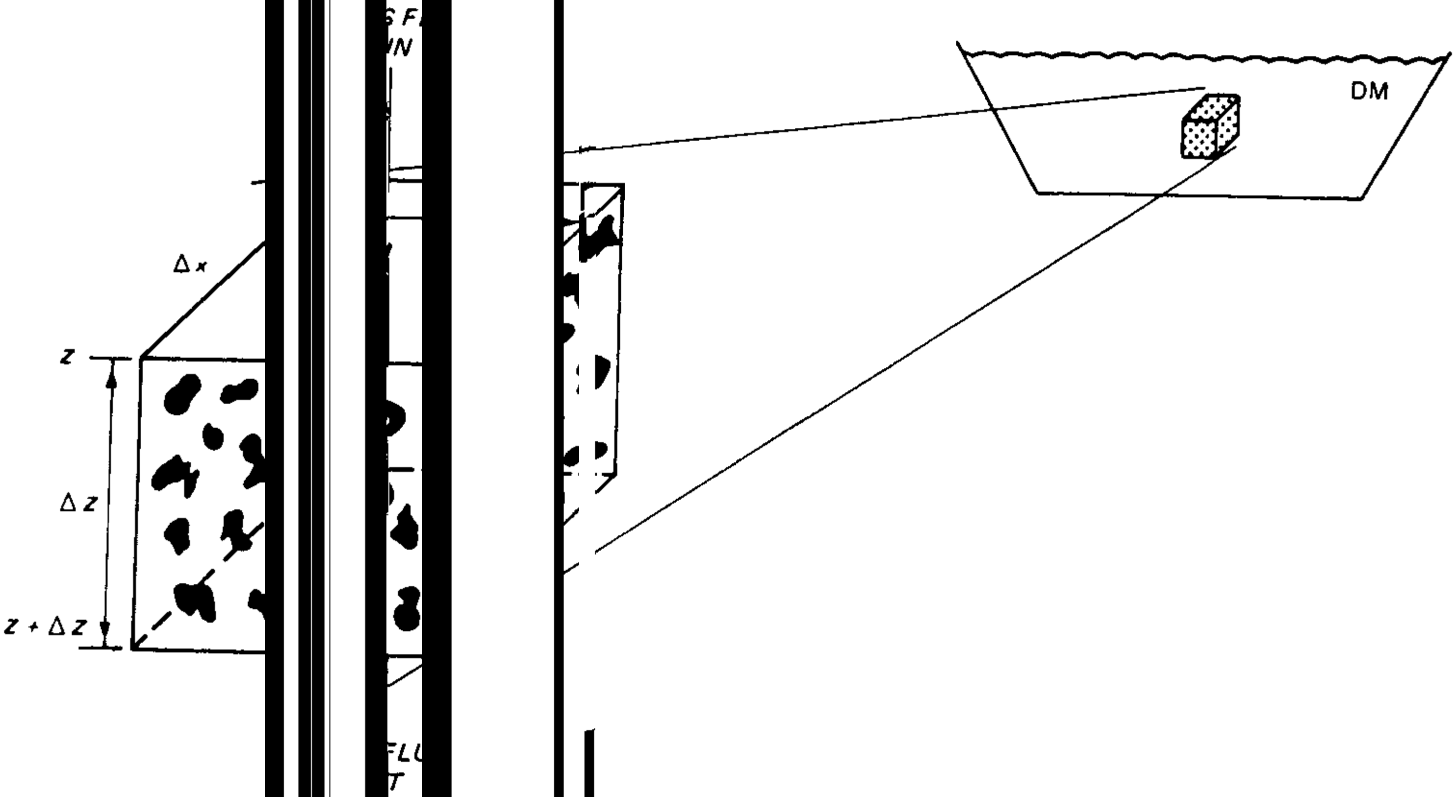


Figure G2. R at n for dredged material in a confined disposal facility

[redacted]

cess, and the source term for interphase transfer can be formulated as equi-

[redacted]

Stollenwerk 1984):

$$(\partial C/\partial t) + (\rho K_d/\theta)\ (\partial C/\partial t) = D_p(\partial^2 C/\partial z^2) - V(\partial C/\partial z) \qquad \text{(G2)}$$

where K_d is the distribution coefficient, ℓ/kg. The leach tests described

[redacted]

[redacted]

32. A first-order kinetic equation for a reversible reaction at the sedi-

[redacted]

$$dq/dt = -K_F q + K_R C \qquad \text{(batch)} \qquad \text{(G3a)}$$

$$\partial q/\partial t = -K_F q + K_R C \qquad \text{(continuous flow)} \qquad \text{(G3b)}$$

where K_F and K_R are the forward and reverse reaction rates, respectively. If the percolation of water through the sediment is slow in relation to the

[redacted]

solids-water interface approaches steady-state as the reaction proceeds to equilibrium. For steady-state conditions, Equations G3a and G3b can be written as follows:

$$q = K_d C \qquad \text{(G4)}$$

[redacted]

$$q = K_d C + q_r \qquad \text{(G5)}$$

[redacted]

continuous flow system, q and C at any point do not remain constant over time but change as percolating water leaches contaminants. Applying Equa-

[redacted]

$$\partial q/\partial t = K_d\ (\partial C/\partial t) \qquad \text{(G6)}$$

Equation G6 describes a local, linear equilibrium at the sediment solids-water interface in a continuous flow system. Substitution of Equation G6 into Equation G1 yields Equation G2.

33. Equation G5 is the basis of design for the sequential batch leaching tests, described earlier. By sequentially leaching a portion of sediment with

[redacted]

34. As shown in Figure G3, the difference between the initial sediment contaminant concentration

[redacted]

know if the isotherm goes through the origin. If it does not, then evaluation of the leaching potential on the basis of bulk sediment concentration can be seriously misleading.

35. The isotherm intercept q_r has a direct bearing on how K_d should be determined. For q_r equal to zero, one other point on the isotherm is all that is required to compute K_d. Distribution coefficients are frequently determined using the batch equilibrium method, i.e., without sequential leach-

[redacted]

its slope, since q_r is not known prior to conducting the leach test. Thus, a slope-derived K_d does not require assumptions regarding q_r. Sequential batch leaching tests provide multipoint isotherms from which slope-derived K_d and q_r values can be obtained by fitting the isotherm data to Equation G5.

into

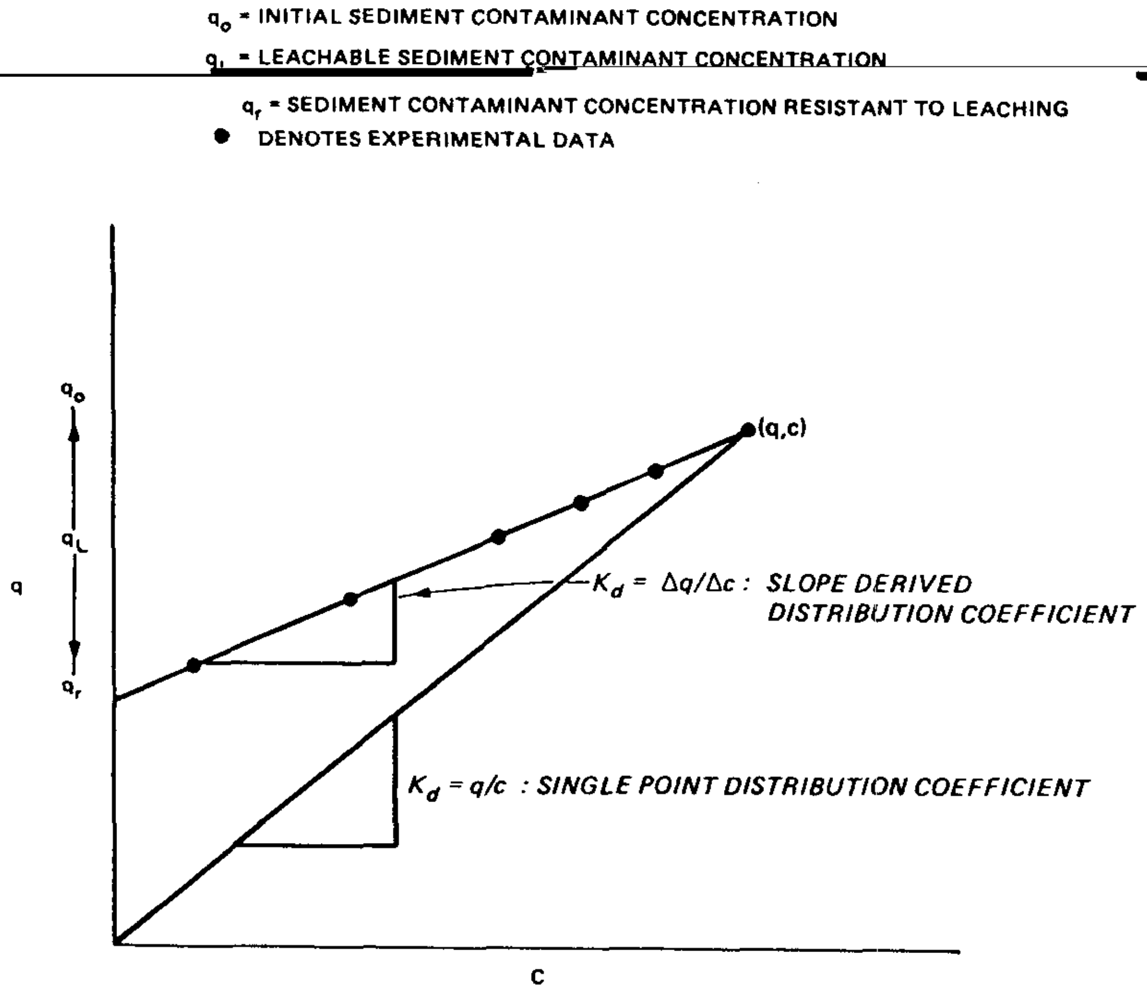


Figure G3. Ideal desorption isotherms for slope-derived and single-point distribution coefficients

The difference between single-point and slope distribution coefficients is illustrated in Figure G3.

36. The above discussion presents the basic theory behind the development and use of the sequential, batch leach tests for Indiana Harbor sediment. It [redacted] dredged material the contaminant concentration in the leachate over time is determined not only by the source term but also by the effects of dispersion [redacted] interface in a shake test is higher than that in a continuous-flow system and can affect interphase transfer.

37. In a column test, film effects can be an important factor that inhibits interphase transfer (Grove and Stollenwerk 1985). In a continuous-flow [redacted] [redacted] [redacted] that coefficients determined in batch tests can be used to describe the source term in continuous flow systems, data from continuous flow laboratory columns are needed.

Integrated approach

38. As previously stated, the integrated approach consists of using results from batch leach tests, column leach tests, and Equation G2 to test the hypothesis that contaminant leaching from Indiana Harbor sediment can be described as equilibrium-controlled, linear desorption. Application of the [redacted]

39. Before Equation G2 can be used to predict permeameter leachate quality as a function of volume throughput (time), specific parameters are

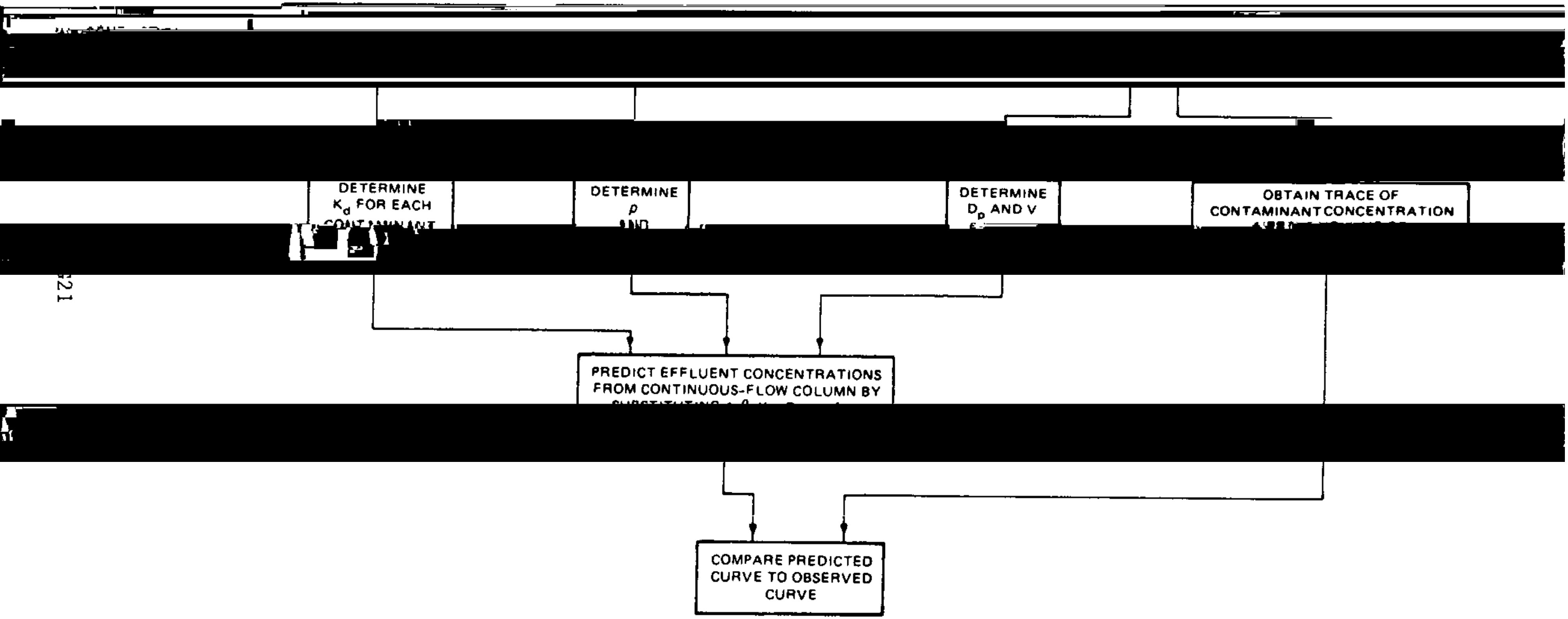


Figure G4. Schematic of integrated approach for examining the source term required. These include porosity and bulk density (obtainable from standard soils tests) and average pore water velocity (obtainable from column operating records). In addition, dispersion in the permeameters must be measured. Distribution coefficients and the initial pore water contaminant concentrations are evaluated independently of the column. Distribution coefficients are

[redacted]

[redacted]

volume of water passing through the dredged material. An analytical solution to this equation for equilibrium-controlled, linear desorption is presented below (Ogata and Banks 1961).

$$C(z,t) = C_I + (C_o - C_I)\ 0.5\ \mathrm{erfc}\ \frac{Rz - Vt}{2(DRt)^{0.5}} + 0.5\ \exp\frac{Vz}{D}\ \mathrm{erfc}\ \frac{Rz + Vt}{2(DRt)^{.5}} \qquad \text{(G7)}$$

[redacted]

C_o = contaminant concentration in the water entering the sediment, mg/ℓ, equal to zero for the test procedures used in this study

$R = 1 + \frac{\rho K_d}{\theta}$ = retardation coefficient, dimensionless

[redacted]

[redacted]

$$\partial C/\partial z\ (\infty,t) = 0$$

41. If test procedures are free from error, the solution obtained from Equation G7 should agree with observed effluent concentrations from the permeameters. Thus, the integrated approach can be used to verify the mathematical form of an assumed source term. If the predicted and observed effluent

curves agree, it may be concluded that transfer of contaminant from the dredged material solids is adequately described as equilibrium-controlled, linear desorption. If not, other source term formulations can be tried. Once a reasonable description of contaminant transfer has been found, a planning

[redacted]

in part, dependent on the hydrodynamic properties of the continuous-flow system (Valocchi 1985).

The role of the distribution coefficient

[redacted]

$$C_I = q_L/K_d \tag{G8}$$

where q_L is the leachable solid phase contaminant concentration (mg/kg). This equation assumes that the contaminant is distributed or partitioned between sediment solids and aqueous phases such that the chemical potentials in the two phases are equal, i.e., the sediment-pore water system is at equilibrium. Equation G8 shows that the higher K_d, the lower the initial water phase contaminant concentration.

[redacted]

or C_I can be estimated using Equation G8 if K_d is known and is not equal to zero.

44. The value of K_d also affects the shape of the curve predicted by Equation G7. The higher K_d, the longer the initial concentration will tend [redacted] sediment concentration q_L, is graphed as a function of pore volume for two values of K_d. As shown, the initial concentration is lower for the higher K_d. However, this concentration tends to persist while the leachate concentration for the lower value of K_d washes out. When K_d is equal to zero, the leachate concentration theoretically drops to zero once the initial pore water has been displaced.

[redacted] readily apparent. For high distribution coefficients, the leachate concentration is essentially constant. For low distribution coefficients, the flux [redacted]

Table G4. Specific congeners of Aroclor 1248 were analyzed and reported [redacted] aroclors). Congeners were selected for quantitation based on their preponderance in Aroclor 1248, the major PCB source of contamination in Indiana Harbor sediment. Metal concentrations in Indiana Harbor sediment and interstitial water are presented in Table G5. The sediment contained low concentrations of mercury, but high concentrations of zinc, lead, copper, and chromium. The total organic carbon concentration was 7.39 percent sediment dry weight. Oil and grease analysis was 3.88 percent sediment dry weight. In previous work, sediment samples from Indiana Harbor Canal contained from 2.8 to 4.4 percent [redacted]

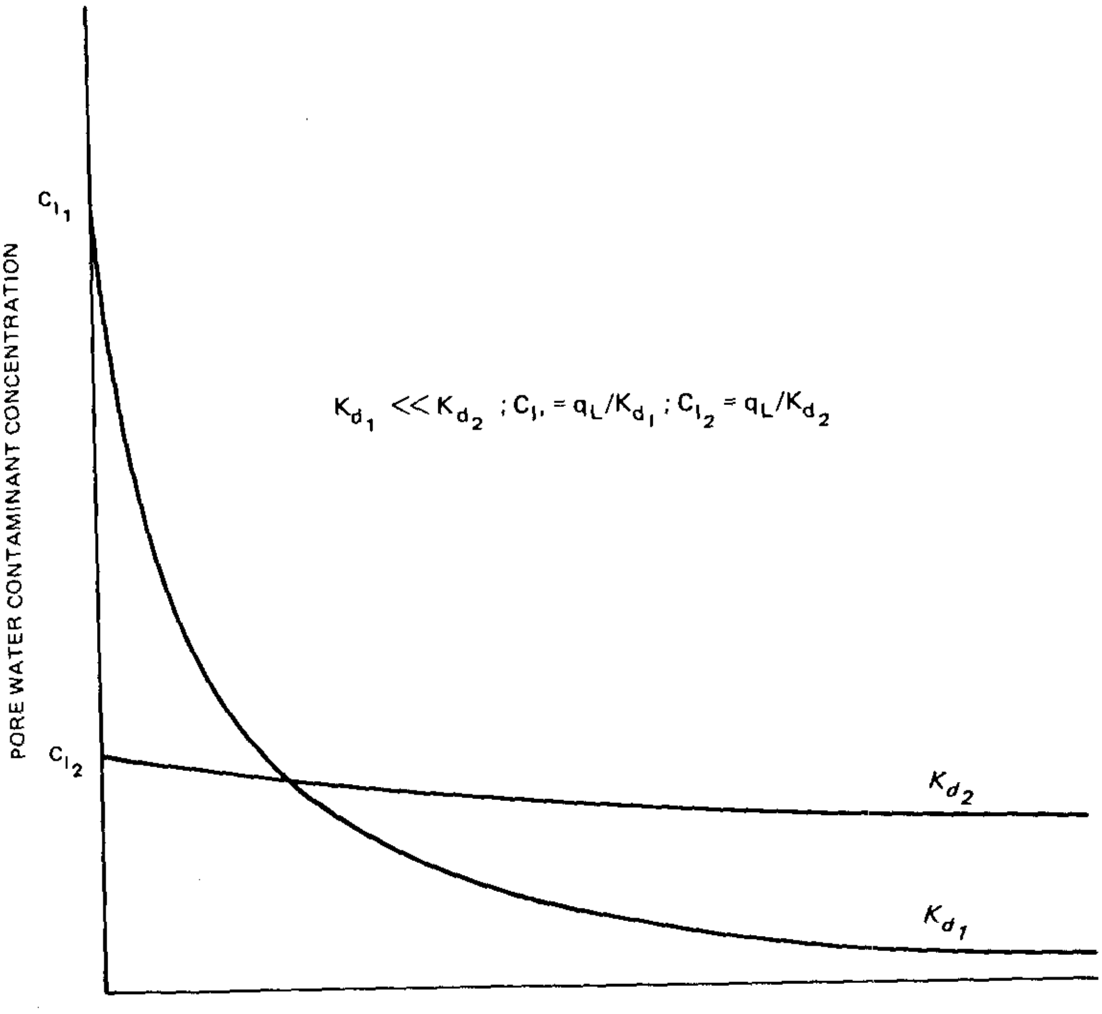


Figure G5. Dependency of contaminant persistence on k_d

Table G5

Metal Concentration in Indiana Harbor Sediment and Interstitial water (standard error)

Metal	*Sediment, $\mu g/g$*	*Interstitial Water, $\mu g/\ell$*
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
Mercury	0.5	

[redacted]

When the anaerobic sediment was centrifuged, oil was separated from the sediments. As shown in Table G6, oil separated from anaerobic Indiana Harbor [redacted] concentrations were correlated with total sediment concentration (r = 0.983, $P < 0.01$), indicating that the oil was a primary repository of organic contam- [redacted] Misleadingly high batch leachate organic contaminant concentrations would [redacted]

sured before and after 6 months of wet exposure to air are presented in [redacted] concentration was noted in aerobic sediment compared with anaerobic sediment.

49. A thorough analysis of the processes involved in the losses noted above was beyond the scope of this study. However, a brief discussion of the implications may be useful. Volatilization and biological degradation are two [redacted] processes that could have been responsible for the reduction in PAH and PCB concentrations, volatilization is probably the process primarily responsible. Under the passive aeration that was provided, aerobic biological processes occurred, but at a limited rate. Further, PAHs and PCBs are toxic compounds that are biodegraded slowly. Volatilization of organic compounds from moist sediment depends on Henry's Law constant and can be significant if the Henry's Law constant is high, as is the case with PAHs and PCBs. The fact that PCBs [redacted]

Table G6

Oil and Sediment Organic Contaminant Concentration

[redacted]	Anaerobic Sediment Contaminant Concentration in Oil from Anaerobic [redacted]	Anaerobic Sediment Contaminant [redacted]	Aerobic Sediment Contaminant [redacted]
1	1,165	2,000	81.9
2	33	22	<7
3	155	96	10.8
4	115	69	11.6
5	278	200	35.5
6	77	62	12.8
7	197	150	63.45
8	177	140	85.2
9	73	92	42.8
10	90	86	30.9
11	101	140	64.7
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
16	4.3	10.8	0.13
17	17.5	19.5	2.14
18	27.0	31.9	5.24
19	7.8	3.5	1.14
20	35.0	19.5	6.99
21	17.5	19.3	2.14
22	4.55	5.2	0.94
23	1.55	1.7	<0.00001
24	4.9	5.7	0.87
25	2.6	3.7	0.59
26	1.3	2.2	0.36
27	<0.002	<0.002	<0.002
28	11.5	12.4	2.30
29	1.85	1.98	0.31

* See Table G4.

environmental media, where as often as not Henry's Law constant determines volatility (Mackay et al. 1983).

50. The losses shown in Table G6 are not indicative of the volatilization that would occur in a CDF. The Indiana Harbor sediment used for aerobic leachate analysis was kept moist, and turned weekly for 6 months. This may represent a gross exaggeration of conditions at the surface layer in an upland [redacted]

[redacted]

Indiana Harbor sediments which were air dried without rewetting for plant uptake experiments (Appendix D) showed less volatile loss of PAHs than occurred from moist sediments and no loss of PCBs.

Kinetic batch testing

51. Kinetic testing was performed to determine shake time necessary to [redacted]

gated. Kinetic and shaking procedure results for metals are presented in [redacted]

24 hr, after which no significant changes were observed. No release of mer- [redacted]

[redacted]

metals. In cases where the metal concentration decreased when shaken longer [redacted]

[redacted]

Table G7

[redacted]

hr	As	Zn	Cd	Pb	Hg
6	8 (1)	480 (170)	5 (2)	80 (30)	<2
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
48	12 (10)	890 (510)	10 (2)	100 (60)	<2
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
96	12 (2)	850 (450)	7 (5)	140 (60)	<2

Table G8

Metal Concentrations in Anaerobic Indiana Harbor Sediment Leachate as a Function of Horizontal Shaking time [μg/ℓ (standard error)]

[redacted]

Time [redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

Table G9

Summary of Indiana Harbor Organic Contaminant Kinetic Testing Data [µg/ℓ (standard error)]

Compound	Time of Shaking, days		
	1	2	7
1	ND	ND	ND
2	ND	ND	ND
3	1.9 (0.85)	ND	ND
4	3.4 (2.1)	ND	ND
5	ND	ND	ND
6	2.6 (1.7)	ND	ND
7	3.3 (2.0)	11 (1.7)	8 (3.5)
8	8 (3.5)	7 (2.3)	8 (1.4)
9	3 (0.07)	4 (0.6)	3 (0.7)
[illegible]	[illegible]	[illegible]	[illegible]
14	ND	ND	ND
15	ND	ND	ND
16	0.09 (0)	0.07 (0.04)	0.1 (0.06)
17	0.28 (0.007	0.25 (0.03)	0.38 (0.16)
18	0.44 (0.02)	0.35 (0.05)	0.21 (0.11)
19	0.10 (0.0)	0.10 (0.003)	0.25 (0.09)
20	0.28 (0.007)	0.24 (0.003)	0.50 (0.01)
21	0.28 (0.007)	0.25 (0.03)	0.38 (0.16)
[illegible]	[illegible]	[illegible]	[illegible]
24	0.08 (0.007)	0.06 (0.003)	0.10 (0.04)
25	0.08 (0.005)	0.04 (0.01)	0.07 (0.04)
26	0.02 (0.01)	ND	ND
27	ND	ND	ND
28	0.22 (0.02)	0.19 (0.0[illegible]	0.28 (0.14)
29	0.05 (0.007)	0.02 (0.01)	0.05 (0.01)
30	2.04 (0.10)	1.63 (0.17)	2.42 (0.49)

52. Centrifuge tubes shaken horizontally showed increased reproducibility (smaller coefficients of variation) between replicates for leachate metal concentration when compared with leachate obtained by shaking the sediment- water mixture in a vertical position (Table G10). The increase in reproducibility [redacted]

53. Batch leaching tests were also conducted to determine the minimum liquid-solids ratio that could be used in the sequential batch leach tests. [redacted] appropriate at another if the liquid-solids ratios differ by orders of magnitude. The liquid-solids ratio is approximately 1:1 for unconsolidated dredged material in a CDF after sedimentation. To be a practical laboratory proce- [redacted] sufficient magnitude to produce enough leachate for organic contaminant analy- [redacted] the comparison of single-point distribution coefficients for the interstitial water-sediment system with those for water-sediment mixtures at the 2:1 and higher liquid-solids ratios. Indiana Harbor sediment is highly contaminated with oil and grease--so much so that a separate oil phase was obtained during [redacted]

55. The effect of the liquid-solids ratio on single-point distribution [redacted] interstitial water system were generally higher than those obtained using higher liquid-solids mixtures, a result of higher metal concentrations in the

Table G10

[redacted]

24	2.7	2.6	15.5	24.2	100.0	9.2	60.0	27.0
48	16.7	8.0	100.0	40.6	30.0	26.0	60.0	40.6
72	15.4	3.2	50.0	27.1	50.0	7.7	40.0	27.1

Note: Coefficients of variation are given only where direct comparisons can be made (24-, 48-, and 72-hours sampling times).

Table G11

Single-Point Heavy Metal Distribution Coefficients [ml/g (standard error)] for Anaerobic Indiana Harbor Sediment at Various Water to Sediment Ratios

Ratio	As	Cd	Cr	Pb	Zn
2:1	648 (87)	2,377 (127)	2,700 (300)	2,721 (985)	3,179 (560)
4:1	767 (41)	3,603 (239)	9,500 (4000)	4,133 (971)	5,752 (139)
8:1	901 (60)	2,913 (393)	4,700 (1000)	5,110 (1084)	4,681 (827)

leachate than in the interstitial water. A similar situation was found for [illegible] single-point distribution coefficients for the aerobic sediment (Table G12). These differences were probably a result of the high oil and grease content of the sediment, as discussed below.

56. The effects of oil in the sediment on the distribution of metals between sediment and interstitial water have not been documented. But, since the interstitial water tests did not involve shaking, it is highly probable [illegible] concentrations to be low relative to leachate concentrations at the other [illegible]

57. The variability of the single-point distribution coefficients for most metals, for both anaerobic (Table G11) and aerobic (Table G12) sediment, was high. This was a function of the high sediment contaminant concentration and the low levels of heavy metals measured in the leachate. For example, if a parameter has an equilibrium sediment concentration of 1,000 µg/g dry weight sediment, and the leachate concentration is 0.003 µg/ml, the distribution coefficient would be 333,333. If the leachate concentration were 0.002 µg/ml, however, the distribution coefficient would rise to 500,000. There is, therefore, an apparent high degree of variability in the single-point [illegible]

[illegible]

water concentrations in Table G13, however, are the result of analysis of a single sample. Preparation of this sample required nine separate centrifugations in stainless steel centrifuge tubes at 6,500 g for 30 min to completely break the oil dispersion. It is, therefore, possible that organic contaminant losses through volatilization and adsorption occurred during the repeated handling. Due to the difficulty in obtaining this sample and the opportunities present for contaminant losses, interstitial water concentrations for organic contaminants are suspect.

Table G12

Single-Point Heavy Metal Distribution Coefficients (ml/g

[redacted]

Ratio	As	Cd	Cr	Pb	Zn
Interstitial	2369	<2,000,000*	73600	128600	17700
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
2:1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	(60)	(12140)	(3600)	(4070)	(6240)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

* indicates minimum value of single-point distribution coefficient based on [redacted]

Table G13

Steady-State Leachate Concentrations [ng/ml(standard error)]

[redacted]

Compound	Ratio 1:1*	2:1	4:1	8:1	12:1.
1	<5	<5	1230 (260)	<5	<5
2	<5	<5	5.5 (8)	10 (0.8)	11 (0.00)
3	12	7.5 (1.4)	16 (2)	30 (1)	26 (0.8)
4	1.1	4 (3)	10 (1)	19 (1)	14 (1.4)
5	3.9	8.7 (4)	20 (2)	25 (0.8)	15 (0.4)
6	<5	5.0 (0.5)	3.7 (0.6)	5 (0.0)	3 (0.2)
7	19	16 (4)	9.3 (1.8)	12 (0.4)	6 (0.2)
8	16	13 (2.5)	9.2 (2)	8 (0.6)	5 (0.1)
9	10	8 (0.5)	3.1 (2)	6 (0.1)	<3
10	8	7 (0.7)	3 (1)	5 (0.3)	<3
11	9	7 (0.6)	<5	6 (0.4)	<5
12	<5	<5	<5	<5	<5
13	<5	<5	<5	<5	<5
14	<5	<5	<5	<5	<5
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
21	<0.01	0.40 (0.08)	0.18 (0.03)	<	<0.01
22	0.04	0.07 (0.004)	0.08 (0.01)	0.06 (0.01)	0.05(0.02)
23	<0.01	<0.01	<0.01	<0.01	<0.01
24	0.04	0.07 (0.01)	0.05 (0.01)	0.04 (0.01)	0.03 (0.00)
25	0.03	0.04 (0.00)	0.04 (0.02)	0.06 (0.04)	0.03 (0.01)
26	0.01	0.02 (0.00)	0.03 (0.006)	0.02 (0.00)	0.02 (0.008)
27	<0.01	<0.01	<0.01	<0.01	0.01
28	0.09	0.17 (0.02)	0.10 (0.02)	0.09 (0.01)	0.07 (0.01)
29	0.01	0.02 (0.00)	0.02 (0.00)	0.04 (0.01)	0.03 (0.01)

* Interstitial water extraction

59. Leachate concentrations in the 4:1 liquid-solids ratio tests were generally similar to those obtained in the 2:1 liquid-solids ratio testing for all contaminants. For example, single-point distribution coefficients for anaerobic and aerobic metals at the 4:1 liquid-solids ratio were within the standard error of those measured using a 2:1 liquid-solids ratio. It was, therefore, found appropriate to use a 4:1 water-to-sediment ratio for the sequential batch and challenge leach testing. This was the highest water to sediment ratio tested that was deemed operationally suitable from the [illegible] and, therefore, would not be expected in the leachate in a field situation.

[illegible] during both the anaerobic and aerobic testing (Table G14). Leachate from aerobic sediments was generally lower in conductivity than that from anaerobic sediments initially, but the situation was reversed by the end of the leaching period. Challenging fresh anaerobic sediment with leachate from either anaerobic or aerobic sediment increased the conductivity in the leachate.

61. Leachate pH from anaerobic sediment ranged from 7.4 to 7.6 with only a slight drop as leaching continued (Table G15). Challenging anaerobic sediment with leachate from anaerobic sediment did not result in any marked changes in leachate pH. Leachate from aerobic sediments was approximately one pH unit lower than leachate from anaerobic sediment. Challenging fresh anaerobic sediment with leachate from aerobic sediment lowered the pH of leachate [illegible] leachate. This difference in pH between anaerobic and aerobic leachate was not of a magnitude sufficient to cause pronounced differences in metal solubility.

62. Metal releases sequential batch leach tests. The steady-state sediment q and leachate C metal concentrations obtained from the sequential [illegible]

Table G14

Conductivity (μmhos/cm) in Indiana

Aerobic	1038 (64)	585 (20)	495 (3)	398 (3)	495 (3)
Aerobic Challenged	1678 (35)	840 (30)	585 (6)	550 (3)	550 (13)

Table G15

Serial Batch Leachate pH [mean (standard error)] for Indiana Harbor

Test	Time, days 1	2	3	4	5
Anaerobic	7.6 (0.03)	7.6 (0.03)	7.5 (0.03)	7.5 (0)	7.4 (0.03)
Anaerobic Challenged	7.6 (0.05)	7.6 (0)	7.5 (0.03)	7.4 (0.03)	7.2 (0)
Aerobic	6.6 (0.03)	6.6 (0)	6.7 (0.03)	6.6 (0.03)	6.8 (0.03)
Aerobic Challenged	7.0 (0)	6.8 (0.03)	6.6 (0.03)	6.7 (0)	6.7 (0)

Table G16

Steady-State Sediment and Leachate Concentrations [mean (standard error)] for Indiana Harbor Sediments

Following Anaerobic Sequential Leaching

Time days	Concentration				
	As	Cr	Pb	Cd	Zn
	Sediment, μg/g				
1	29.36 (0.01)	281.18 (0.14)	877.45 (0.34)	19.96 (0.0006)	4119.8 (1.0)
2	29.28 (0.02)	280.91 (0.12)	876.78 (0.32)	19.94 (0.007)	4117.3 (0.9)
3	29.23 (0.02)	280.85 (0.12)	876.64 (0.35)	19.93 (0.02)	4116.3 (1.2)
4	29.17 (0.02)	280.83 (0.12)	876.59 (0.35)	19.92 (0.02)	4115.8 (1.2)
	[illegible]				
1	0.034 (0.002)	0.195 (0.031)	0.370 (0.08)	0.009 (0.001)	1.27 (0.22)
2	0.020 (0.001)	0.062 (0.012)	0.156 (0.04)	0.004 (0.0006)	0.60 (0.14)
3	0.016 (0.002)	0.014 (0.002)	0.033 (0.01)	0.004 (0.003)	0.22 (0.06)
4	0.012 (0.001)	0.005 (0.001)	0.011 (0.001)	0.001 (0.003)	0.12 (0.02)

Table G17

Steady-State Sediment and Leachate Concentrations [mean (standard error)] for Indiana Harbor Sediment Following Aerobic Sequential Leaching

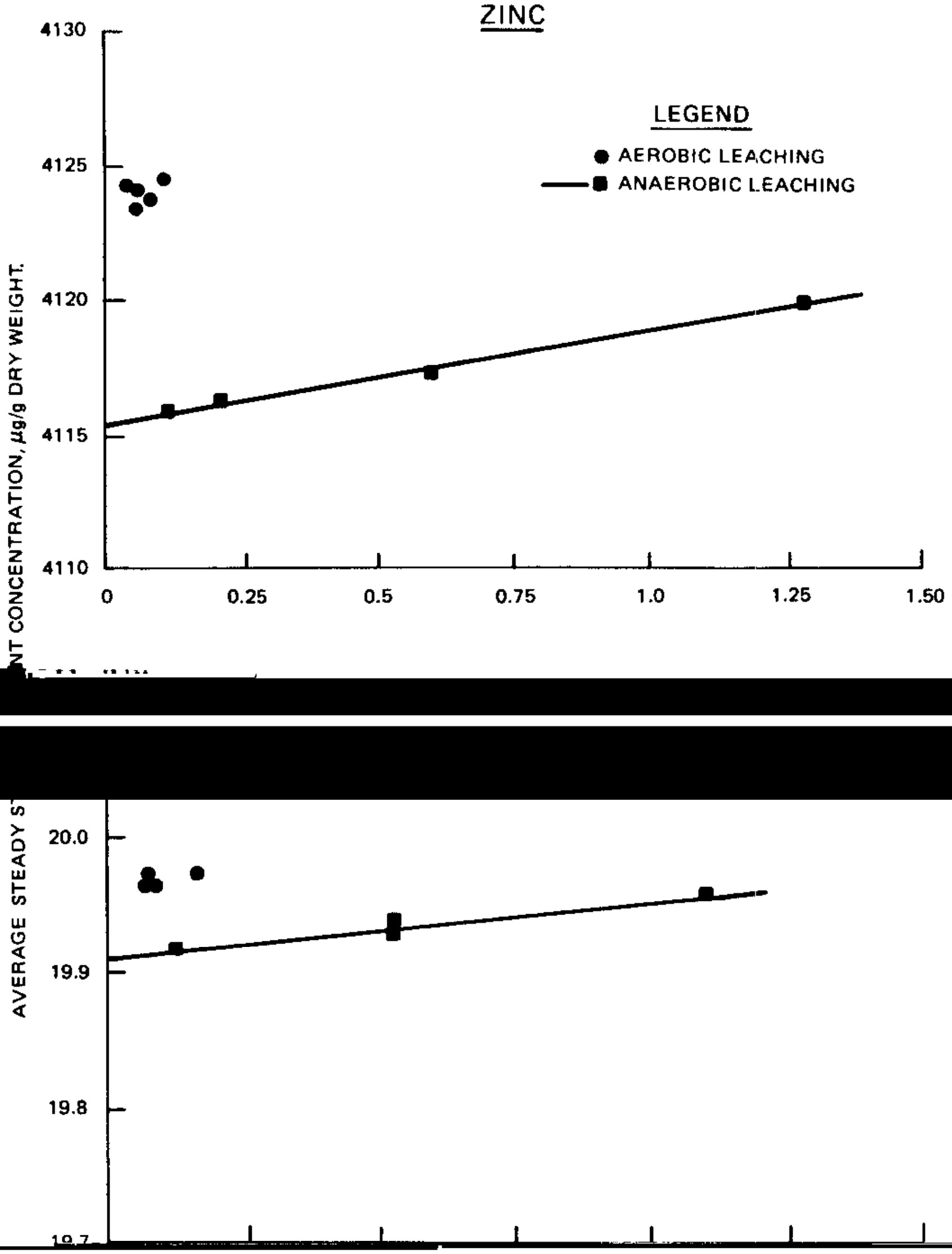
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
1	29.5 (0.00)	281.98 (0.00)	878.97 (0.005)	19.98 (0.006)	4124.5 (0.06)
2	29.48 (0.00)	281.96 (0.003)	878.93 0.006)	19.97 (0.008)	4124.32 (0.06)
3	29.45 (0.003)	281.91 (0.01)	878.89 (0.007)	19.97 (0.008)	4124.05 (0.05)
4	29.42 (0.004)	281.87 (0.02)	878.81 (0.02)	19.97 (0.007)	4123.71 (0.02)
5	29.39 (0.003)	281.85 (0.02)	878.78 (0.02)	19.97 (0.007)	4123.47 (0.02)
			Leachate, μg/ml		
1	<0.005 (0.00)	0.004 (0.0003)	0.009 (0.001)	0.006 (0.002)	0.126 (0.016)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted] (0.0009)	[redacted] (0.002)	[redacted] (0.002)	[redacted] (0.002)	[redacted] (0.005)
4	0.006 (0.0007)	0.01 (0.002)	0.019 (0.004)	0.0007 (0.0001)	0.085 (0.014)
5	0.009 (0.004)	0.006 (0.002)	0.055 (0.0009)	0.0006 (0.00008)	0.061 (0.008)

[redacted]

desorption of metals under anaerobic conditions is compared in Figures G6-G8 to the ill-defined clusters observed for metal desorption from the aerobic sediment. [illegible] Indiana Harbor sediment is high in iron concentration. Under aerobic conditions, these and other sediments were observed to fix both native and added antimony in more immobile sediment iron fractions (Brannon and Patrick 1985). Similar fixation processes for heavy metals were apparently active during the 6 months that Indiana Harbor sediment was exposed to air. Thus, exposure to air decreased the mobility of metals under aerobic leaching conditions.

63. In order to examine the assumption that the release of metals is governed by linear desorption, the values of q and C obtained from sequential batch leach tests were regressed onto Equation G5. The results are presented [illegible] replicate data for each contaminant were not pooled, and each experimental [illegible] determined by least squares analysis are presented in Tables G18 and G19 along with supporting statistics.

64. With one exception (cadmium), the regression coefficients for the anaerobic sediment are high, indicating good fit. The probability that the values for the distribution coefficients in Table G18 result by chance is small. Thus, the regression statistics support the assumption that the release of metals from anaerobic Indiana Harbor sediment is governed by linear desorption (Equation G5). In addition, it should be noted that 99 percent or more of the bulk sediment metal concentrations was resistant to leaching. [illegible] for zinc and cadmium were highly clustered. Thus, the release of metals from the aerobic sediment did not follow a well-defined desorption isotherm similar to the anaerobic results. The regression statistics in Table G19 showed that Equation G5 is not a satisfactory model for the aerobic metal data due to poor fit. The fit was poor as indicated by the r^2 values because the data were clustered. For clustered desorption isotherms, meaningful values for K_d and



[redacted]

[redacted]

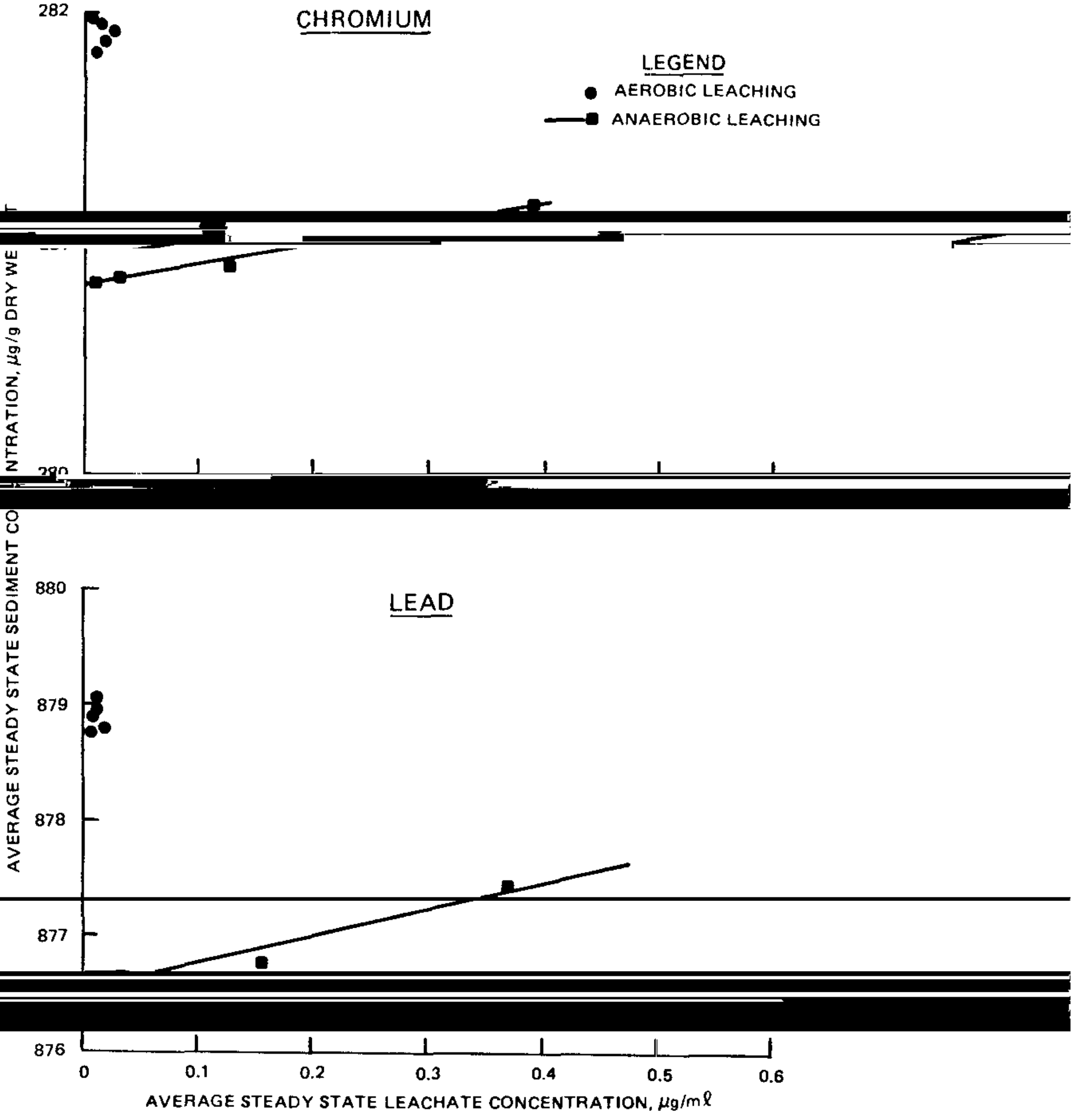
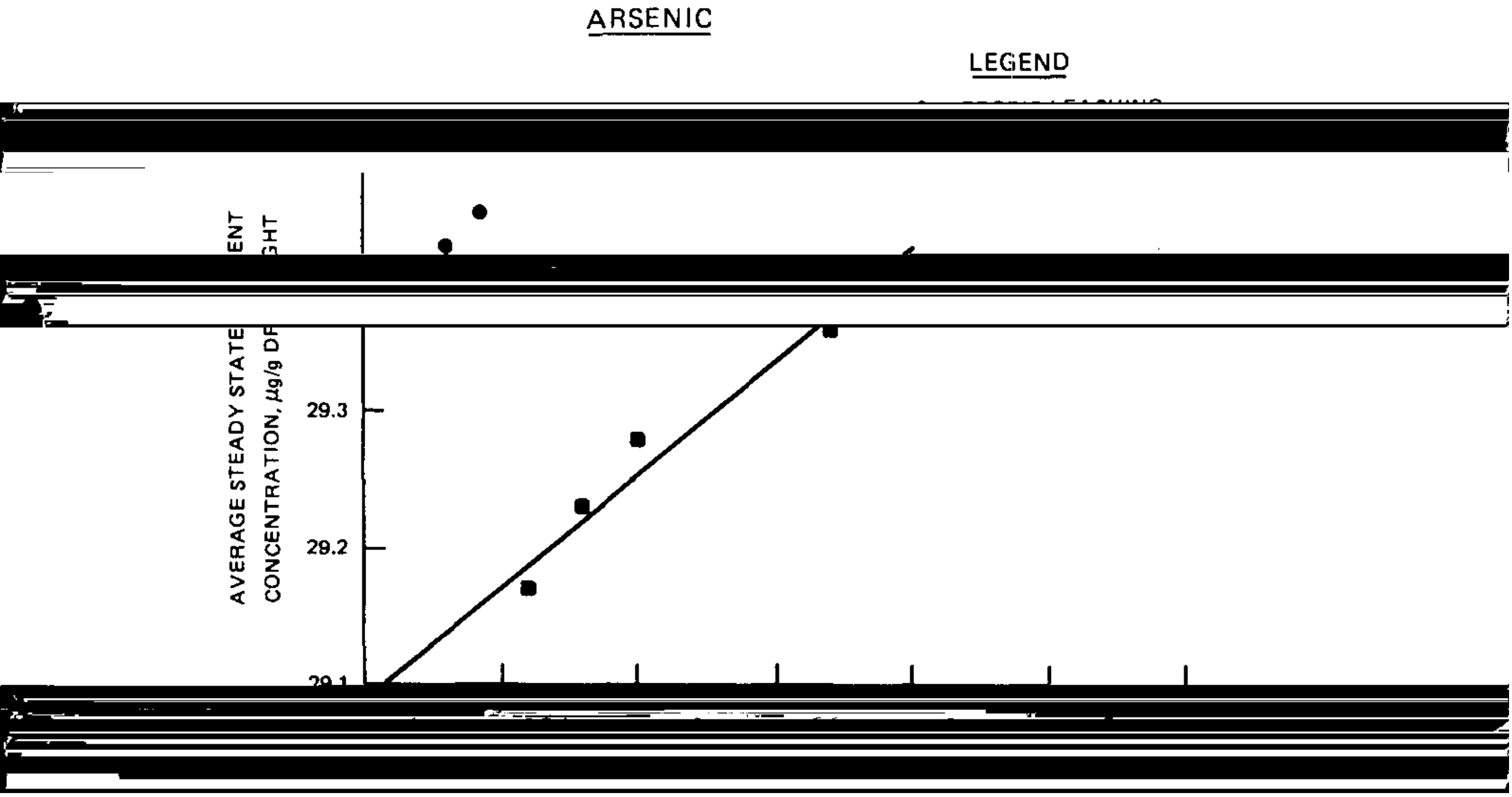


Figure G7. Desorption isotherm for lead and chromium in Indiana Harbor sediment



'Figure G8. Desorption isotherms for arsenic in Indiana Harbor sediment

Table G18
Linear Regression of q versus C for Sequential Batch Leaching of Metals From Anaerobic Indiana Harbor Sediment*

Metal	Replicate	n	r^2	K_d ℓ/kg	SE ℓ/kg	Ave. K_d ℓ/kg	q_r mg/kg	q_r/q_o %
Arsenic	1	4	0.898	7.47	1.77		29.1	98.8
	2	4	0.83	8.21	2.61	7.46	29.1	99.0
	3	4	0.95	6.70	1.01		29.1	98.8
Cadmium	1	4	0.63	3.30	1.76		19.94	99.7
	2	4	0.82	2.17	0.73	2.86	19.94	99.7
	3	4	0.214	3.10	4.20		19.89	99.4
Chromium	1	4	0.84	2.73	0.84		648.91	99.9
	2	4	0.99	1.53	0.093	1.85	648.94	99.8
	3	4	0.99	1.29	0.059		648.59	99.8
Lead	1	4	0.79	2.99	1.09		876.21	99.6
	2	4	0.84	2.90	.88	2.39	877.22	99.8
	3	4	0.97	1.29	.15		876.17	99.6
Zinc	1	4	0.66	3.88	1.96		4115.57	99.7
	2	4	0.996	2.59	0.102	3.01	4117.78	99.8
	3	4	0.899	2.56	0.60		4113.56	99.7

* n = number of points in each replicate (steps in sequential leaching).
r^2 = Correlation coefficient.
K_d = slope of the regression line.
SE = Standard error of the mean.
q_r = intercept of regression line.
q_o = bulk sediment concentration at the beginning of leaching.

Table G19

Linear Regression of q Versus C for Sequential Batch Leaching of Metals from Aerobic Indiana Harbor Sediment

Metal	Replicate	n	r^2	K_d ℓ/kg	SE ℓ/kg	Ave. K_d ℓ/kg	q_r mg/kg	Ave.* q_r mg/kg	q_r/q_o %
Arsenic	1	4	.795	-19.7	7.06				
	2	4	.064	-3.33	8.98	-13.43	29.45		
	3	4	.114	-8.51	16.74		29.49	29.39	99.6
	4	4	.766	-22.2	8.67		29.59	(.003)*	
Cadmium	1	5	.70	2.62	.968		19.85		
	2	5	.033	2.22	6.9	1.41		19.85	
	3	5	.10	.83	1.41		19.97	19.97	99.8
	4	5	.0	.0	.0		19.96	(.007)*	
Chromium	1	5	.119	-5.67	8.86		281.96		
	2	5	.018	-1.92	8.07	-2.93	281.91	281.85	99.9
	3	5	.33	-7.3	6.00	(-4.52)	281.96	(.02)*	
	4	5	.042	3.17	8.71		281.91		
Lead	1	5	.192	-5.65	6.69		878.93		
	2	5	.168	-4.44	[illegible]	[illegible]	878.92	878.78	<99.9
	3	5	.005	-1.27	9.65		878.88	(0.02)*	
	4	5	.528	11.5	5.66		878.81		
Zinc	1	4	.05	3.52	8.78		4123.77		

---

* Average sediment concentration at the end of sequential leaching.

[redacted]

isotherms.

[redacted]

This implies that most of the metals in the aerobic sediment are resistant to leaching, i.e., q_r is large relative to the bulk concentration. If q_r is

[redacted]

procedure, regardless of the value for K , will be small relative to the

[redacted]

ing on the variability associated with the leaching and chemical analysis procedures. Thus, the clustering or scatter associated with the desorption isotherms for aerobic metals is probably due to small q_L (large q_r) relative to the testing variability.

[redacted]

tioned among several geochemical forms (phases) ranging from a fraction that

[redacted]

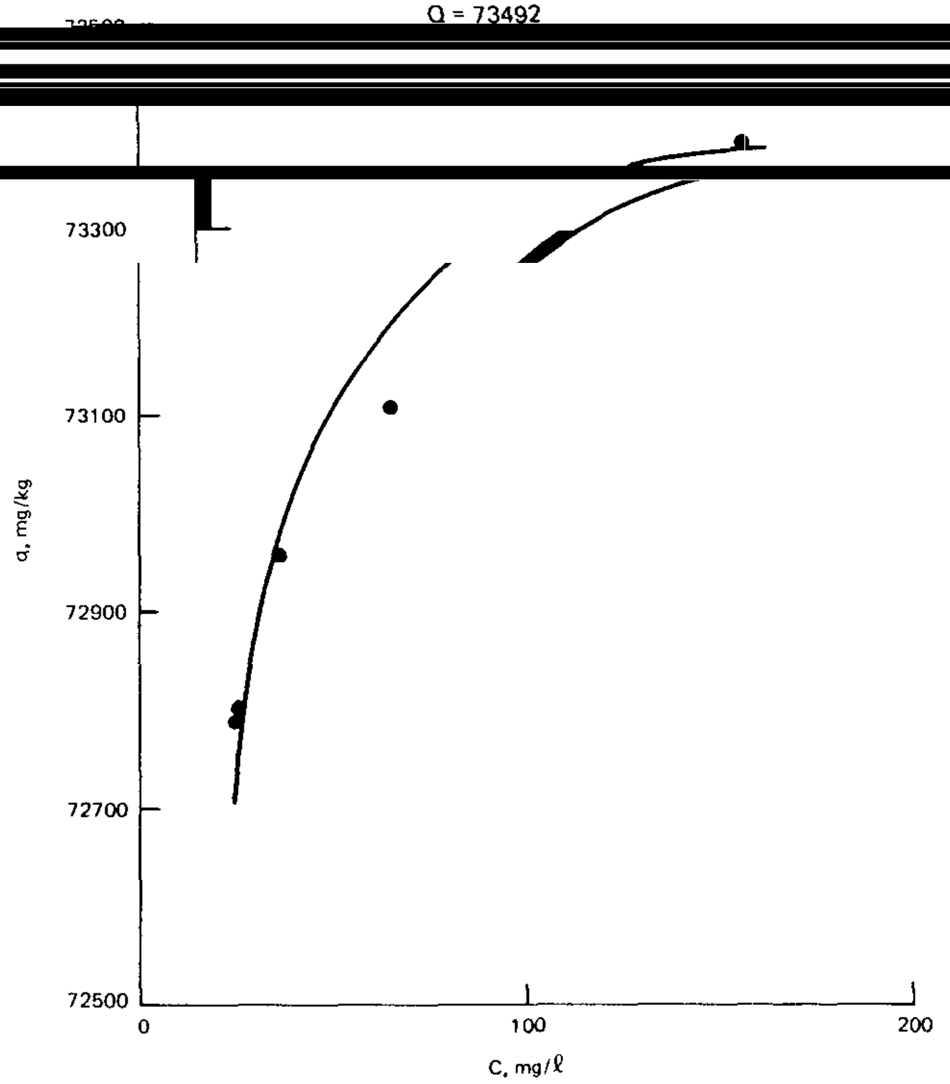
part of mineral crystalline lattices.

[redacted]

mobility of a metal contaminant in dredged material depends on the geochemical partitioning of the metal (Brannon, Plumb, and Smith 1978).

68. Since the regression analysis for aerobic metals was not satisfac- [illegible] aerobic, sequential leach tests. These values are presented in Table G19. As indicated, greater than 99 percent of the bulk metal concentrations were not [illegible] leach tests for anaerobic and aerobic sediment show that the metals in Indiana [illegible] dissolved organic carbon (DOC) concentrations in the filtered leachate from sequential batch leach tests for anaerobic and aerobic conditions are pre- [illegible] aerobic sediments, respectively. As shown in Table G20, the leachate DOC decreased with each step in the sequential leach procedure until the fourth step. At this point, DOC became constant at 25 mg/ℓ in the anaerobic tests and 45 mg/ℓ in the aerobic tests. The data produced a well-defined isotherm for anaerobic sediment as shown in Figure G9. The isotherm is curvilinear. A plot for aerobic data is not available because TOC in the aerobic sediment was not measured. The sequential leach data, however, indicate that a curvilinear isotherm similar to the one shown in Figure G9 would also be obtained for aerobic organic carbon desorption. Curvilinear isotherms can be modeled by the Langmuir adsorption-desorption equation (Equation H6). Application of this equation to curvilinear desorption isotherms is discussed in Appendix H. Langmuir coefficients for the anaerobic organic carbon isotherm were determined using least squares analysis of the linearized form of the Langmuir equation (Equation H7). Langmuir coefficients for the anaerobic TOC isotherm were Q = 73492 mg/kg and b = 3.864 ℓ/mg (r = 0.9999). Q and b are defined as the monolayer sorption capacity and the Langmuir distribution constant, respectively. These data show that the distribution of TOC between solid and [illegible]

70. An analysis of the various components that make up the DOC in the [illegible]



[illegible]
anaerobic Indiana Harbor sediment

Table G20

Steady-State DOC Concentration [mg/ℓ (standard error)] in Leachate for Sequential Batch Leach [redacted]

Treatment	Sequential Leach Number 1	2	3	4	5
Anaerobic	156 (19)	65 (3)	39 (2)	25 (3)	24 (4)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

to sediments and soils. These substances could act to stabilize in solution weakly soluble and highly sorbed contaminants such as PCB congeners (Voice, Rice, and Weber 1983; Gschwend and Wu 1985). Thus, DOC was considered a potentially important index of overall organic contaminant mobility. If gross [redacted] the partitioning of organic compounds (Voice, Rice, and Weber 1983; Gschwend and Wu 1985). If this is the case, the DOC measurement will lack the resolution necessary to measure the effect.

71. The steady-state sediment q and leachate C concentrations for PAHs and Aroclor 1248 congeners obtained from the sequential batch leach tests for anaerobic and aerobic leaching are presented in Tables G21-G24. When plotted, [redacted] number 19 in Table G4). These desorption isotherms, typical of the PAH and [redacted]

[redacted] were obtained from the sequential batch leach data by regressing the q and C values onto Equation G5. The regression statistics for anaerobic coefficients are presented in Table G25. The regression statistics showed that regression of Equation G5 onto the data produced very poor fit and that the [redacted] because all the PAH and PCB desorption isotherms were clustered. As previously noted for the aerobic metals, when isotherm data are clustered, a well- [redacted] that the clusters shown in Figures G10 and G11 cannot be described using straight lines or simple curves.

73. Release of organic contaminants from aerobic Indiana Harbor sediment showed the same clustering effect as did organic contaminant release from the [redacted]

Table G21

Steady-S ate Sedim Organic Contaminant Conce tion
[ug/g d weight ndard error)] for Indiana por
Sedim t Follow Anaerobic Sequential Leac

pound		Sequential Leach Number 2	3	4	5
1	19 (1.322)	1 36.25 (2.	1975.10 (1.98)	19 (3.1	1951.33 (4.19)
2	(0.004)	1.95 (0.	21.91 (0.006)	(0.0	21.84 (0.01)
3	(0.01)	5.83 (0.	95.72 (0.01)	(0.0	95.51 (0.02)
4	(0.005)	8.89 (0.	68.82 (0.01)	(0.0	68.70 (0.01)
5	1 (0.01)	9.81 (0.	199.72 (0.02)	1 (0.0	199.56 (0.006)
6	(0.003)	1.97 (0.	61.95 (0.003)	(0.0	61.94 (0.008)
7	1 (0.009)	9.91 (0.	149.87 (0.007)	1 (0.0	149.83 (0.009)
8	1 (0.007)	9.91 (0.	139.88 (0.009)	1 (0.0	139.85 (0.01)
9	(0.009)	1.96 (0.	91.95 (0.01)	(0.0	91.94 (0.01)
10	(0.006)	5.97 (0.	85.96 (0.008)	(0.0	85.95 (0.007)
11	No	etectabl	lease*		
12	No	etectabl	lease*		
13	No	etectabl	lease*		
14	No	etectabl	lease*		
15	No	tectable	ease**		
16	(0.0001)	0.799(0.	) 10.798 (0.0006)	8(0.0)	10.797(0.0007)
17	(0.0002)	9.499(0.	) 19.499 (0.0003)	9(0.0)	19.499(0.0003)
18	(0.0004)	1.899(0.	) 31.898 (0.0006)	8(0.0)	31.898(0.0007)
19	(0.0001)	3.499(0.	) 3.499 (0.0001)	9(0.0)	3.499(0.0001)
20	(0.0006)	9.487(0.	) 19.496 (0.0004)	5(0.0)	19.495(0.0006)
21	(0.0002)	9.299(0.	) 19.299 (0.0002)	9(0.0)	19.299(0.0002)
22	(0.0001)	5.199(0.	) 5.199 (0.0002)	9(0.0)	5.199(0.0002)
23	No De	ctable R	ses **		
24	(0.0001)	5.700(0.	) 5.699 (0.0001)	9(0.0)	5.699(0.0002)
25	(0.0001)	3.700(0.	) 3.700 (0.0001)	0(0.0)	3.700(0.0001)
26	(0.00003)	2.200(0.	3) 2.200 (0.0001)	0(0.0)	2.200(0.0001)
27	No De	ctable R	ses **		
28	(0.0002)	2.400(0.	) 12.399 (0.0003)	9(0.0)	12.398(0.0003)
29	No De	ctable R	ses **		

Detection li 0.005 mg/ℓ.
Detection li 0.00001 mg/ℓ.

Table G22

[redacted]

Sequential Leaching

Compound	1		2		3		4		5	
1	1.23	(0.026)	1.52	(0.30)	2.23	(0.18)	2.57	(0.27)	2.18	(0.25)
2	0.006	(0.0008)	0.005	(0.001)	0.007	(0.0006)	0.0007	(0.0007)	0.007	(0.0003)
3	0.016	(0.002)	0.017	(0.003)	0.022	(0.002)	0.021	(0.002)	0.021	(0.006)
4	0.010	(0.001)	0.011	(0.001)	0.013	(0.001)	0.012	(0.001)	0.012	(0.000)
5	0.020	(0.002)	0.018	(0.001)	0.018	(0.001)	0.015	(0.001)	0.016	(0.001)
6	0.004	(0.001)	0.003	(0.0002)	0.003	(0.000)	0.002	(0.000)	0.002	(0.000)
7	0.009	(0.002)	0.009	(0.001)	0.007	(0.001)	0.004	(0.000)	0.003	(0.000)
8	0.009	(0.002)	0.009	(0.001)	0.006	(0.000)	0.004	(0.000)	0.002	(0.000)
9	0.003	(0.002)	0.005	(0.004)	0.002	(0.001)	0.001	(0.0001)		<0.001
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
14	0.005		<0.005		<0.005		<0.005			
15	<0.00001		<0.00001		<0.00001		<0.00001			
16	0.00011	(0.00006)	0.00007	(0.00002)	0.00007	(0.00001)	0.00009	(0.00001)	0.00012	(0.00012)
17	0.00016	(0.00004)	0.00009	(0.00004)	<0.00001		<0.00001		<0.00001	
18	0.00016	(0.00008)	0.00011	(0.00004)	0.00008	(0.0002)	0.00008	(0.00002)	0.00005	(0.00001
19	0.00008	0.00002)	0.00003	(0.00002)	0.00003	(0.0003	0.0003	(0.000003)	(0.00003	(0.00001)
20	0.0005	(0.00011)	0.00019	(0.00004)	0.00016	(0.00003)	0.00014	(0.00001)	<0.00001	
21	0.00018	(0.00003)	0.00009	(0.00004)	<0.00001		<0.00001		<0.00001	
22	0.0008	(0.00001)	0.00005	(0.00004)	0.00004	(0.00001)	0.00003	(0.000003)	0.00003	(0.00001)
23	<0.00001		<0.00001		<0.00001		<0.00001		<0.00001	
24	0.00005	(0.00001)	0.00004	(0.00002)	0.00004	(0.00001)	0.00003	(0.000003)	0.00002	(0.00003)
25	0.00003	(0.00002)	0.00003	(0.00002)	0.00002	(0.00001)	0.00002	(0.000003)	0.00002	(0.00001)
26	0.00003	(0.00001)	0.00001	(0.000003)	0.00002	(0.00001)	0.00001	(0.000003)	0.00001	(0.00000)
27	<0.00001		<0.00001		<0.00001		<0.00001		<0.00001	
28	0.00011	(0.00002)	0.00008	(0.00005)	0.00006	(0.00002)	0.00004	(0.00007)	0.00003	(0.00006)
29	<0.00001		<0.00001		<0.00001		<0.00001		<0.00001	

Table G23

[redacted]

for Indiana Harbor Sediments Following Aerobic Leaching

Compound	Sequential Leach Number 1	2	3	4	5
1	81.73 (0.026)	81.72 (0.022)	No Further Changes in Sediment Concentration		
2	No Change in Sediment Concentration				
3	10.74 (0.0007)	10.72 (0.001)	10.71 (0.0019)	No Further Changes in Sediment Concentration	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
6	No Change in Sediment Concentration				
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
10	No Change in Sediment Concentration				
11	No Change in Sediment Concentration				
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
14	No Change in Sediment Concentration				
15	No Change in Sediment Concentration				
16	0.131 (0.00003)	0.131 (0.00003)	0.130 (0.00003)	0.130 (0.00003)	0.130 (0.00007)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
21	No Change in Sediment Concentration				
22	0.9438 (0.00003)	0.9437 (0.00006)	0.9435 (0.00006)	0.9432 (0.00006)	0.9431 (0.00006)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
26	0.3549 (0.00006)	0.3548 (0.00006)	0.3547 (0.00007)	0.3546 (0.00007)	0.3545 (0.00007)
27	No Change in Sediment Concentration				
28	2.2997 (0.00003)	2.2996 (0.0001)	2.2992 (0.0001)	2.2988 (0.0001)	2.2986 (0.0002)
29	0.3088 (0.00009)	0.3088 (0.00009)	0.3086 (0.00001)	0.3086 (0.00009)	0.3086 (0.00009)

Table G24

[redacted]

Indiana Harbor Sediment Following Aerobic Leaching

Compound	Sequential Leach Number 1	2	3	4	5
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
4	0.0015 (0.00006)	<0.001	<0.001	<0.001	<0.001
5	0.0036 (0.0003)	<0.002	<0.002	<0.002	<0.002
6	<0.005	<0.005	<0.005	<0.005	<0.005
7	0.0032 (0.0003)	0.003 (0.0003)	0.0028 (0.0001)	0.0025 (0.0003)	0.0024 (0.0003)
8	0.0041 (0.0003)	0.0041 (0.0004)	0.0038 (0.0003)	0.0044 (0.0005)	0.0038 (0.0004)
9	<0.005	<0.005	<0.005	<0.005	<0.005
10	<0.005	<0.005	<0.005	<0.005	<0.005
11	<0.005	<0.005	<0.005	<0.005	<0.005
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
15	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
16	0.00008 (0.00001)	0.00003 (0.00001)	0.00003 (0.00001)	0.00005 (0.00001)	0.00003 (0.00001)
17	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
18	0.00009 (0.00001)	0.00011 (0.00001)	0.00014 (0.00002)	0.00015 (0.00001)	0.00007 (0.00002)
19	0.00004 (0.00001)	0.00003 (0.000003)	0.00005 (0.00001)	0.00004 (0.00001)	0.00003 (0.00000)
20	0.00016 (0.00002)	0.00017 (0.000000)	0.00014 (0.00007)	0.00022 (0.00001)	0.00005 (0.00004)
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
23	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
24	0.00004 (0.00001)	0.00003 (0.00000)	0.00004 (0.00000)	0.00004 (0.00001)	0.00003 (0.00000)
25	0.00004 (0.00001)	0.00002 (0.00000)	0.00004 (0.00001)	0.00003 (0.00001)	0.00003 (0.00000)
26	0.00002 (0.00001)	0.00003 (0.00002)	0.00002 (0.00001)	0.00002 (0.00001)	0.00002 (0.00001)
27	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001
28	0.00006 (0.00001)	0.00005 (0.00002)	0.00009 (0.00001)	0.00009 (0.00001)	0.00006 (0.00001)
29	0.00005 (0.00002)	0.00001 (0.00000)	0.00004 (0.00001)	0.00002 (0.00001)	0.00002 (0.00001)

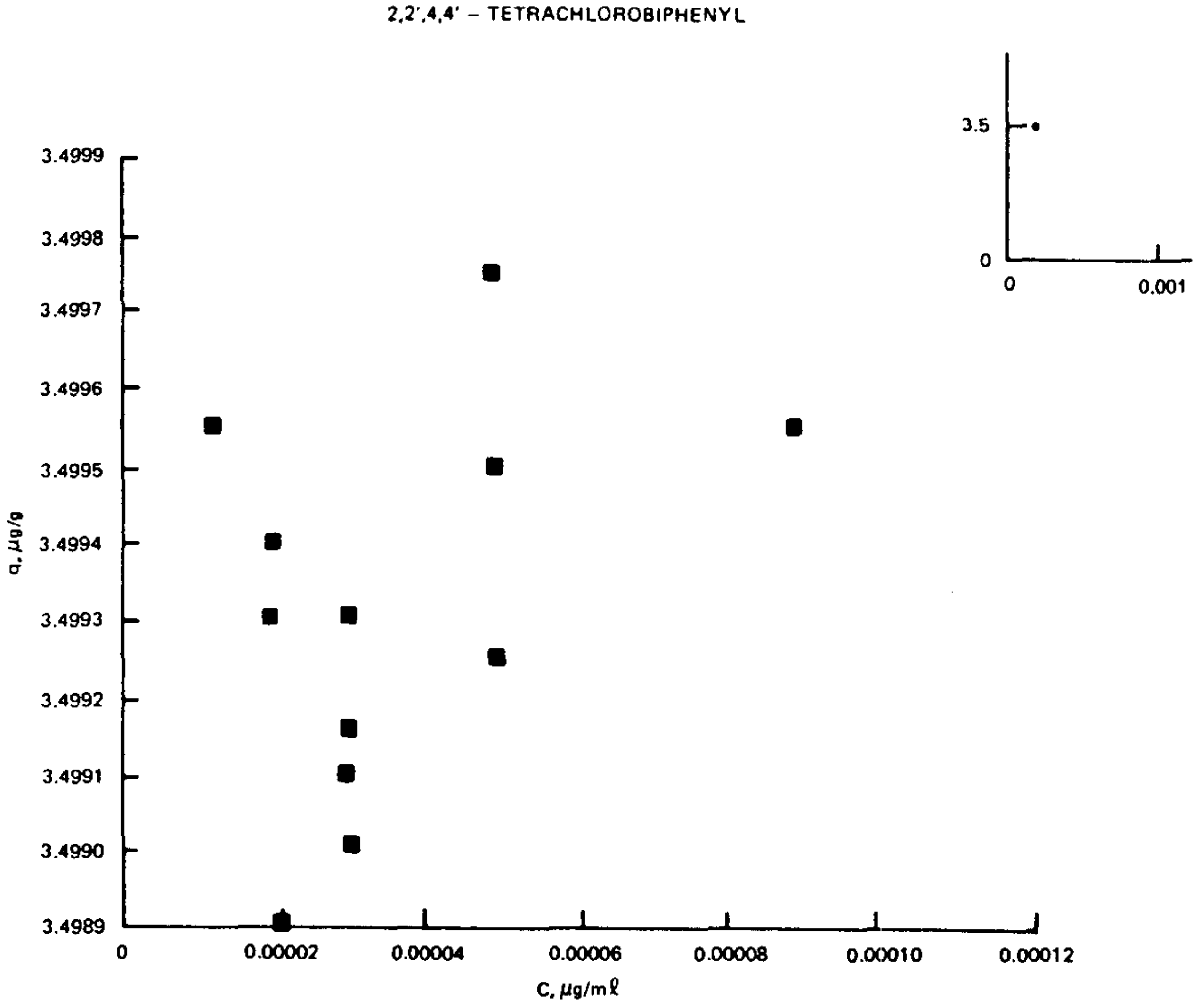


Figure G10. Desorption isotherm for 2, 2', 4,4' -tetrachlorobiphenyl

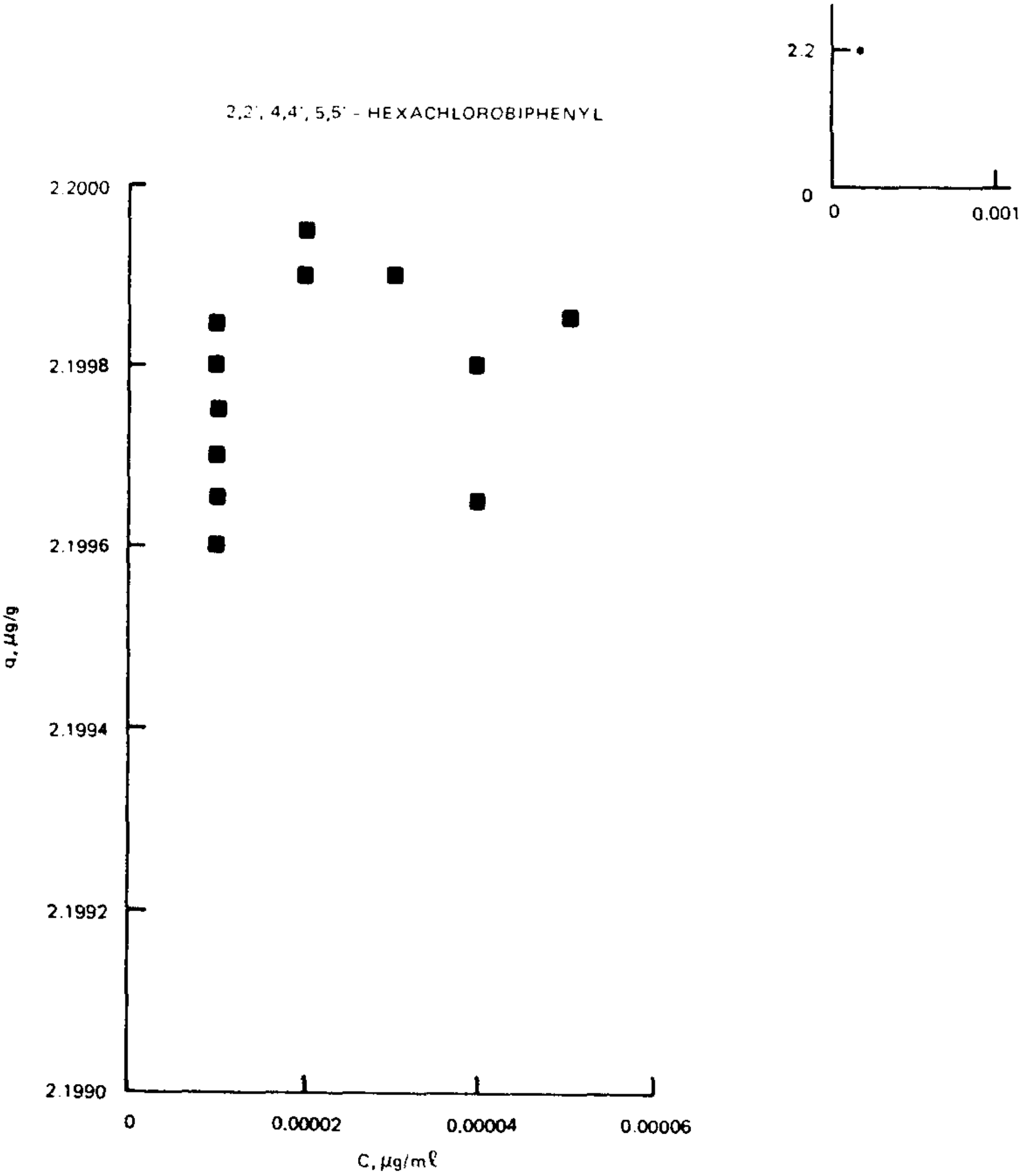


Figure G11. Desorption isotherm for 2,2',4,4',5,5' -hexachlorobiphenyl

Table G25

Linear Regression of q Versus C for Sequential Batch Leaching

[redacted]	[redacted]	[redacted]	[redacted]
2	1	5	0.144
	2	5	0.56
	3	5	0.26
3	1	5	0.188
	2	5	0.75
[redacted]	[redacted]	[redacted]	[redacted]
	2	5	0.66
	3	5	0.182
[redacted]	[redacted]	[redacted]	[redacted]
	3	5	0.72
6	1	5	0.76
	2	5	0.64
	3	5	0.86
7	1	5	0.93
	2	5	0.80
	3	5	0.54
8	1	5	0.54
[redacted]	[redacted]	[redacted]	[redacted]
9	1	5	0.14
	2	5	0.07
	3	5	0.014
10	1	5	0.63
	2	5	0.77
	3	5	0.32

(Sheet 1 of 3)

Table G25 (Continued)

Compound	Replicate	n	r^2
11	1	5	BDL*
	2	5	
	3	5	
12	1	5	BDL
	2	5	
	3	5	
13	1	5	BDL
	2	5	
	3	5	
14	1	5	BDL
[redacted]	[redacted]	[redacted]	[redacted]
	3	5	
16	1	5	0.01
	2	5	0.19
	3	5	0.74
17	1	5	0.29
	2	5	0.95
	3	5	0.86
18	1	5	0.56
	2	5	0.89
	3	5	0.41
19	1	5	0.45
	2	5	0.61
	3	5	0.107
20	1	5	0.310
	2	5	0.67
	3	5	0.63
21	1	5	0.03
	2	5	0.88
	3	5	0.98

---

* All leachate samples were below the detection limit (see Table G38 for detection limits)

(Sheet 2 of 3)

Table G25 (Concluded)

Compound	Replicate	n	r^2
22	1	5	0.116
	2	5	0.67
	3	5	0.04
23	1	5	BDL
	2	5	
	3	5	
24	1	5	0.17
	2	5	0.82
	3	5	0.13
25	1	5	0.23
	2	5	0.63
	3	5	0
26	1	5	0
	2	5	0.5
	3	5	0.47
27	1	5	BDL
	2	5	
	3	5	
28	1	5	0.09
	2	5	0.68
	3	5	0.13
29	1	5	BDL
	2	5	
	3	5	

(Sheet 3 of 3)

Table G26

Linear Regression of q Versus C for Sequential Batch Leaching of Organic Contaminants From Aerobic Indiana Harbor Sediment

[redacted]

[illegible]	Replication	n	r^2
2	1	5	
	2	5	BDL*
	3	5	
3	1	5	0.61
	2	5	0.57
	3	5	0.67
4	1	5	0.5
	2	5	0.5
	3	5	0.75
5	1	5	0.40
	2	5	0.58
	3	5	0.60
6	1	5	
	2	5	BDL
	3	5	
7	1	5	0.35
	2	5	0.67
	3	5	0.25
8	1	5	0.35
	2	5	0.127
	3	5	0.04
9	1	5	
	2	5	BDL
	3	5	
10	1	5	
	2	5	BDL
	3	5	

---

* All leachate samples were below the detection limit (see Table G38 for detection limits.

(Sheet 1 of 3)

Table G26 (Continued)

[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]
12	1	5	
	2	5	BDL
	3	5	
13	1	5	
	2	5	BDL
	3	5	
14	1	5	
	2	5	BDL
	3	5	
15	1	5	
	2	5	BDL
	3	5	
16	1	5	0.122
[redacted]	[redacted]	[redacted]	[redacted]
	3	5	0.43
17	1	5	
	2	5	BDL
	3	5	
18	1	5	0
[redacted]	[redacted]	[redacted]	[redacted]
19	1	5	0.703
	2	5	0.102
	3	5	0.03
20	1	5	0.29
[redacted]	[redacted]	[redacted]	[redacted]
	3	5	

[redacted]

Table G26 (Concluded)

Compound	Replicate	n	r^2
22	1	5	0.04
	2	5	0.21
	3	5	0
23	1	5	BDL
	2	5	0.66
	3	5	0.5
24	1	5	0.48
	2	5	0.33
	3	5	0.24
25	1	5	[illegible]
	2	5	0.69
	3	5	0.09
26	1	5	0.1
	2	5	0.02
	3	5	0.007
27	1	5	0.05
	2	5	0
	3	5	BDL
28	1	5	0.27
	2	5	0.29
	3	5	0.12
29	1	5	0.23
	2	5	0.23
	3	5	0.08

(Sheet 3 of 3)

data also showed that the aerobic distribution coefficients obtained by regression were not meaningful.

74. Contaminant released during the aerobic testing was less than the [redacted]

75. The clustering that characterizes the PAH and PCB desorption isotherms indicates that these contaminants were tightly bound to the sediment [redacted] sequential leaching procedure, or both. The clustering effect for tightly bound sediment contaminants is due to a very large K_d. Literature values for sediment-water partitioning of PCBs, for example, range from 10^3 to [redacted] 10 ℓ/kg (Pavlou 1980, Neely 1983). If distribution coefficients are high, the aqueous phase concentrations are low in each step of the sequential leaching due to partitioning. Clustered data result because the differences in leachate concentrations are within the noise level of the combined variability of the batch leaching and chemical analytical procedures.

[redacted]

$$K_d = 0.63\ f_{oc} K_{oc} \tag{G9}$$

where

f_{oc} = fraction of the solids, by weight, composed of organic carbon

K_{ow} = octanol-water partition coefficient

Equation G9 indicates that K_d is directly proportional to sediment TOC. During sequential leaching, sediment TOC varied no more than 10 percent from step 1 to step 4. Therefore, if K_d was variable during the sequential [redacted] discussed earlier, components of the aqueous phase TOC are a more likely source of variability.

77. In order to calculate meaningful distribution coefficients for the PAHs and PCBs from the sequential, batch leach data, two assumptions were necessary. First, the bulk sediment concentration was assumed to be leachable, i.e., q_r is equal to zero. Second, the batch data cluster about some point (C,q) that represents the overall or net distribution coefficient for the sequential leaching. Using these assumptions, an approximate K_d was calculated by computing the average K_d from all the single-point estimates provided by the data from the sequential batch leach tests. The distribution coefficients determined by this method are presented in Table G27. These values are in the upper range of the values reported in the literature.

78. It is realized that there may be a non-reversible component, up to 90 percent, for PAHs and PCBs (Di Toro and Horzempa 1982, Di Toro 1985). If there is a significant nonreversible component, then the explanation for the clustering is similar to the explanation previously developed for the aerobic [illegible] with. Clustering results in each case because the concentrations that are measured in the leachate are low enough to be influenced by the combined vari[illegible]

79. The basis for a nonreversible component for organic contaminants, [illegible] contaminants is as follows. The leaching resistant component is adsorbed to surfaces in intraparticle pores. The water in intraparticle pores is immo[illegible] centration is assumed to be nonreversibly sorbed, the K_d values in Table G27 become one order of magnitude lower. There is no change, however, in an estimated C_I (Equation G8) because q_L is also one order of magnitude lower.

Table G27

Single-Point Distribution Coefficients for PAHS and Aroclor 1242 Congeners, Cluster Centroid Method*

	Distribution Coefficient, ℓ/kg	
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
2	3 440	2 790
3	5 120	3 900
4	5 980	5 260
5	11 700	13 600
[redacted]	[redacted]	[redacted]
7	26 800	23 400
8	29 700	21 500
9	32 200	> 8 560
10	37 300	> 6 180
11	> 28 000	>12 940
12	> 17 400	>
	> 10 000	> 3 150
14	> 7 000	> 2 360
15	UD	UD
16	163 000	4 160
17	2 430 000	42 800
18	423 000	55 400
19	145 000	31 000
[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]
22	194 000	24 800
23	> 1 660 000	UD
24	266 000	27 300
25	375 000	23 700
26	203 000	22 300
27	UD	UD
28	410 000	47 600
29	> 33 000	26 100
Total PAH	1 600	30 800
Total congeners	256 000	38 700

[redacted]

[redacted]

As discussed later, there is no difference in the shape of predicted concentration curves for K_d in the range of E+02 to E+06. Since there is no prac- [redacted]

nants, the conservative assumption that all of the organic contaminant is [redacted]

81. Metal releases in challenge tests. When leachate from anaerobic and [redacted]

Steady-state sediment and leachate metal concentrations for anaerobic Indiana [redacted]

Arsenic and chromium concentrations increased to near that observed in anaerobic leachate. Cadmium, chromium, lead, and zinc did not, suggesting that the effect that aerobic leachate has on the desorption characteristics of anaerobic sediment is apparently metal specific. In no case did the aerobic leach- [redacted]

[redacted]

Table G28

Steady-State Sediment and Leachate Metal Concentration [mean (standard error)] in Anaerobic Indiana Harbor Sediment Challenged

[redacted]

1	29.46 (0.11)	281.64 (0.009)	878.64 (0.04)	19.99 (0.003)	4123.29 (0.16)
2	29.44 (0.03)	281.24 (0.22)	878.39 (0.27)	19.99 (0.016)	4121.63 (1.42)
3	29.43 (0.03)	281.33 (0.09)	878.96 (0.43)	19.99 (0.032)	4122.76 (1.69)
4	29.43 (0.03)	281.33 (0.09)	878.87 (0.45)	19.98 (0.033)	4121.09 (1.24)
5	29.44 (0.03)	281.33 (0.09)	879.19 (0.29)	19.99 (0.023)	4122.86 (0.61)
			Leachate Concentration, μg/mℓ		
1	0.033 (0.002)	0.21 (0.004)	0.22 (0.02)	0.009 (0.004)	0.98 (0.02)
2	0.027 (0.004)	0.027 (0.03)	0.22 (0.009)	0.012 (0.006)	1.49 0.15
3	0.021	0.14	0.09	0.012	0.89
4	0.016 (0.001)	0.11 (0.03)	0.05) (0.04)	0.0007 (0.003)	0.87 (0.18)
5	0.013 (0.0003)	0.02 (0.002)	0.04 (0.005)	0.005 (0.0002)	0.16 0.02)

Table G29

Steady State Sediment and Leachate Concentration [mean (standard [redacted]

Time, days	Cs	Cr	Pb	Cd	Zn
			Sediment Concentration, μg/g		
1	29.43	281.96	878.99	20.00	4125.08
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	(0.03)	(0.01)	(0.02)	(0.005)	(0.05)
3	29.31	281.95	878.95	20.00	4124.91
	(0.01)	(0.02)	(0.03)	(0.005)	(0.09)
4	29.27	281.95	878.98	20.01	4124.96
	(0.02)	(0.02)	(0.04)	(0.005)	(0.10)
5	29.24	281.95	878.97	20.01	4124.98
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
			[redacted]		
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
2	0.033	0.017	0.014	0.001	0.077
	(0.002)	(0.002)	(0.002)	(0.0002)	(0.016)
3	0.019	0.014	0.018	0.0008	0.081
	(0.0005)	(0.001)	(0.003)	(0.00009)	(0.014)
4	0.020	0.011	0.011	0.0007	0.076
	(0.0000)	(0.002)	(0.003)	(0.0001)	(0.014)
5	0.017	0.006	0.008	0.0005	0.049
	(0.003)	(0.0007)	(0.0004)	(0.0001)	(0.007)

organic contaminant distribution coefficients for this challenge testing are presented in Table G30. Anaerobic distribution coefficients for the anaerobic sediment determined during the first phase of the challenge testing did not [redacted] ously, even though the challenge testing was conducted 3 months later. When leachate from the first phase of the challenge testing was used to challenge fresh anaerobic Indiana Harbor sediment, partition coefficients for organic [redacted] presented in Table G30, even though no statistical statements can be made due to the lack of replication. Steady state leachate and sediment organic contaminant concentrations obtained prior to challenge testing are presented in Tables G31 and G32, respectively. These test results did not generally differ [redacted] ment, leachate concentrations of organic contaminants did not change substantially (Table G33). This was paralleled by very little change in organic contaminant concentrations in fresh anaerobic sediment exposed to leachate from anaerobic sediment (Table G34). These results indicate that distribution coefficients for organic contaminants in Indiana Harbor sediment should be [redacted]

[redacted] umes of water passed through the sediment increased, the contaminant concentrations in the leachate decreased. Specific results are presented below and discussed in the following section.

84. Anaerobic permeameters: metals, conductivity, and DOC. Measured [redacted] data from this table for metals, dissolved organic carbon, and conductivity are plotted on Figures G12-G15. Predicted permeameter leachate concentrations [redacted]

Table G30

Single-Point Distribution Coefficients (ml/g) for Organic Contaminants from Challenge Testing of Anaerobic Indiana Harbor Sediment

Compound	Sequential Leach Number 1	2	3	4	5
1	1626	1318	879	777	917
2	4000	4400	3200	3250	3320
3	6000	5650	4360	4570	4570
4	6590	6350	5190	5600	5750
5	3400	3770	3830	4510	4395
6	16760	20000	20670	33880	39490
7	16130	16670	22060	34090	43230
8	15220	16470	23730	37840	82350
9	29680	17040	61330	65710	92000
10	35830	19240	53750	86000	> 86000
11	>28000	>28000	> 28000	> 28000	> 28000
12	>17400	>17400	> 17400	> 17400	> 17400
13	>10000	>10000	> 10000	> 10000	> 10000
14	> 7000	> 7000	> 7000	> 7000	> 7000
15	None Detected in Sediment				
16	95580	161200	154300	124100	90000
17	121900	209700	1950000	> 1950000	> 1950000
18	203200	282300	425300	425300	679000
19	42170	129600	106100	129630	116670
20	39000	104300	121900	142300	> 1950000
21	109000	214400	1930000	> 1930000	> 1930000
22	67800	98100	130000	173000	173000
23	>166000	>166000	>166000	>166000	>166000
24	114000	154000	154000	211000	248000
25	123000	123000	161000	161000	218000
26	73000	314000	132000	220000	169000
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
29	>198000	>198000	>198000	>198000	>198000

Table G31

Steady-State Leachate Concentrations (ug/ℓ) for Indiana Harbor Sediment

Compound	1	2	3	4
1	650	950	1800	1800
2	<5	5.1	5.8	5.1
3	14	17	19	16
4	10	13	12	9.1
5	18	21	16	13
6	3.3	8.5	1.8	2.9
7	9.5	11	6.2	3.8
8	8.8	9.8	5.9	3.1
9	2.8	3.4	1.5	<1
10	3.1	3.2	1.5	5
11	7	5.9	3.2	5
12	<5	<5	<5	<5
13	<5	<5	<5	<5
14	<5	<5	<5	<5
15	<0.01	<0.01	<0.01	<0.01
16	0.07	0.06	0.03	<0.01
17	0.37	0.33	0.12	0.26
18	0.75	0.68	0.20	2.5
19	0.13	0.12	0.05	0.19
20	0.71	0.73	0.34	<0.01
21	0.37	0.33	0.12	0.26
22	0.13	0.10	0.03	<0.01
23	<0.01	<0.01	<0.01	<0.01
24	0.12	0.10	0.03	0.38
25	0.01	<0.01	0.02	<0.01
26	0.04	<0.01	0.01	<0.01
27	<0.01	<0.01	<0.01	<0.01
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
29	0.04	0.04	0.01	<0.01

Table G32

Steady-State Sediment Concentration (ug/g Dry Weight) for Indiana Harbor Sediment Following Anaerobic Leaching Prior to Challenge Testing

Compound	Sequential Leach Number			
	1	2	3	4
1	1997.4	1993.6	1986.4	1979.2
2	21.98	21.96	21.94	21.92
3	95.94	95.88	95.80	95.74
4	68.96	68.91	68.86	68.82
5	199.93	199.84	199.78	199.78
6	61.99	61.95	61.95	61.94
7	149.96	149.92	149.89	149.88
8	139.96	139.93	139.90	139.90
9	91.99	91.98	91.97	91.95
10	85.99	85.97	85.97	85.95
11	139.97	139.95	139.94	139.92
12	86.98	86.96	86.94	86.92
13	50	50	50	50
14	35	35	35	35
15	NONE DETECTED IN SEDIMENT			
16	10.79	10.79	10.79	10.79
17	19.499	19.497	19.497	19.496
18	31.897	31.894	31.894	31.884
19	3.499	3.499	3.499	3.498
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
22	5.199	5.199	5.199	5.199
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
25	3.700	3.6999	3.6998	3.6998
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
28	12.3899	12.3889	12.3886	12.3886
29	1.9798	1.9797	1.9796	1.9796

Table G33

Steady-State Leachate Concentrations (ug/l) for Anaerobic Indiana Harbor Sediment Following Challenge Testing with Anaerobic Indiana Harbor Leachate

	Sequential Leach Number			
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	4.8	19	17	22
3	<5	6.2	5.5	7.1
4	<5	13	11	14
5	<5	21	17	21
6	<5	4.3	2.9	3.9
7	9.1	12	7	8
8	8.8	11	6.4	7.5
9	5	4.3	2.4	3
10	3.5	3.4	1.9	2.2
11	5.5	6.1	3.7	3.8
12	<5	<5	<5	<5
13	<5	<5	<5	<5
14	<5	<5	<5	<5
15	<0.01	<0.01	<0.01	<0.01
16	<0.01	0.07	0.08	0.06
17	0.52	0.33	0.22	0.20
18	<0.01	0.64	0.42	0.36
19	0.29	0.11	0.08	0.07
20	<0.01	0.60	0.44	0.46
21	[illegible]	[illegible]	[illegible]	[illegible]
22	0.34	0.10	0.09	0.08
23	0.34	<0.01	<0.01	<0.01
24	0.35	0.10	0.07	0.06
25	0.32	0.08	0.07	<0.01
26	0.28	0.04	0.04	0.02
27	<0.01	<0.01	<0.01	<0.01
28	0.47	0.23	0.17	0.14
29	0.28	0.04	0.03	0.03

Table G34

Steady-State Sediment Concentration (µg/g Dry Weight) for Anaerobic Indiana Harbor Sediment Following Challenge

[redacted]

Compound	Sequential Leach Number 1	2	3	4
1	2002.6	2000.0	2000.4	1999.8
2	96.03	96.03	96.04	96.02
3	22.00	22.00	22.00	21.99
4	69.02	69.02	69.02	69.01
5	200.05	200.05	200.05	200.02
6	61.99	61.99	61.99	61.98
7	150.00	149.99	149.99	149.98
8	140.00	139.99	139.99	139.98
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
12	87.00	87.00	87.00	87.00
13	50.00	50.00	50.00	50.00
14	35.00	35.00	35.00	35.00
15	10.80	10.80	10.80	10.80
16	19.50	19.50	19.50	19.50
17	31.90	31.90	31.90	31.91
18	3.499	3.499	3.499	3.500
19	19.50	19.50	19.50	19.50
20	19.29	19.29	19.29	19.29
21	5.199	5.199	5.199	5.199
22	1.659	1.659	1.659	1.659
23	5.199	5.199	5.199	5.198
24	1.659	1.659	1.659	1.659
25	5.699	5.699	5.699	5.700
26	3.699	3.698	3.698	3.698
27	21.99	21.99	21.99	21.99
28	12.39	12.39	12.39	12.39

[redacted]

Table G35

Indiana Harbor Anaerobic Metals Permeameter Tests:

[redacted]

Permeameter No. 1

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
0.14	0.015	0.0020	0.011	0.005	0.047	90.3	*
0.41	0.013	0.0005	0.011	0.003	<.030	50.5	3200.0
0.68	0.010	0.0010	0.008	0.003	<.030	61.3	3200.0
1.04	0.006	0.0026	0.008	0.003	<.030	37.2	2900.0
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

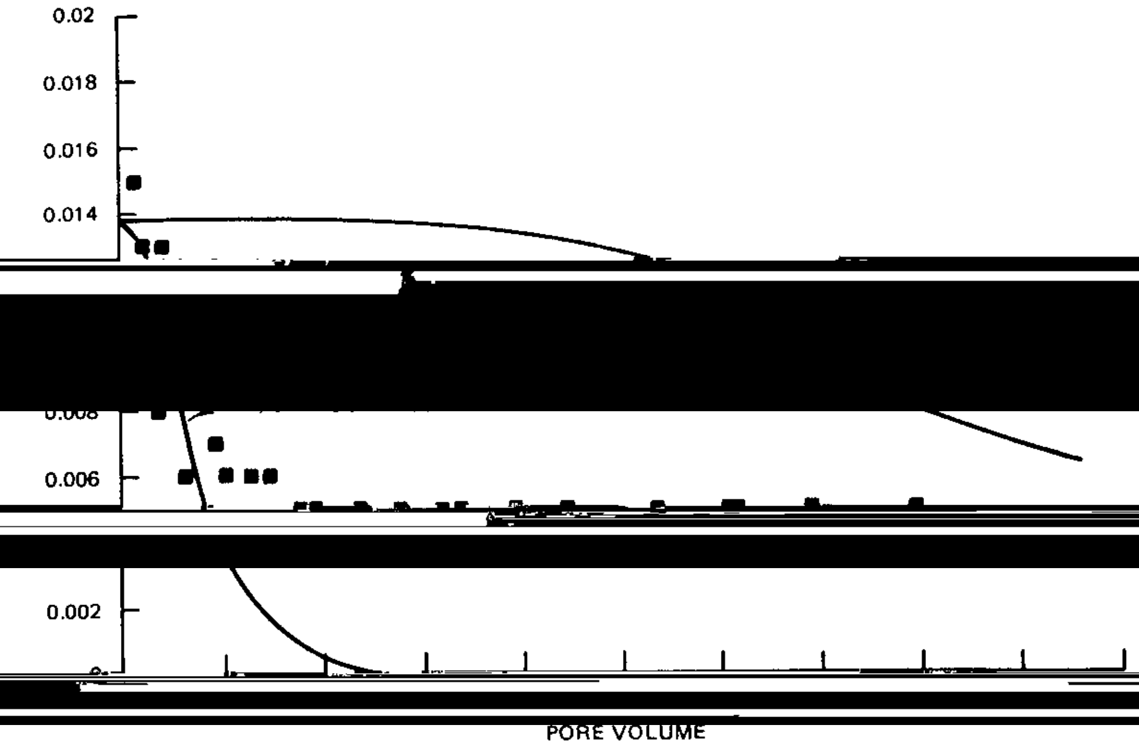
Permeameter No. 2

0.22	0.013	0.0017	0.011	0.004	0.191	48.5	*
0.40	0.008	0.0014	0.009	0.003	0.030	57.1	3200
0.64	0.006	0.0004	0.009	0.005	0.030	76.1	3400
0.94	0.007	0.0008	0.009	0.002	<.030	09.8	0.009 2500
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
3.35	<.005	0.0004	0.008	0.003	<.030	29.1	640
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Permeameter No. 3

0.15	0.011	0.0070	0.010	0.006	0.081	63.9	*
0.50	0.009	0.0009	0.009	0.002	<.030	45.1	2800
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
1.28	0.006	0.0003	0.007	0.003	<.030	80.0	2300
1.78	<.005	0.0003	0.008	0.002	<.030	89.2	1900
2.38	<.005	0.0005	0.011	0.003	<.030	56.2	1150
3.18	<.005	0.0003	0.008	0.003	<.030	45.6	860
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

* No data.



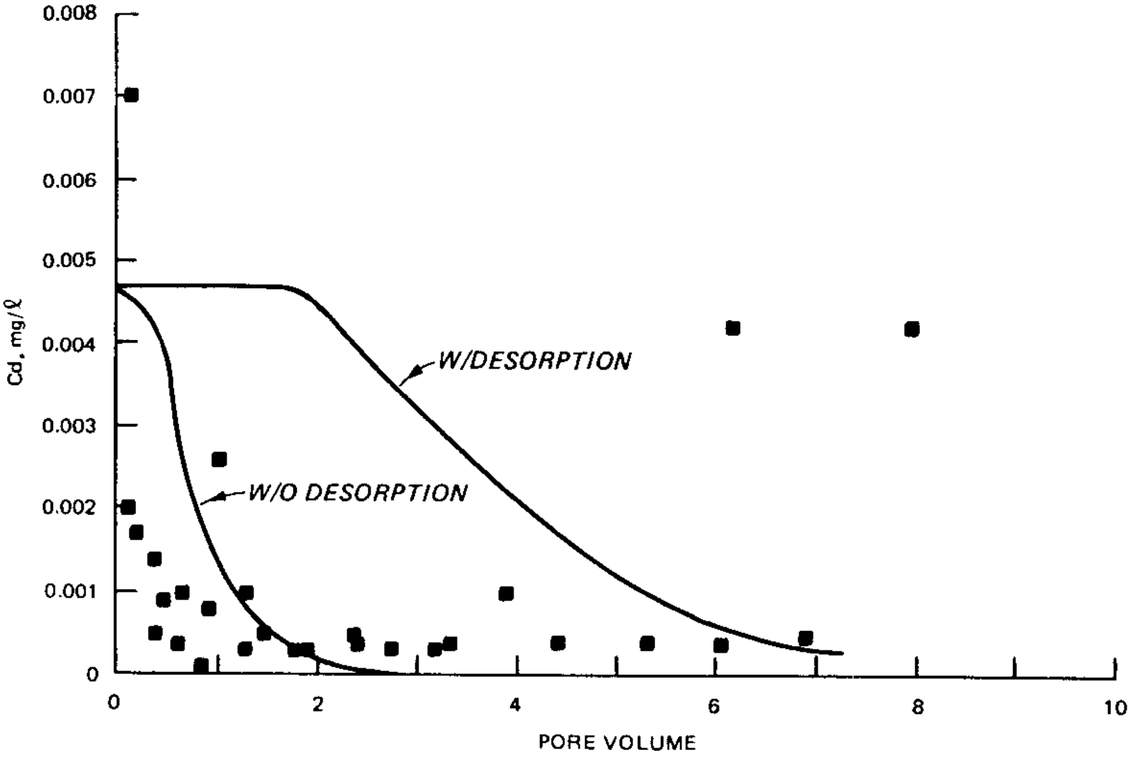


Figure G12. Comparison of [illegible]

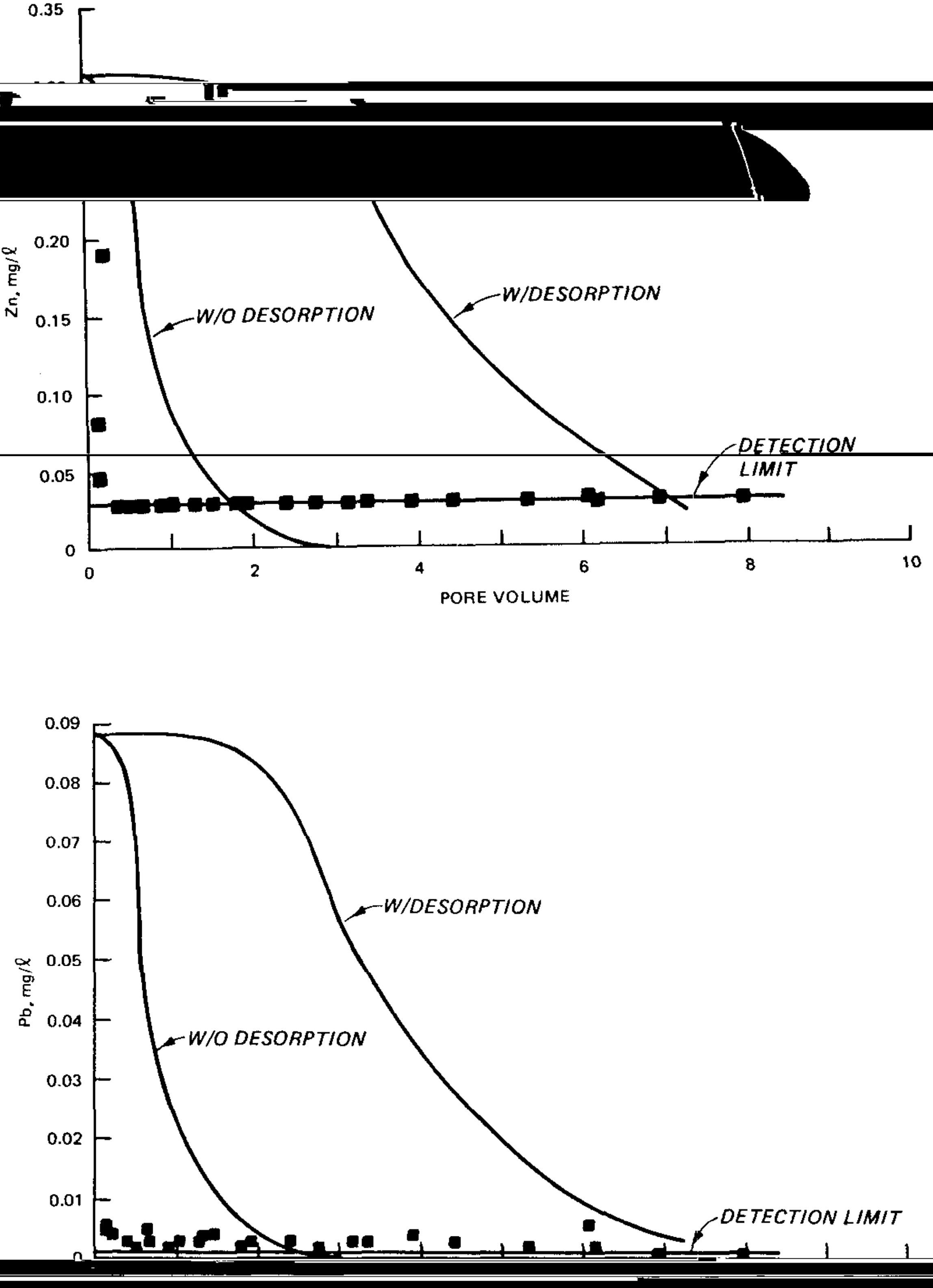


Figure G13. Comparison of zinc and lead concentrations in anaerobic

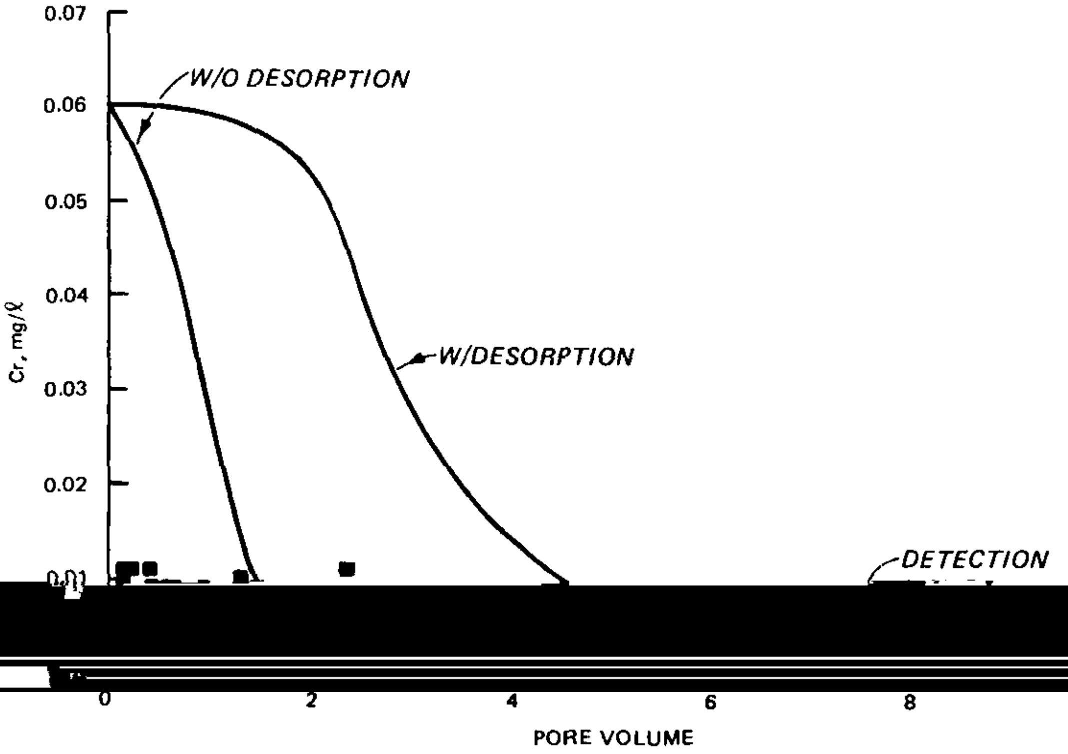


Figure G14. Comparison of chromium concentrations in anaerobic permeameter leachate with predicted values

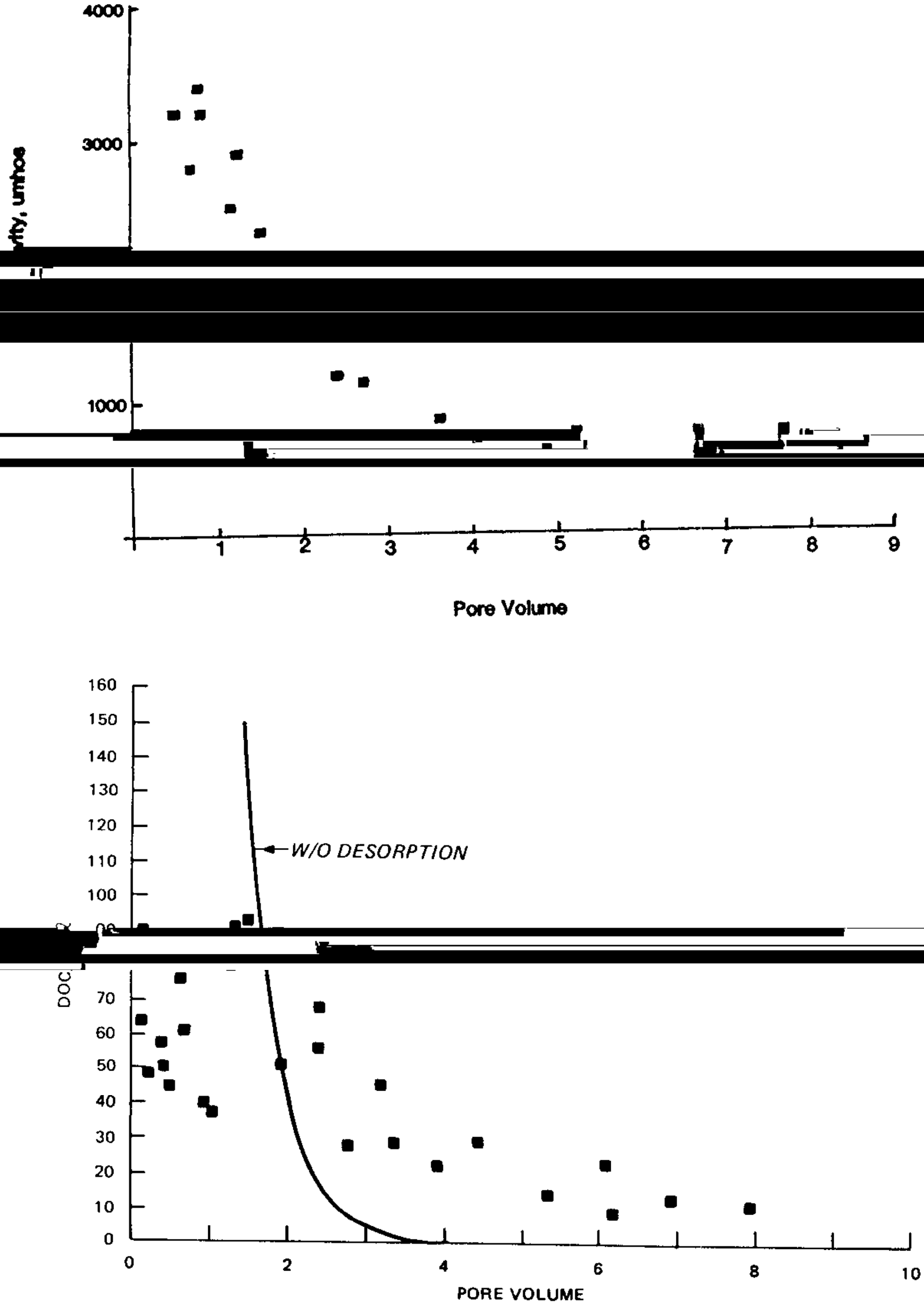


Figure G15. Conductivity and dissolved organic carbon in anaerobic permeameter leachate during metal leach test

[redacted]

Table G5.

85. Predicted concentrations have been plotted for two conditions. The [redacted] equilibrium-controlled, linear desorption and that the equilibrium distribution coefficient is adequately described by the K_d obtained using sequential batch leach tests. The second condition assumes that desorption does not occur; that is, K_d is equal to zero. In both cases, the interstitial water [redacted]

c. Chromium concentrations were above detection limits but did not follow either predictive curve.

d. Observed DOC concentrations were somewhat erratic; however, the shape of the plot suggests that desorption was involved during the release of organic carbon.

e. The conductivity data showed a typical washout curve with some desorption occurring.

86. Anaerobic permeameters: organic compounds and DOC. The concentra- [redacted] detected in the anaerobic permeameter leachates. One of the Aroclor 1248 con- [redacted] but not in all samples. The concentrations of each congener that was detected [redacted]

87. Predicted and observed curves were prepared for total Aroclor 1248 [redacted] E-05 cm^2/sec, $\rho = 0.741$ kg/ℓ, and $\theta = 0.61$. The K_d value that was used is listed in Table G27, and the C_I value is listed in Table G38. As with the anaerobic metals, two predictive curves were developed. One assumed that

Table G36

Summary of Organic Contaminants that were Below the Detection Limit in Anaerobic Permeameter Leachates

Compound	Detection Limit mg/ℓ
1	0.005
2	0.005
[redacted]	[redacted]
4	0.005
5	0.005
6	0.005
7	0.005
8	0.005
9	0.005
10	0.005
11	0.005
12	0.005
[redacted]	[redacted]
14	0.005
15	0.00001
20	0.00001
2 7Permeameter (15	0.00001

Table G37

[redacted]ongeners and DOC Concentrations (mg/ℓ)

[redacted]ates from Anaerobic Permeameters

					[redacted]ompound								
Pore Volume	16	17	18	19	[redacted]	23	24	25	26	[redacted] 8	29	DOC	Total Detected Aroclor 1248 Congeners
						Permeameter No. 4							
0.40	0.00002	0.00002	0.00004	<0.00001	[redacted] 002	<0.00001	0.00003	<0.00001	0.00003	[redacted] 0006	0.00006	173	0.00030
1.19	<0.00001	<0.00001	<0.00001	<0.00001	< [redacted] 001	<0.00001	<0.00001	<0.00001	<0.00001	[redacted] 0001	0.00001	104	-
1.98	<0.00001	0.00001	0.00001	<0.00001	[redacted] 001	0.00001	0.00001	0.00002	<0.00001	[redacted] 0002	0.00001	72	0.00011
2.76	<0.00001	<0.00001	<0.00001	<0.00001	< [redacted] 001	0.00002	0.00002	<0.00001	<0.00001	[redacted] 0005	<0.00001	45	0.00009
						Permeameter No. 5							
0.35	0.00002	<0.00001	<0.00001	<0.00001	< [redacted] 001	<0.00001	0.00003	<0.00001	0.00001	< [redacted] 0001	<0.00001	160	0.00006
1.05	<0.00001	<0.00001	<0.00001	<0.00001	< [redacted] 001	<0.00001	<0.00001	<0.00001	<0.00001	[redacted] 0001	0.00001	90	-
1.76	<0.00001	<0.00001	<0.00001	<0.00001	< [redacted] 001	0.00001	0.00001	<0.00001	<0.00001	< [redacted] 0001	<0.00001	70	0.00003
2.46	0.00002	0.00001	<0.00001	<0.00001	< [redacted] 001	<0.00001	<0.00001	<0.00001	<0.00001	< [redacted] 0001	<0.00001	43	0.00003
						Permeameter No. 6							
0.35	0.00002	0.00002	0.00003	<0.00001	[redacted] 001	<0.00001	<0.00001	<0.00001	0.00002	[redacted] 0002	<0.00001	160	0.00013
1.04	<0.00001	<0.00001	<0.00001	<0.00001	< [redacted] 001	<0.00001	<0.00001	<0.00001	<0.00001	[redacted] 0001	0.00001	118	-
1.73	<0.00001	<0.00001	<0.00001	0.00006	< [redacted] 001	<0.00001	<0.00001	<0.00001	<0.00001	< [redacted] 0001	<0.00001	72	0.00007
2.45	<0.00001	<0.00001	<0.00001	<0.00001	< [redacted] 001	<0.00001	<0.00001	0.00009	<0.00001	< [redacted] 0001	<0.00001	45	0.00009

Note: Compound numbers 15, 20, and 27 were <0.00001 [redacted]ples.

Table G38

Comparison of C_I to C_{max} for Anaerobic Permeameter

[illegible]	[illegible]	[illegible]
1	1.172	<0.005
2	0.006	<0.005
3	0.019	<0.005
4	0.012	<0.005
5	0.017	<0.005
6	0.002	<0.005
7	0.006	<0.005
8	0.005	<0.005
9	0.003	<0.005
10	0.002	<0.005
11	0.005	<0.005
12	0.005	<0.005
13	0.005	<0.005
14	0.005	<0.005
15	UD	<0.00001
16	0.00007	0.00002
17	0.00001	0.00002
18	0.00008	0.00004
19	0.00002	0.00006
20	0.00003	<0.00001
21	0.00001	0.00002
[illegible]	[illegible]	[illegible]
26	0.00002	0.00003
27	UD	<0.00001
[illegible]	[illegible]	[illegible]
Total PAH	[illegible]	[illegible]
Total PCB	0.00054	0.00030

[illegible]

** C_{max} = maximum value observed in anaerobic permeameter leachate.

UD not detected in sediment.

[redacted]

and the other assumed that no desorption was occurring, i.e., K_d was equal to zero. Figure G16 is a plot of total Aroclor 1248 congener concentration

[redacted]

[redacted]

and the other assumed that no desorption was occurring, i.e., K_d was equal to zero. Figure G16 is a plot of total Aroclor 1248 congener concentration

[redacted]

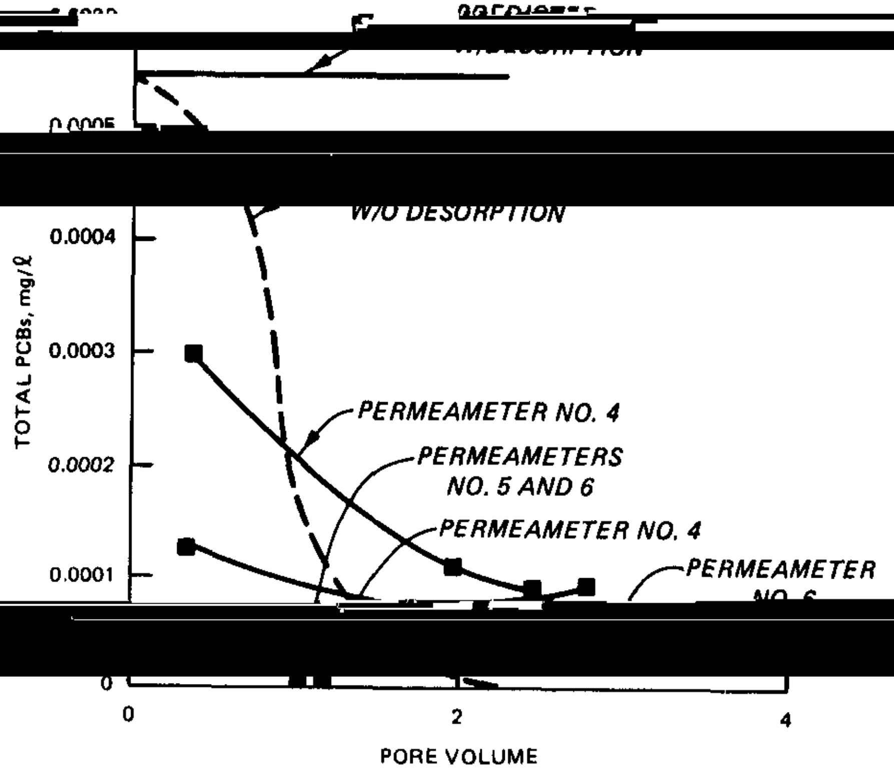
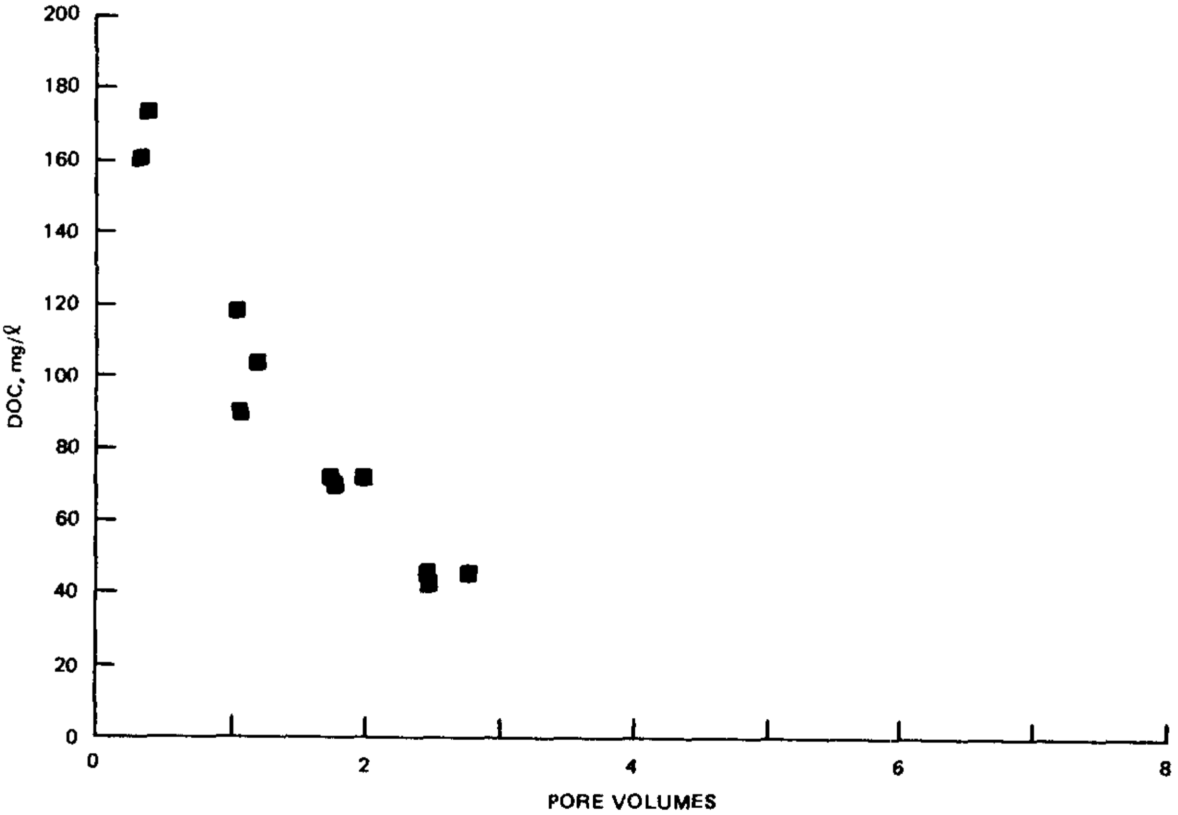


Figure G16. Total PCB concentrations in anaerobic permeameter leachate



[redacted]

Table 39

Metal and DOC Concentrations and Conductivity in Leachate from Aerobic Permeameters

Permeameter 1A

Pore Volume	As (mg/ℓ)	Cd (mg/ℓ)	Cr (mg/ℓ)	Pb (mg/ℓ)	Zn (mg/ℓ)	DOC mg/ℓ	Conductivity μmhos
0.27	0.008	0.0414	0.009	0.002	0.305	603	4500
0.72	0.003	0.0462	0.008	0.001	0.289	621	4300
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
2.64	0.016	0.0005	0.007	0.009	<0.03	246	3350
3.04	0.015	0.0005	0.006	0.004	<0.03	197	3300
4.40	0.013	0.0005	0.004	<0.001	<0.03	119	2800
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
8.98	*	*	*	*	*	64	1975
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

Pore Volume	As (mg/ℓ)	Cd (mg/ℓ)	Cr (mg/ℓ)	Pb (mg/ℓ)	Zn (mg/ℓ)	DOC mg/ℓ	Conductivity μmhos
0.14	0.011	0.0125	0.009	0.003	0.113	637	4100
0.44	0.010	0.0995	0.010	0.002	0.116	542	4400
0.74	0.010	0.0134	0.009	0.003	0.107	604	4600
1.10	0.013	0.0103	0.011	0.002	0.070	433	4300
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
2.36	0.005	0.0130	0.002	0.003	0.027	20	740
3.29	<0.005	0.0005	<0.001	0.001	<0.03	20	600

Permeameter 3A

Pore Volume	As (mg/ℓ)	Cd (mg/ℓ)	Cr (mg/ℓ)	Pb (mg/ℓ)	Zn (mg/ℓ)	DOC mg/ℓ	Conductivity μmhos
0.14	0.012	0.0130	0.009	0.001	0.089	549	4100
0.47	0.012	0.0276	0.007	0.003	0.114	560	4400
0.80	0.012	0.0025	0.008	0.001	0.104	541	4400
1.18	0.012	0.0100	0.009	0.006	0.084	434	4000
1.54	0.012	0.0127	0.008	0.002	0.002	292	3750
2.36	0.013	0.0009	0.007	0.001	0.036	227	3100
3.16	0.009	0.0003	0.004	0.002	<0.030	121	2350
3.92	0.015	0.0006	0.004	0.008	<0.030	88	2300
4.65	0.011	0.0031	0.006	0.005	0.044	87	2100
6.38	0.011	0.0019	0.003	0.001	0.041	76	2300
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

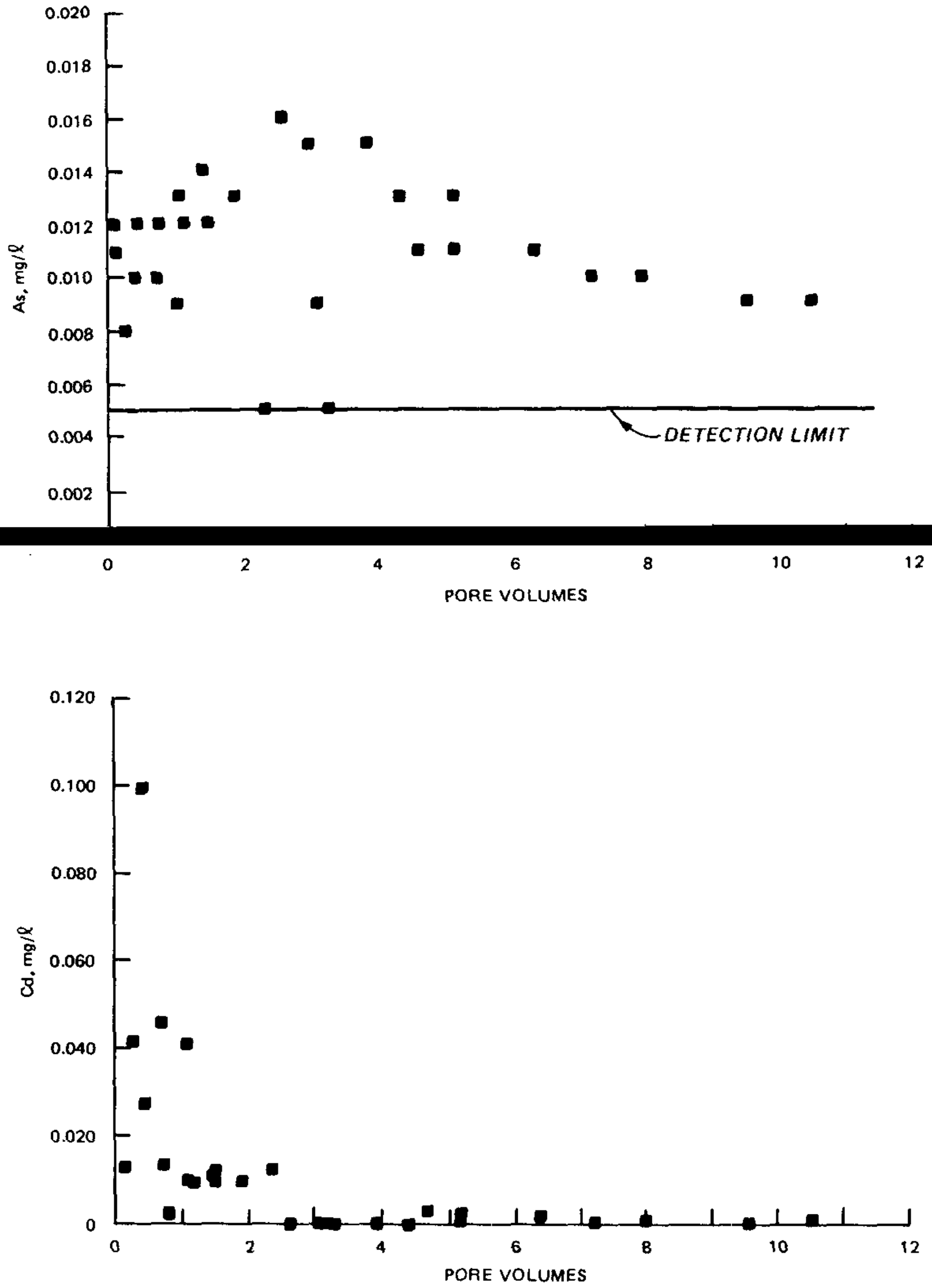


Figure G18. Arsenic and cadmium in aerobic permeameter leachate

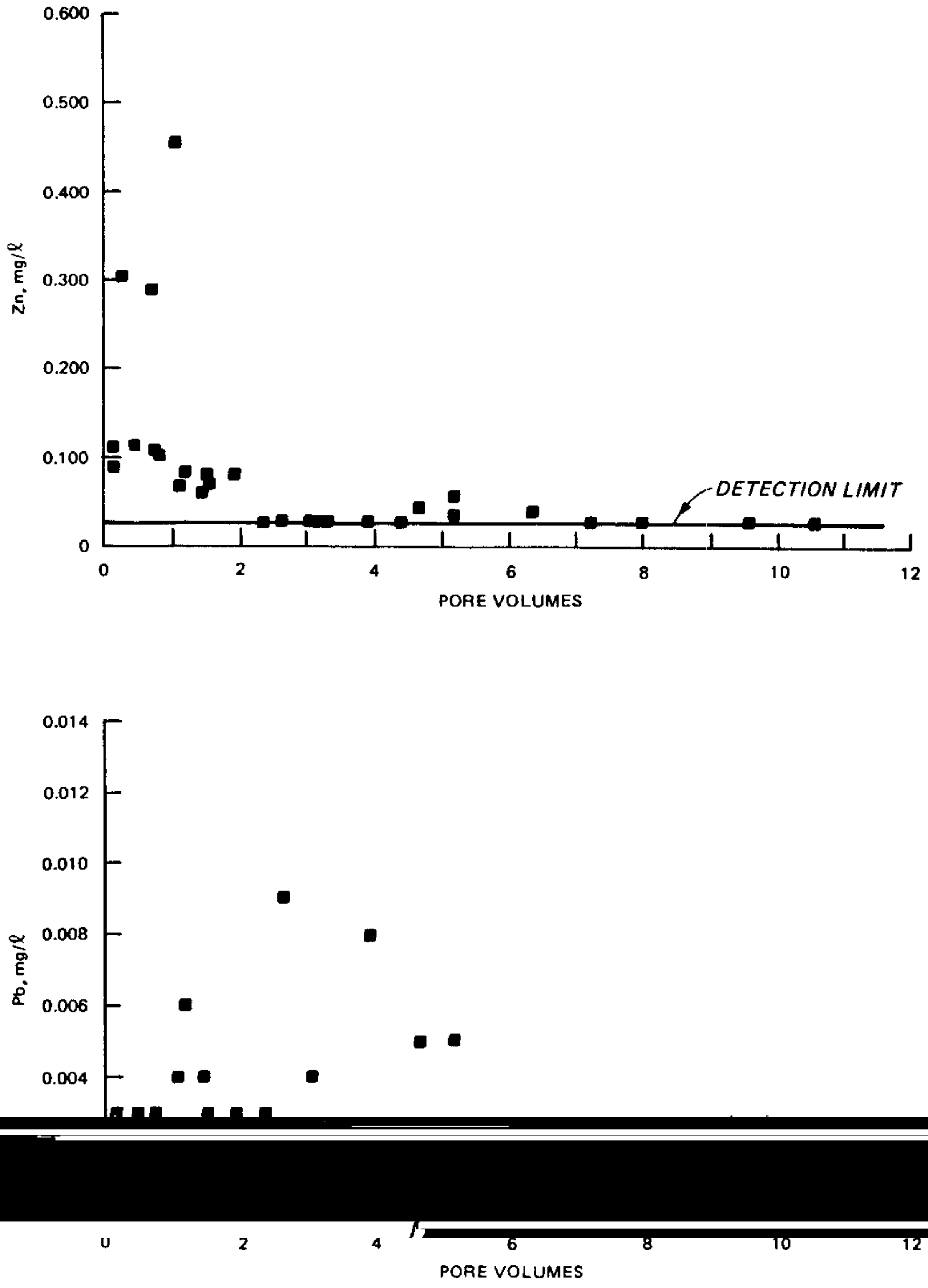
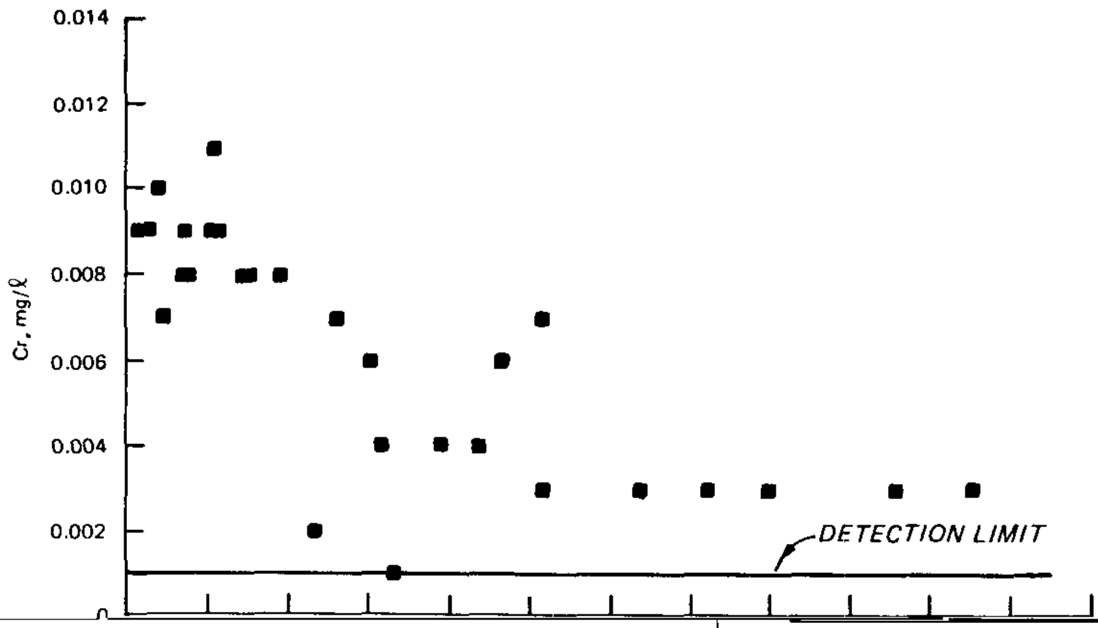
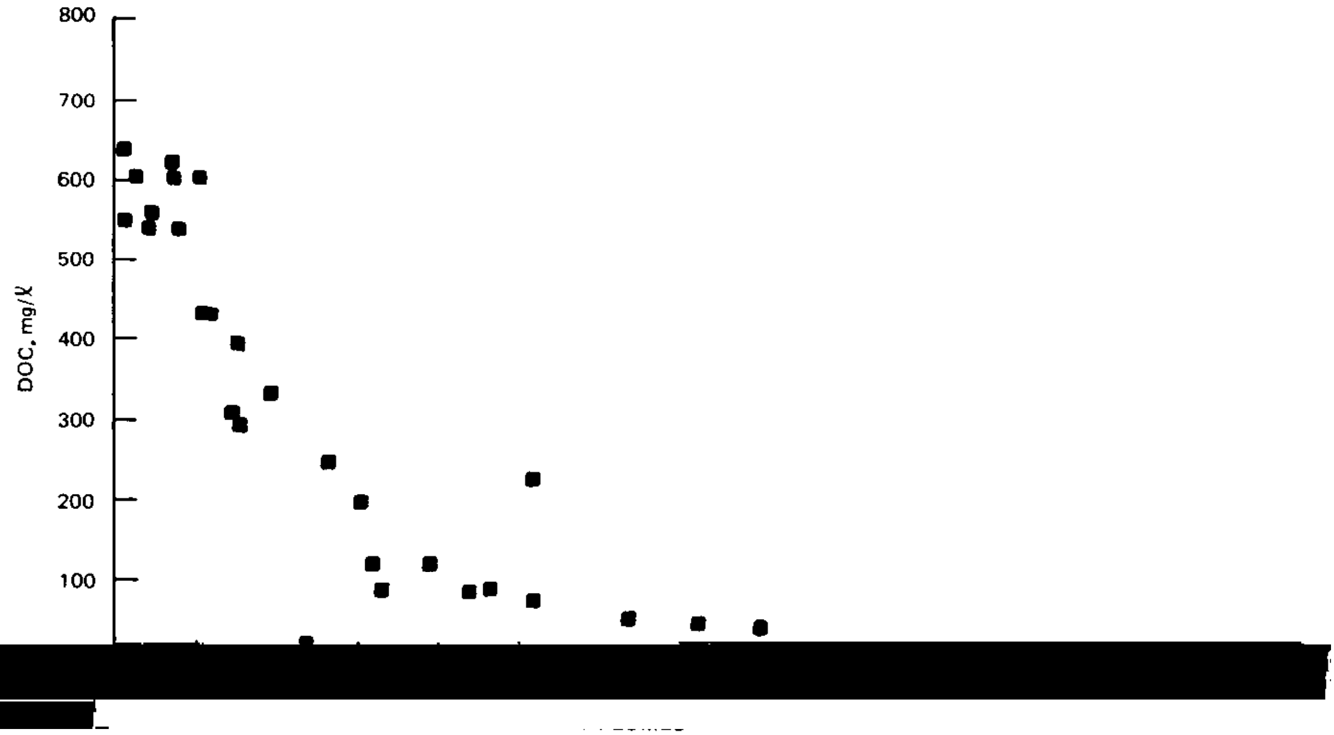


Figure G19. Zinc and lead in aerobic permeameter leachate


0.014
0.012
0.010
0.008
0.006
0.004
0.002
Cr, mg/ℓ
DETECTION LIMIT



[redacted]

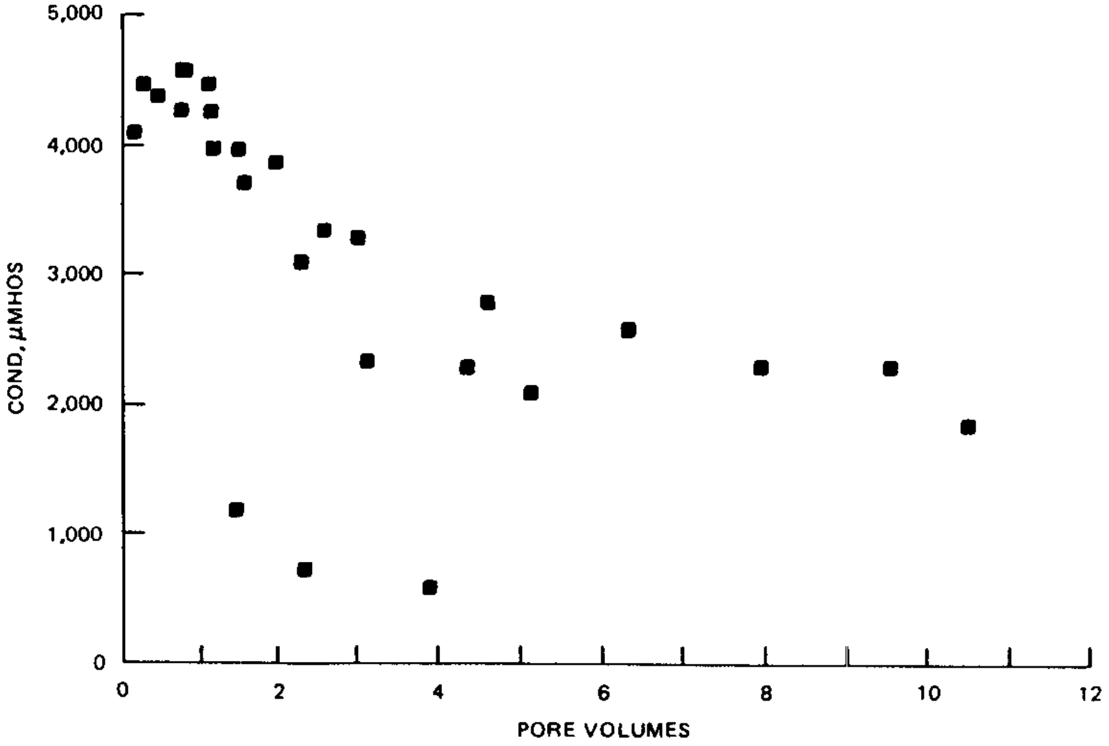


Figure G81. Dissolved organic carbon and conductivity in aerobic

[redacted]

Table G40

Summary of Organic Contaminants that were Below the

[redacted]

Compound	mg/ℓ
2	0.005
3	0.005
4	0.005
5	0.005
6	0.005
7	0.005
8	0.005
9	0.005
10	0.005
11	0.005
12	0.005
[redacted]	[redacted]
14	0.005
15	0.00001
27	0.00001

concentration and the corresponding pore volumes for each aerobic permeameter are listed in Table G41. Plots similar to those for anaerobic sediment are shown in Figure G22 for total Aroclor 1248 congener concentration and Fig-

[redacted]

[redacted]

detection limits to 0.07136 mg/ℓ.

[redacted]

permeameters at uniform density and moisture content. Initially, the sediment

[redacted]

tom were retained by the Teflon fabric in the bottom. Consolidation occurred from the bottom up (denser layers at the bottom) as additional particles accumulated at the bottom. At the conclusion of the permeameter leaching tests,

[redacted]

ity decreases, the permeability of the sediment decreased as the permeameter tests proceeded. Column operating records indicated that the permeability of anaerobic permeameters was 8.66 × 10^{-8} cm/sec at the beginning of the tests

[redacted]

operation of the permeameters. In the field, self-weight consolidation is much slower than the flow-induced consolidation observed in the permeameters.

[redacted]

Discussion of permeameter results and integrated approach

[redacted]

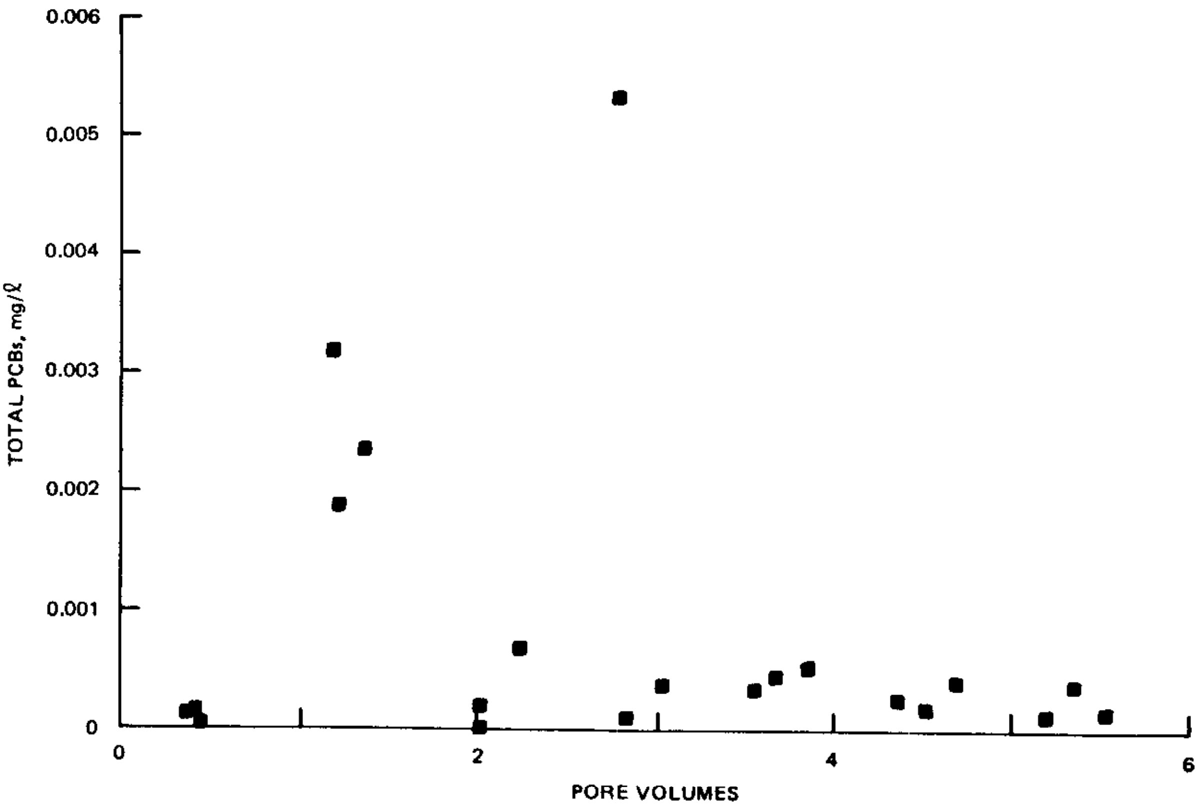


Figure G22. Total PCB concentrations in aerobic permeameter leachate

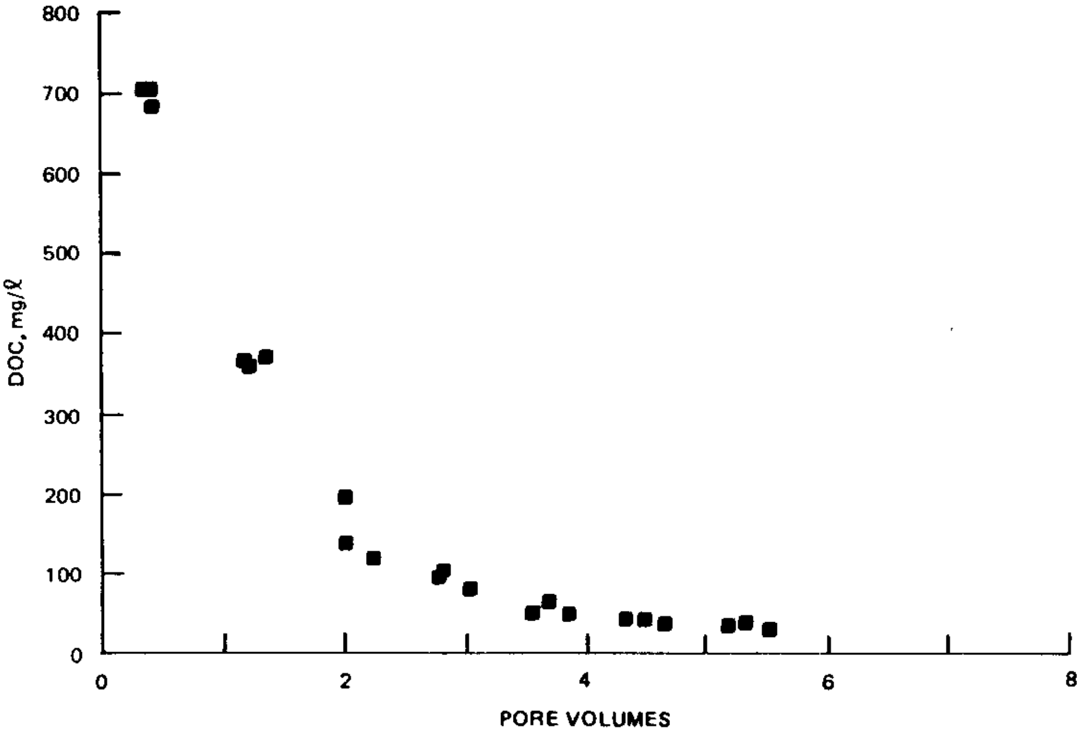


Figure C23. Dissolved organic carbon concentrations in aerobic

Table G41

Aroclor 1248 Congener and DOC Concentrations (mg/ℓ) in Leachates from Aerobic Permeameters

Pore	Organic Compound Number														DOC	Total Detected Aroclor 1248
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
3.57	<0.006	0.00006	<0.00001	<0.00001	<0.00001	0.00006	<0.00001	<0.00001	0.00005	<0.00001	0.00001	0.00008	0.00005	0.00005	52	0.00035
4.36	<0.006	0.00008	<0.00001	<0.00001	<0.00001	0.00004	<0.00001	<0.00001	<0.00001	<0.00001	0.00003	0.00005	0.00007	<0.00001	42	0.00027
5.19	<0.006	0.00011	<0.00001	<0.00001	0.00001	<0.00001	<0.00001	<0.00001	<0.00001	<0.00001	0.00001	<0.00001	<0.00001	<0.00001	35	0.00013
								Permeameter No. 9								
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
4.51	<0.006	0.00006	<0.00001	<0.00001	<0.00001	0.00004	<0.00001	<0.00001	<0.00001	<0.00001	0.00005	<0.00001	0.00005	<0.00001	41	0.00020
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

and observed are discussed below.

[redacted]

departure of predicted from observed began with the initial value. The average value for the interstitial water extractions for these metals did not provide a good estimate for C_I, the starting point for the predicted curves. The average interstitial water concentrations for chromium, lead, and zinc were well above the concentrations in the first permeameter leachate samples. Consequently, the predicted curves started out higher than the observed per-

[redacted]

is considered, the starting point for the predicted curve can be placed closer to the observed data, but still not with the observed range. Chromium and lead were at or near the detection limit throughout the permeameter tests. Zinc was initially measurable in the permeameter leachate, but after the first sample, zinc concentrations were below the detection limit.

93. The starting point of the predicted curves for arsenic and cadmium was in the range of metal concentrations observed in the first sample collected from the anaerobic permeameters. However, the concentrations of arsenic and cadmium in the permeameter leachates decreased more rapidly than the batch K_d predicted. This indicates that the batch K_d for arsenic and cadmium overestimated the apparent K_d for the permeameters. This difference in batch K_d and apparent permeameter K_d is probably related to the high oil and grease concentrations originally present in the sediment. In the sequential batch tests the oil and grease were dislodged from the sediment by the vigorous shaking inherent in the procedure. In the permeameters the oil

[redacted]

metal sorption processes between the sediment solids and the pore water.

94. The differences between interstitial water metal concentrations and the initial concentrations in permeameter leachates are not as easily

[redacted]

95. The predicted concentrations for total Aroclor 1248 congeners were also conservative (larger) compared with the observed concentrations. As

[redacted]

was noted. When K_d is large, the source term completely overwhelms the other terms in the permeant-porous media equation. Figure G24 shows the

[redacted]

of Equation [illegible] to predict contaminant concentration is not necessary when K_d

[redacted]

in the batch testing for the organic compounds did not produce reliable val-

[redacted]

97. Table G38 also presents the maximum concentration measured in the permeameter leachates for each organic compound. The differences between C_I and C_{max} are an indication of how conservative predictions based on batch leach data are relative to observed data from a continuous-flow system. Theoretically, C_I should always be greater than C_{max}. A situation where C_{max} is greater than C_I implies that the continuous-flow system in the permeameters has departed significantly from model assumptions, or it may indicate

[redacted]

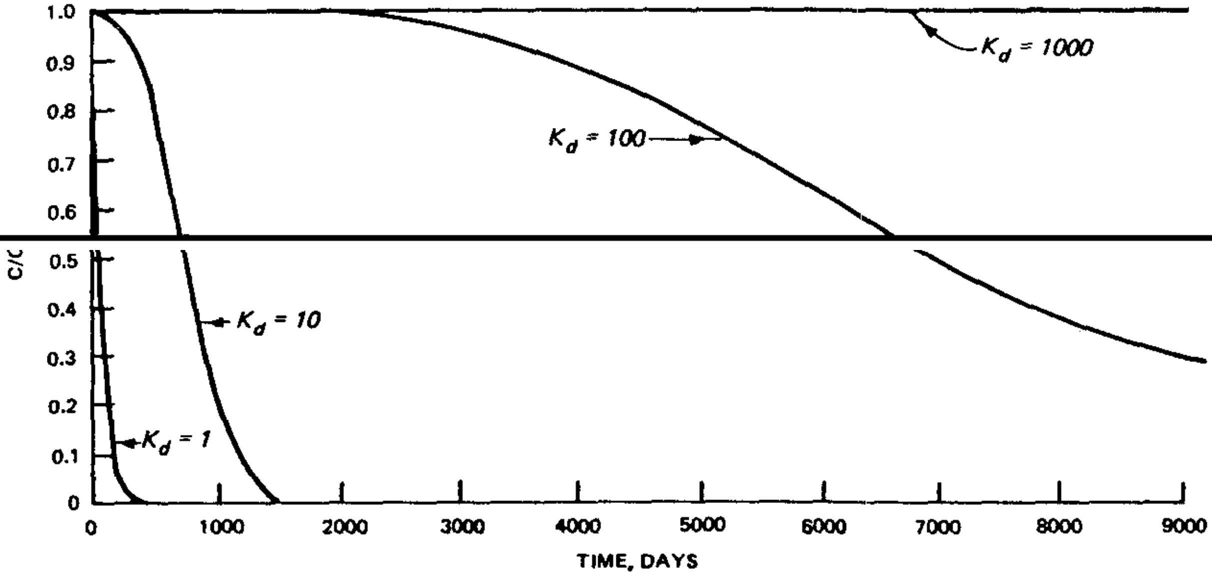


Figure G24. Fraction initial concentration remaining in permeameter leachate for various distribution coefficients

[redacted]

the permeameter leachate. Initially, the leachate was reddish-orange (ferric oxyhydroxides) and turbid, then turned black and turbid and remained so throughout the remainder of the test. Therefore, since aerobic batch and permeameter leach tests did not undergo equivalent leaching conditions, batch-determined distribution coefficients were not considered applicable to leaching in the "aerobic" permeameters.

100. Another point requiring explanation is the relative scatter in the aerobic column data compared with the anaerobic column data. This scatter is

[redacted]

the oxidation-reduction potential of the sediment in the "aerobic" permeam-

[redacted]

eral possible explanations are:

a. Initially, contaminants were adsorbed onto the surfaces of col-

[redacted]

c. The peaks are experimental artifacts caused by contamination

[redacted]

e. The peaks are related to changes in sediment geochemistry and desorption properties.

102. It is difficult to reconcile the first two explanations with all of the data. If contaminants are initially adsorbed and the delayed peaks represent the time required for the permeameter leachate and the collection appa-

[redacted]

classic washout curve and no indication that the permeameters were not functioning properly hydraulically or that slugs of oil were being released from the permeameters. On the basis of this analysis, it is likely that explanations d and e, alone or in combination, account for the peaks. Since the peaks represent a significant increase in contaminant concentration further study is needed to determine the cause or causes.

103. The aerobic permeameter tests, as discussed above, did not simulate contaminant leaching in a crust of oxidized sediment in a mature CDF. It is difficult, probably impossible, to determine exactly what type of field situation the aerobic permeameter tests represent. It should be noted that the leaching environment that began in a moist, aerobic condition followed by a

[redacted]

that the desorptive properties of dredged material may change for the worse in an upland CDF in particular, if the oxidation-reduction potential varies widely. This does not necessarily mean that contaminant flux will be worse since interphase contaminant transfer must be coupled with hydraulic flux in

[redacted]

constants. Several of these parameters depend on sediment porosity. The dispersion coefficient D_p and the pore water velocity V are flow-related [redacted] therefore D_p , V , ρ , θ , and the sediment pore volume used to calculate [redacted] coefficients could be used to develop predictive curves that account for consolidation. Although a more sophisticated predictive equation would be expected to improve the accuracy of the predicted curves, such an equation was not used in this study for two reasons.

[redacted] sitive to D_p , and extremely sensitive to C_I and K_d . Since C_I and K_d are not related to consolidation, the use of a predictive model that accounts for the effects of consolidation would not change the starting point for the predictions, C_I , or significantly change the shape of the predicted curve, K_d .

106. Second, development of the functional relationships for consolidation [redacted] not within the scope of this study.

computer q0n62 a26 Tc 028 2 Tw (wscop) Tj 0 Tr 20.5714 0 TD 3 Tr -0.3 Tc 0.8071 Tw (analysis) Tj 0 Tr 61.7141 0

107. The final limitation of the predictive equation relates to biodegradation. Equation G7 does not include a term for biodegradation. For contaminants with high distribution coefficients, Equation G7 predicts that the initial leachate concentration will persist indefinitely. In this case, the the biodegradation term could become important. The rates at which organic [redacted]

Conclusions

108. An integrated approach to leachate testing involving batch and column [illegible] useful tool for investigating the processes that govern contaminant leaching from sediment solids. Results of the test procedures described in this appendix showed that metal and organic contaminants associated with Indiana Harbor sediment are tightly bound to the sediment. The leachate data provided in this appendix, in part, provide the basis for performing contaminant flux [illegible]

General

109. General conclusions include:

a. Evaluation of the governing principles of leachate formation and [illegible] the sediment solids to the aqueous phase must be coupled with hydraulic flux in order to adequately evaluate contaminant leaching. Without hydraulic flux, leachate is not transported, and without interphase transfer, contaminated leachate is not formed.

b. [illegible] for 6 months resulted in losses of PAHs and PCBs on the order of 80 percent. If volatilization is assumed to be the mechanism [illegible]

c. The amount of contaminant released from batch and column leach [illegible]

Batch testing

110. Batch testing conclusions include:

a. The presence of contaminated oil imposed severe operational and analytical difficulties on all phases of batch testing. Complete separation of oil from leachate samples was required in order to obtain valid distribution coefficients.

[illegible] tests.

c. Organic contaminants in Indiana Harbor sediment are tightly [illegible] for PCBs.

d. The batch procedures for determining distribution coefficients for organic compounds can be simplified by using the batch equilibrium method instead of the sequential leach procedure.

Additional study, development, and verification of the integrated [illegible]

4. Sediment acquisition, mixing, and transportation procedures have been

[redacted]

commercially available. Firmix was obtained from Trident Engineering, Balti-

[redacted]

strength testing, standard Corps of Engineers (CE) compaction molds for trafficability and chemical leach testing, and 2.8-in. diam cylindrical molds for permeability testing. The samples were cured at 98-percent relative humidity and 23 °C until tested. A standard cure time of 28 days was used in all of

[redacted]

cement process. Four portland cement formulations were tested. The formulations for each process differed in respect to the dosage of setting agent used,

[redacted]

lations, data were obtained for making comparisons among processes and process formulations.

7. The experimental matrix for the physical/chemical testing is presented in Table H1. The matrix was developed to give a general indication of the

[redacted]

Table H1

Experimental Matrix for Testing of Solidified/Stabilized Indiana Harbor Sediment*

Process	Test UCS	I	P	SCT	Leach
Portland Cement	X	X	X	X	X
Lime-Fly Ash	X	X		X	X
Portland Cement- [redacted]	X			X	X
[redacted]					
Portland Cement-Firmix	X			X	X
Portland Cement-WP	X			X	X
Firmix-WP					X
Firmix	X			X	X

[redacted]

P = permeability.

SCT = strength-cure time curve

[redacted]

conducted on each process formulation and unconfined compressive strength

[redacted]

each determination.

9. Permeability. Triaxial, upflow permeability (hydraulic conductivity)

[redacted]

cast in standard CE compaction molds using a cone penetrometer. Trafficability is reported in terms of cone index (CI) in pounds per square inch. The CI is

[redacted]

above ranges, both penetrometers give satisfactory results. Five replicates were made for each CI determination.

Serial, graded batch leach tests

11. Background. The serial, graded batch leach procedure is a simplifi-

[redacted]

ratios (Houle and Long 1980). A table of solid phase and aqueous phase concentrations is developed from analyses of the leachates produced. These data are plotted to produce a desorption isotherm. This procedure is simpler than the sequential leach procedure because the mass of solids being leached has to be

[redacted]

be accounted for at each step in the sequence.

12. From the desorption isotherm, contaminant-specific coefficients can be obtained that describe the interphase transfer of contaminant from the solid phase to the aqueous phase. The interpretation of data from serial, graded batch leach tests is similar to the interpretation previously described in Appendix G for data from sequential batch leach tests. Of particular impor- [illegible]

$$q = K_d C + q_r \qquad (G5)$$

Equation G5 assumes that a fraction of the solid phase contaminant concentration is resistant to leaching and the solid to liquid phase transfer of the [illegible] concentration C is linear. Two parameters describe the relationship, a distribution coefficient K_d that relates leachable solid phase concentration to [illegible] for solidified/stabilized sediment.

13. Serial, graded batch leach tests can provide the information needed for a permeant-porous media mass transport equation, given certain simplifying assumptions. (Permeant-porous media equations are discussed in Appendix G.) Water is assumed to be the transport medium for the contaminants. Only contaminants on surfaces in contact with moving pore water are available for leaching. Contaminants that are not solubility limited are released by ion exchange and desorption of adsorbed contaminants. It is further assumed that the water [illegible]

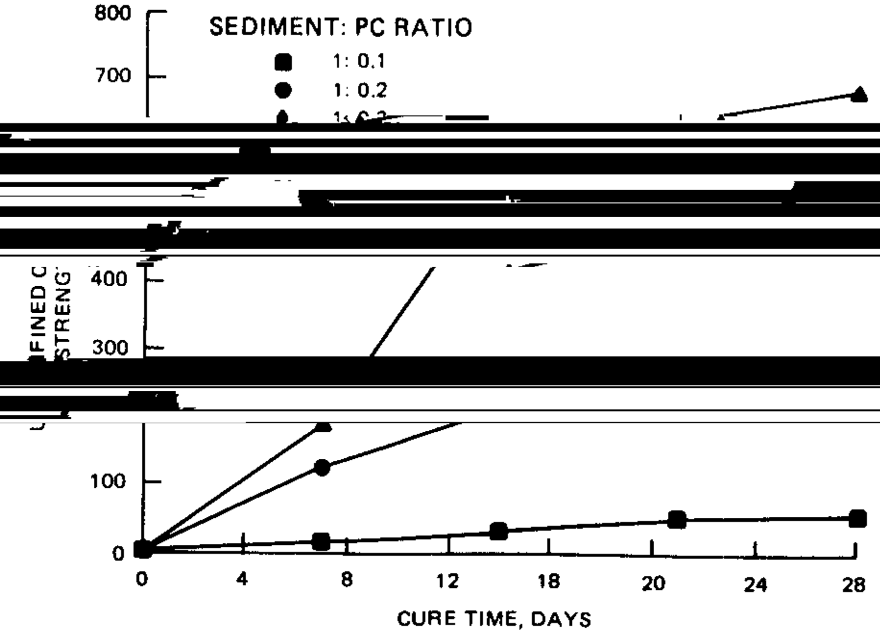
14. The equilibrium assumption is a common assumption in the practical application of permeant-porous media equations (Grove and Stollenwerk 1985; [illegible] 1985). [illegible] chemical kinetics. The transfer of contaminant from the solid phase to the aqueous phase is assumed to be fast in relation to the rate at which water percolates through the solidified/stabilized material. As water percolates [illegible]

through the material, a piecewise equilibrium in space and time is established [illegible] phase concentration versus aqueous phase concentration, as in Figure G-2. The term "desorption" is used here to represent the net result of all reversible processes.

15. The serial, graded batch leach procedure also assumes that the liquid-solids ratio does not affect the chemistry of the leaching process, i.e., the [illegible] ture indicates that this assumption is probably not correct for untreated sediment, although the reason for this is not entirely clear (Voice, Rice, and Weber 1983; Di Toro et al. 1986). For solidified/stabilized sediment, changes in the chemistry of the aqueous phase with varying liquid-solids ratio probably have a more profound effect on interphase contaminant transfer than changes in the concentration of solids. Specifically, if pH varies significantly, the solubility of metals will vary. The excess alkalinity of the solidification reagents, however, tends to stabilize pH.

16. Chemical leach tests. Serial, graded batch leach tests were run on samples taken from the center of the 4-in.-diam specimens cast in compaction [illegible] dure consisted of contacting solidified sediment samples with distilled-deionized water on a mechanical shaker for 24 hr in liquid-solids ratios of: 100 ml:50 g, 100 ml:10 g, 100 ml:5 g, and 100 ml:1 g. In some of the tests, a 100 ml:20 g liquid-solids ratio was included. The extractions were run in triplicate in 250-ml polyethylene bottles laid in the horizontal position. [illegible] Organic carbon was not included in the analysis of leachates from portland cement with fly ash and/or sodium silicate. Blanks were prepared by carrying [illegible] Chemical analysis procedures are described in Appendix G.

17. The chemical leach data were reduced to tables of solid and aqueous phase concentrations using the calculations described below. The solid phase



a. Portland Cement

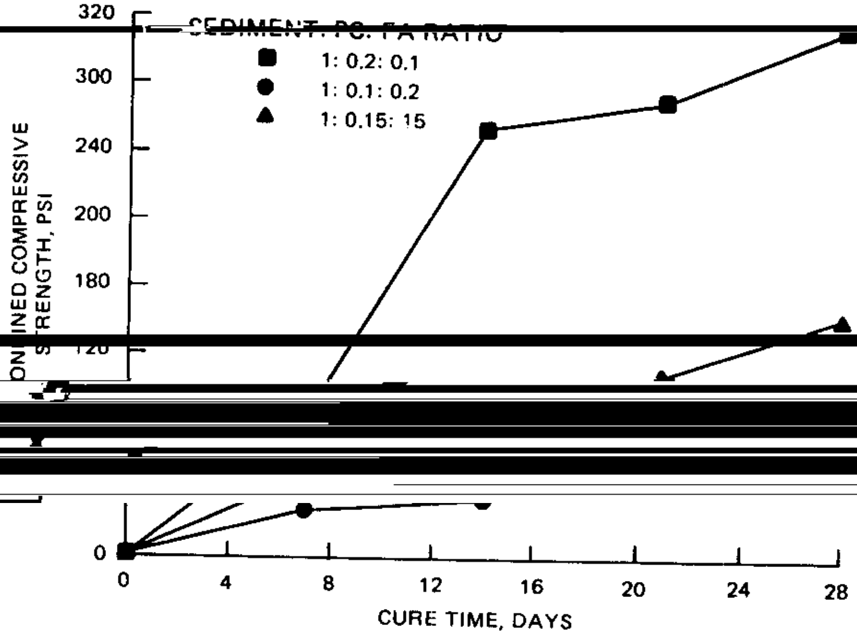
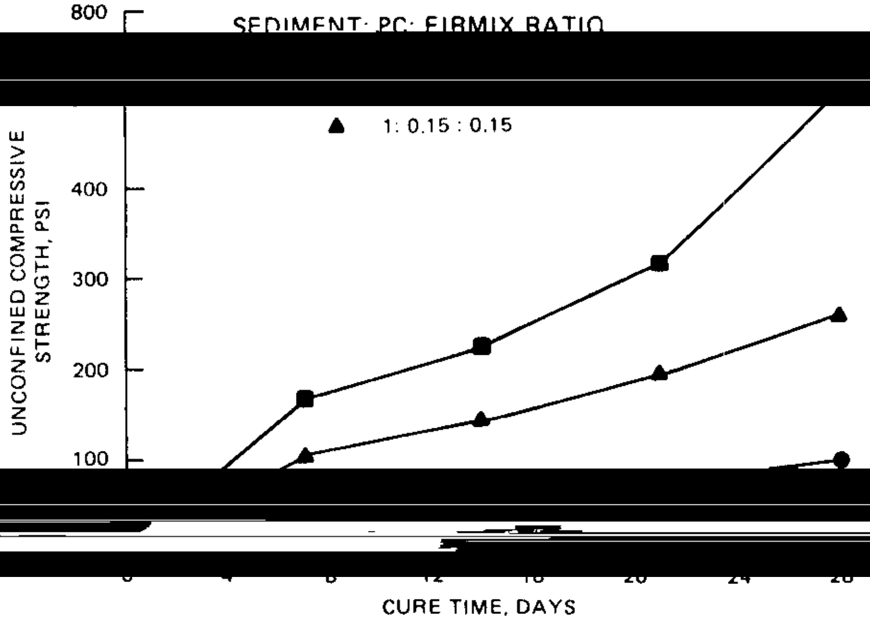
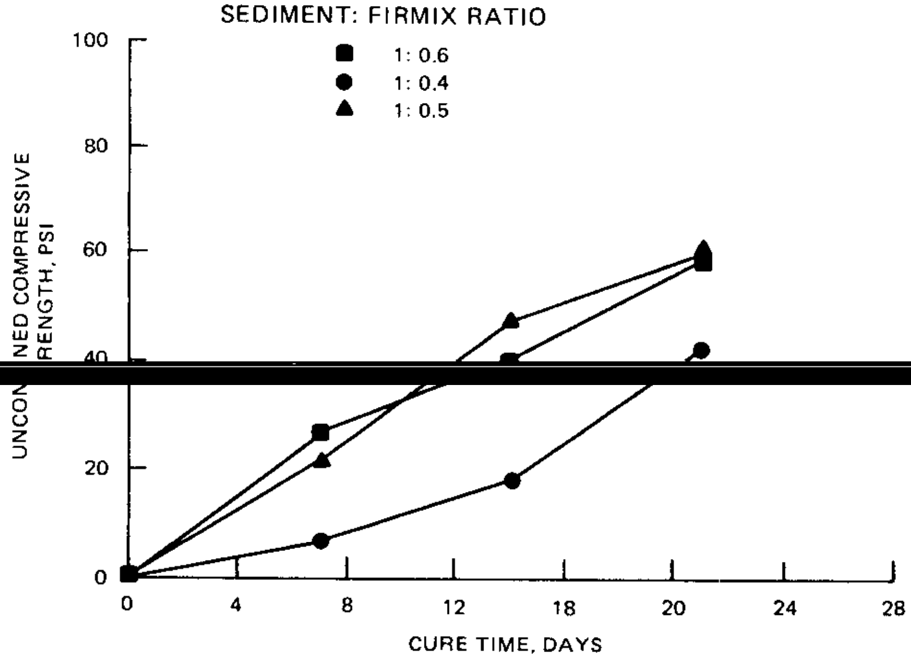


Figure H1. Unconfined Compressive Strength-Cure Time Curves for



a. Portland Cement with Firmix



b. Firmix

Figure H2. Unconfined Compressive Strength-Cure Time Curves for [illegible]

[illegible]

[illegible]

After [illegible] | Before [illegible] | Mass Solidified [illegible]

[illegible]

$$q = q_o - C(V/M) \qquad \text{(H1)}$$

where

[illegible]

q_o initial contaminant concentration in the solid phase, mg/kg

[illegible]

Equation H1 relates to a single contaminant. Since the liquid-solids ratio L/S is given by

$$L/S = V/M$$

Equation H1 can be written as

$$q = q_o - C(L/S) \qquad \text{(H2)}$$

Equation H-1 was used to calculate the solid phase concentration q corresponding to the aqueous phase concentration determined by chemical analysis for the liquid-solids ratio used. Since all the tests used 100 ml of distilled deionized water [illegible]

[illegible]

given by the following equation:

[illegible]

$$q_o = \frac{S_x}{(1 + w)\ (1 + R)} \qquad \text{(H-3)}$$

where

S_x = contaminant concentration in the sediment before solidification, mg/kg (dry weight basis)

w = moisture content of the wet sediment, kg water/kg sediment solids

R = dosage of solidification/stabilization reagents,

[redacted]

given in Table 1 in the main body of this report.

[redacted]

plotting q versus C . Determination of the distribution coefficient K_d and the solid phase contaminant concentration resistant to leaching q_r varied slightly, depending on the liquid-solids ratios at which contaminants were detected in the leachates. When the aqueous phase concentration was above the detection limit at three or more liquid-solids ratios and the data were not clustered K_d and q_r were determined by least squares analysis of the line

[redacted]

[redacted]

In this case q_r was reported as a greater than value.

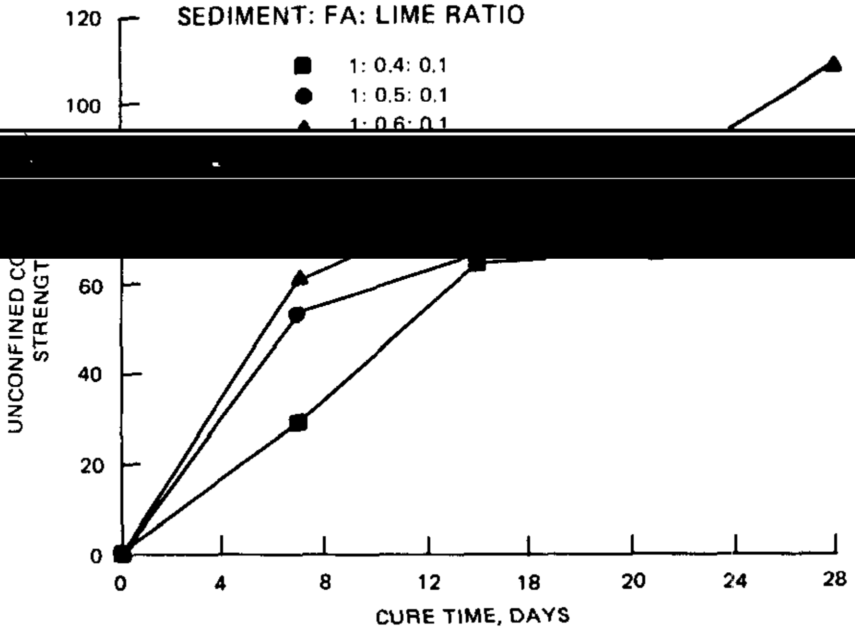
Results

Physical properties

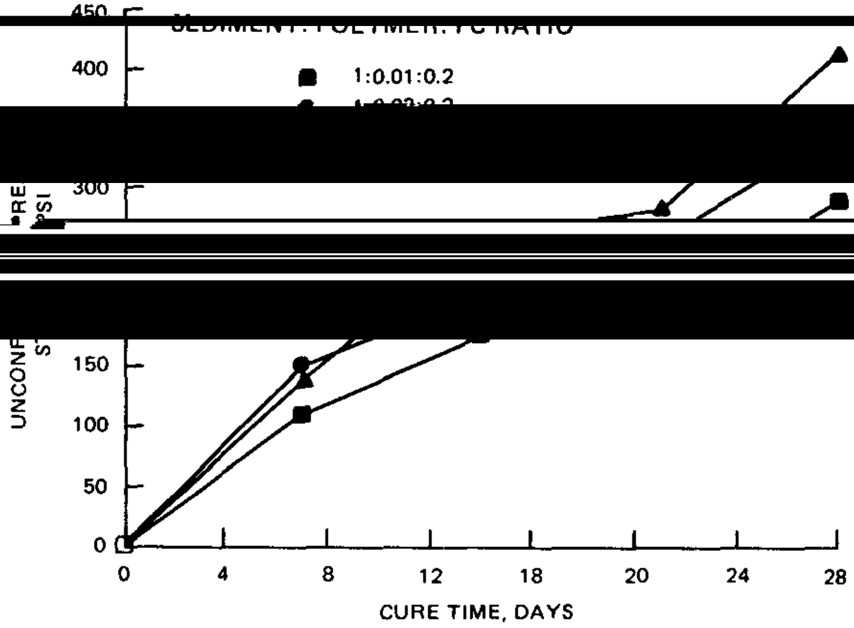
[redacted]

cement with fly ash, portland cement with Firmix, portland cement with WEST-P, Firmix, and lime with fly ash processes was measured at cure times of 7, 14,

[redacted]



a. Fly Ash with Lime



b. Portland Cement with Polymer

Figure H3. Unconfined Compressive Strength-Cure Time Curves for Indiana Harbor Sediment Solidified/Stabilized Using Fly Ash with Lime and Portland Cement with WEST-Polymer the figures are averages of either three or six replicates. The 7- and 21-day [redacted]

cement to sediment was 682 psi. In the processes involving portland cement [redacted]

as the setting agent showed increased strength for dosages above a 0.4:1 weight [redacted]

cement:sediment formulation.

23. The UCS data in Figures H1b and H2a show the relative effect of portland cement substitution using either fly ash or Firmix. The UCS for 0.2 portland cement:1 sediment and 0.3 portland cement:1 sediment formulations were compared with the UCS for the 0.1 fly ash:0.2 portland cement:1 sediment and the 0.1 Firmix:0.2 portland cement:1 sediment formulations. The data for this comparison are summarized in Table H2. It should noted that these formulations have a total additive-to-sediment weight ratio of 0.3:1. Substitution with fly ash produced a product with strength no better than that of the 0.2:1 portland cement process. These results indicate that there would be no eco- [redacted]

Table H2

Comparison of UCS for Various Portland Cement/Additive Formulations

	UCS, psi, for Indicated Cure Time, days			
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
0.1:0.2:1 (FM:PC:S)	168.3	226.2	319.1	507.9
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

* S = sediment.
PC = portland cement.
FM = Firmix.
FA = fly ash with lime.

require about the same amount of portland cement. Substitution with Firmix provided a product strength in between that for the 0.2:1 and 0.3:1 portland cement:sediment formulations. Thus, portland cement substitution with Firmix

[redacted]

grease and other contaminants in the sediment. However, the steady gain in strength with cure time that was recorded for most of the process formulations

[redacted]

the strength versus cure time curves for the various processes showed that

[redacted]

clean sediments. Firmix usually reaches maximum strength in about 30 days with clean sediments.*

26. The range in product strengths, 48.5 to 682 psi, is indicative of the versatility and flexibility of solidification as a treatment process for immobilizing the contaminated solids in Indiana Harbor Sediment. For compari-

[redacted]

Table H3

UCS of Various Materials

Material	Type	UCS, psi
Clay	Very soft	<3.5
	Soft	3.5-7
	Medium	7-14
	Stiff	14-28
	Hard	28-56
	Very hard	56
[redacted]	[redacted]	[redacted]
Soil-like	FGD sludge	23-43
[redacted]	[redacted]	[redacted]
	Calcium fluoride sludge	25

sediments had strengths above the range normally associated with hard clay andX solidified industrial sludge and below the range normally associated with soft concrete.

27. Permeability. The permeabilities of portland cement:sediment formulations of 0.1:1, 0.2:1, and 0.3:1 (weight ratios) were 1.4×10^{-5}, 3.9×10^{-6}, and 6.7×10^{-6} cm/sec, respectively. Permeability partly determines the rate

[redacted]

for the portland cement products are in the range of published values for

[redacted]

Appendix G), though there is disagreement in the literature as to whether these methods of permability analysis are applicable to solidified wastes.

28. Trafficability. The cone index (CI) for the portland cement and the fly ash with lime processes was measured at various cure times. These data are presented in Table H4. The use of CI as an indicator of trafficability is

[redacted]

passes of tracked vehicles and most all-wheel-drive vehicles. If traffic is limited to tracked bulldozers and loaders, a minimum CI of 50 psi is satisfactory. The CI data showed that all of the portland cement formulations except

[redacted]

for the weakest (0.1:1 weight ratio of portland cement:sediment) were trafficable after 1 day. If traffic is limited to tracked vehicles, the lime with fly ash formulations were trafficable after 1 day. In considering trafficability, a conservative approach is recommended because field application of CI

[redacted]

1986). CI correlates to the amount of critical solidification agent in a process formulation, is indicative of the strength of the solidified product, and follows a predictable increase that is a function of cure time.

Chemical leach data

30. General. A summary of the analysis of 16 blanks is presented in Table H5. Table H5 lists the range, mean, standard deviation, limit of the 95-percent confidence interval for the mean, and detection limits for arsenic, cadmium, chromium, lead, zinc, and organic carbon. The blanks were generally

[redacted]

Table H4

[redacted]

Process**	Day 1	Day 3	Day 7	Day 14	Day 21	Day 28
Portland CementPortland						
0.1 PC:1 Sed	-	32	59	133	258	294
[redacted]						
Lime with Fly Ash						
[redacted]						
0.1 L:0.6 FA:1 Sed	151	220	385	708	-	>750

---

* Average of five determinations.

** Weight ratios of additive(s) to wet sediment.

PC = portland cement.
Sed = sediment.
L = lime.
FA = fly ash.

Table H5

Summary Statistics for Chemical Analysis of Blanks (N=16)

[redacted]

Number of blanks with concentration below the detection limit	16	3	5	5	11	16
Range	<0.005	<0.0001 to 0.0010	<0.001 to 0.005	<0.001 to 0.006	<0.030 to 0.046	<1.0
Mean, mg/ℓ**	<0.005	0.00048	0.0019	0.0022	<0.021	<1.0
Standard deviation mg/ℓ	-	0.00027	0.0014	0.0017	0.0011	-

[redacted]

---

* OC = organic carbon

** Values less than the detection limit were assigned a value of one half the detection limit.

[redacted]

carbon were below the detection limit in each blank. Zinc was detected in five of sixteen blanks. Cadmium, chromium, and lead, were above the detection limits in the majority of the blanks. Leachate samples with contaminant concentrations within the 95-percent confidence interval were reported as less than the 95-percent confidence limit. Except for cadmium, the 95-percent confidence interval determination used one half of the detection limit for values that were below the detection limit. [illegible] of the leachate samples [illegible] of the 95-percent confidence interval for the cadmium blank [illegible]

a given process formulation was typically less than 0.5. Leachate pH as a function of liquid-solid ratio for selected processes is presented in Table H6. [illegible] cantly affect interphase transfer through a pH effect.

32. Desorption isotherm data. The results from the serial, graded batch [illegible] presented in Tables H7-H33. The tables are organized by process and process formulation. Each table contains data for one process formulation. The first [illegible] each table list aqueous phase contaminant concentration C and the corresponding solid phase concentration q for five metals, and organic carbon (if analyzed). [illegible] concentrations at the same liquid-solids ratio reflect slight differences in the amount of solids weighed for leach testing. The aqueous phase concentration C refers to the contaminant concentration in the filtered (0.45-μm) [illegible]

33. Less than values for the aqueous phase concentration C were reported when the aqueous phase concentration was less than the detection limit (including blank if significant). The solid phase concentration was reported as a greater than value when C was below the detection limit. Most of the [illegible] sometimes not, depending on the solidification/stabilization process and the [illegible]

Table H6

[illegible]

Process	Liquid-Solids Ratio	pH
[illegible]	[illegible]	[illegible]
	5	9.73
	2	10.02
0.05 WEST-P:0.5 Firmix:1 sediment	100	10.31
	20	10.26
	10	10.58
	5	10.47
	2	10.57
0.15 portland cement:0.15 fly ash: 1 sediment	100	10.34
	20	10.69
	10	10.85
	5	10.75
	2	10.80

Table H7

Desorption Isotherm Data for Portland Cement Formulation

L/S	Arsenic C	Arsenic q	Cadmium C	Cadmium q	Chromium C	Chromium q	Lead C	Lead q	Zinc C	Zinc q	OC C	OC q
ml/g	mg/l	mg/kg	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
100	<0.003	>13.80	<0.0007	>9.601	0.015	312.71	<0.003	>424.70	<0.030	>1991.7	12	10414.5
20	0.009	14.12	<0.0007	>9.656	0.030	313.44	<0.003	>424.94	<0.030	>1994.1	55	10506.1
20	0.008	14.14	<0.0007	>9.656	0.043	313.18	0.004	424.92	<0.030	>1994.1	56	10486.3
20	0.009	14.12	<0.0007	>9.656	0.034	313.36	<0.003	>424.94	<0.030	>1994.1	53	10546.9
10	0.010	14.20	<0.0007	>9.663	0.057	313.45	0.011	424.89	<0.030	>1994.4	92	10685.2
10	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	0.012	14.18	<0.0007	>9.663	[illegible]	313.56	[illegible]	424.90	[illegible]	1994.3	[illegible]	[illegible]

* PC = Portland cement.
L/S = liquid-solids ratio.

Table H8

Desorption Isotherm Data for Portland Cement Formulation

0.2 PC:1 Sediment*

[redacted]

20	< 0.005	> 13.00	0.0015	8.830	0.010	287.84	0.021	389.58	0.037	1827.3	42	9797.2
20	< 0.005	> 13.00	0.0017	8.826	0.008	287.88	0.024	389.52	< 0.030	> 1827.4	40	9837.4
10	< 0.005	> 13.05	0.0011	8.849	0.010	287.92	0.037	389.63	0.033	1827.7	71	9926.3

[redacted]

[redacted]

OC = organic carbon.

[redacted]

Table H9

Desorption Isotherm Data for Portland Cement Formulation

0.3 PC:1 Sediment*

L/S ml/g	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C	q	C	q	C	q	C	q
[illegible]	[illegible]	11.97	[illegible]	[illegible]	0.007	265.97	0.065	358.6	0.056	1686.1	41	9000
20	<0.005	>11.97	<0.0007	>8.168	0.010	265.91	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.011	[illegible]	0.098	359.7	0.069	1686.0	210	9399
2	0.013	12.05	<0.0007	>8.181	0.013	266.05	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

L/S = liquid-solids ratio.

[illegible]

Table H10

Desorption Isotherm Data for Portland Cement Formulation

0.4 PC:1 Sediment*

L/S	Arsenic		Cadmium		Chromium		Lead		Zinc		OC	
L/S ml/g	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
20	<0.005	>11.11	<0.0007	>7.583	0.014	246.80	0.078	332.59	0.067	1565.2	32	8476.4
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
10	<0.005	>11.16	<0.0007	>7.590	0.009	246.97	0.115	333.00	0.075	1565.8	55	8566.6
2	0.007	11.20	<0.0007	>7.596	0.010	247.03	0.105	333.94	0.067	1566.4	187	8742.4
2	0.007	11.20	<0.0007	>7.596	0.017	247.01	0.115	333.92	0.073	1566.4	188	8740.7

[redacted]

C = contaminant concentration in leachate.

[redacted]

OC = organic carbon.

Table H11

Desorption Isotherm Data for Fly Ash and Portland Cement

0.2 Fly Ash:0.1 Cement:1.0 Sediment*

[redacted]

L/S	Arsenic		Cadmium		Chromium		Lead		Zinc		OC	
ml/g	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg
100	<0.005	>11.57	<0.0007	8.112	0.018	264.37	0.007	359.79	<0.030	>1684.2	13	8518.6
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
10	0.010	11.97	<0.0007	8.175	0.042	265.66	0.012	359.83	<0.030	>1686.9	85	8968.7
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
2	0.022	12.03	<0.0007	8.181	0.004	266.07	0.018	359.87	0.052	1687.1	306	9206.6

---

* PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H12

Desorption Isotherm Data for Fly Ash and Portland Cement

0.1 Fly Ash:0.2 Cement:1.0 Sediment*

	Arsenic		Cadmium		Chromium		Lead		Zinc		OC	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
100	<0.005	>11.58	<0.0007	>8.113	0.019	264.38	0.004	359.49	<0.030	>1684.2	14	8425.6
100	<0.005	>11.57	<0.0007	>8.112	0.012	265.08	0.008	359.09	<0.030	>1684.2	12	8622.2
100	<0.005	>11.58	<0.0007	>8.113	0.015	264.78	0.004	359.49	<0.030	>1684.2	13	8525.1
20	<0.005	>11.97	<0.0007	>8.168	0.020	265.71	0.015	359.59	<0.030	>1686.6	46	8899.5
20	<0.005	>11.97	<0.0007	>8.168	0.027	265.57	0.014	359.61	<0.030	>1686.6	48	8859.4
20	<0.005	>11.97	<0.0007	>8.168	0.028	265.55	0.013	359.63	<0.030	>1686.6	49	8839.8
10	0.006	12.01	<0.0007	>8.175	0.023	265.86	0.015	359.74	<0.030	>1686.9	80	9019.0
10	0.006	12.01	<0.0007	>8.175	0.021	265.88	0.016	359.73	<0.030	>1686.9	78	9038.9
10	0.005	12.02	<0.0007	>8.175	0.024	265.85	0.022	359.67	<0.030	>1686.9	79	9029.1
5	0.009	12.03	<0.0007	>8.179	0.023	265.97	0.026	359.76	<0.030	>1687.0	100	9318.7
[illegible]												
2	0.014	12.05	<0.0007	>8.181	0.029	266.02	0.032	359.83	<0.030	>1687.1	260	9298.6

* PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H13

[redacted]

L/S	C	q	C	q	C	q	C	q	C	q	C	q
100	<0.005	>11.57	<0.0007	>8.112	<0.003	>265.87	0.003	359.59	<0.030	>1684.2	12	8621.0
100	<0.005	>11.57	<0.0007	>8.112	<0.003	>265.77	0.012	358.69	<0.030	>1684.2	10	8820.6
100	<0.005	>11.57	<0.0007	>8.112	0.023	263.78	0.013	358.59	<0.030	>1684.2	11	8719.7
20	<0.005	>11.97	<0.0007	>8.168	0.035	265.37	0.019	359.51	<0.030	>1686.6	47	8879.0
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
10	0.006	12.01	<0.0007	>8.175	0.030	265.77	0.025	359.64	<0.030	>1686.9	70	9118.7
10	0.006	12.01	<0.0007	>8.175	0.033	265.74	0.010	359.79	<0.030	>1686.9	71	9108.7
10	<0.005	>12.02	<0.0007	>8.175	0.039	265.68	0.027	359.62	<0.030	>1686.9	71	9108.7
5	0.010	12.02	<0.0007	>8.179	0.015	266.00	0.019	359.80	<0.030	>1687.0	111	9263.8
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[illegible]	[illegible]	[illegible]	<0.0007	>8.181	0.015	266.04	0.034	359.82	<0.030	>1687.1	276	9266.6
2	0.014	12.05	<0.0007	>8.181	0.011	266.05	0.035	359.82	<0.030	>1687.1	280	9258.6

* PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H14

Desorption Isotherm Data for Sodium Silicate, Fly Ash, and Portland Cement Process

0.05 NaSi:0.1 Fly Ash:0.1 Cement:1 Sediment*

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	mg/kg	mg/ℓ	mg/kg	mg/ℓ	mg/kg	mg/ℓ	mg/kg	mg/ℓ	mg/kg
100	<0.005	>12.06	<0.0007	>8.442	0.010	276.0	0.017	372.70	<0.030	>1752.2
100	<0.005	>12.06	<0.0007	>8.442	0.012	275.8	0.014	373.00	<0.030	>1752.2
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
10	<0.005	>12.51	<0.0007	>8.505	0.009	276.7	0.120	373.20	0.035	1754.9
10	<0.005	>12.51	<0.0007	>8.505	0.009	276.7	0.096	373.44	0.045	1754.8
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
2	0.006	12.55	<0.0007	>8.511	0.011	276.8	0.115	374.17	0.058	1755.1
2	0.007	12.55	<0.0007	>8.511	0.011	276.8	0.010	374.38	0.070	1755.1
2	0.006	12.55	<0.0007	>8.511	0.008	276.8	0.009	374.38	0.065	1755.1

[redacted]

[redacted]

Table H15

Desorption Isotherm Data for Sodium Silicate, Fly Ash, and Portland Cement Process

0.05 NaSi:0.1 Fly Ash:0.2 Cement:1 Sediment*

L/S	Arsenic		Cadmium		Chromium		Lead		Zinc	
	C	q	C	q	C	q	C	q	C	q
[redacted]										
20	<0.005	>11.53	<0.0007	>7.870	0.025	255.9	0.024	346.31	<0.030	>1625.2
20	<0.005	>11.53	<0.0007	>7.870	0.022	256.0	0.023	346.33	0.039	1625.0
20	<0.005	>11.53	<0.0007	>7.870	0.021	256.0	0.024	346.31	<0.030	>1625.2
10	<0.005	>11.58	<0.0007	>7.877	0.020	256.2	0.036	346.43	<0.030	>1625.5
10	<0.005	>11.58	<0.0007	>7.877	0.018	256.2	0.042	346.37	0.040	1625.4
10	<0.005	>11.58	<0.0007	>7.877	0.018	256.2	0.018	346.61	<0.030	>1625.5
2	0.015	11.60	0.0008	7.883	0.058	256.3	0.058	346.67	0.042	1625.7

[redacted]

PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H16

Desorption Isotherm Data for Sodium Silicate, Fly Ash, and Portland Cement Process

0.05 NaSi:0.25 Fly Ash:0.25 Cement:1 Sediment*

[illegible]

L/S ml/g	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg
100	<0.005	> 9.63	<0.0007	>6.793	0.014	221.97	0.009	300.96	<0.030	>1412.1
100	<0.005	> 9.63	<0.0007	>6.793	0.016	221.77	0.003	301.56	<0.030	>1412.1
100	<0.005	> 9.63	<0.0007	>6.793	0.013	222.07	0.004	301.46	<0.030	>1412.1
20	<0.005	[illegible]	<0.0007	>6.849	0.026	222.69	0.019	301.48	<0.030	>1414.5
20	<0.005	>10.93	<0.0007	>6.849	0.022	222.77	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	0.016	10.09	<0.0007	>6.861	0.067	223.04	0.063	301.73	0.044	1415.0
2	0.017	10.09	<0.0007	>6.861	0.072	223.03	0.050	301.76	0.036	1415.1
2	0.017	10.09	<0.0007	>6.861	0.075	223.02	0.054	301.75	0.044	1415.0

---

* PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.

[redacted]

0.05 NaSi:0.25 Cement:1 Sediment*

[redacted]

---

* PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H18

Desorption Isotherm Data for Sodium Silicate and Portland Cement Process

0.05 NaSi:0.5 Cement:1 Sediment*

L/S	Arsenic		Cadmium		Chromium		Lead		Zinc	
ml/g	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg
100	< 0.005	> 9.63	0.0008	6.783	0.015	221.87	0.012	300.66	< 0.030	> 1412.1
100	< 0.005	> 9.63	< 0.0007	> 6.793	0.012	222.17	0.013	300.56	< 0.030	> 1412.1
100	< 0.005	> 9.63	< 0.0007	> 6.793	0.012	222.17	0.014	300.46	< 0.030	> 1412.1
20	< 0.005	> 10.03	< 0.0007	> 6.849	0.016	222.89	0.064	300.58	0.052	1414.1
20	< 0.005	> 10.03	< 0.0007	> 6.849	0.008	223.05	0.061	300.64	0.041	1414.3
20	< 0.005	> 10.03	< 0.0007	> 6.849	0.010	223.01	0.072	300.42	0.037	1414.4
10	< 0.005	> 10.08	< 0.0007	> 6.856	0.006	223.13	0.088	300.98	0.036	1414.8
10	< 0.005	> 10.08	< 0.0007	> 6.856	0.010	223.09	0.079	301.07	0.044	1414.7
10	0.005	10.08	< 0.0007	> 6.856	0.008	223.11	0.063	301.23	0.042	1414.7
2	0.009	10.11	< 0.0007	> 6.861	0.010	223.15	0.021	301.82	0.043	1415.0
2	0.010	10.11	< 0.0007	> 6.861	0.013	223.15	0.023	301.81	0.043	1415.0
2	0.010	10.11	< 0.0007	> 6.861	0.014	223.15	0.008	301.84	0.049	1415.0

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* PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H19

Desorption Isotherm Data for Firmex and Portlan: Cement

0.2 Firmex 0.1 Cement:1.0 Sediment*

L/S	Arsenic		Cadmium		Chromium		Lead		Zinc		OC	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	<0.0007	>8.112	0.023	263.78	0.011	358.79	<0.030	>1684.2	7	9120.0
20	<0.005	>11.97	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	<0.030	>1686.9	54	9278.8
10	<0.005	>12.02	<0.0007	>8.174	0.044	265.63	0.012	359.77	<0.030	>1686.9	53	9289.0
5	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	227	9364.6

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* PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H20

Desorption Isotherm Data for Firmex and Portland Cement

0.1 Firmex:0.2 Cement:1.0 Sediment*

L/S ml/g	Arsenic C mg/ℓ	Arsenic q mg/kg	Cadmium C mg/ℓ	Cadmium q mg/kg	Chromium C mg/ℓ	Chromium q mg/kg	Lead C mg/ℓ	Lead q mg/kg	Zinc C mg/ℓ	Zinc q mg/kg	OC C mg/ℓ	OC q mg/kg
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	<0.030	>1684.2	12	[illegible]
100	<0.005	>11.58	<0.0007	>8.113	0.014	264.68	0.007	359.20	<0.030	>1684.2	13	8526.3
100	<0.005	>11.58	<0.0007	>8.113	0.014	264.68	0.005	359.40	<0.030	>1684.2	9	8924.8
20	<0.005	>11.97	<0.0007	>8.168	0.016	265.75	0.013	359.63	<0.030	>1686.6	37	9079.9
20	<0.005	>11.97	<0.0007	>8.168	0.025	265.57	0.012	359.65	<0.030	>1686.6	37	9079.2
20	<0.005	>11.97	<0.0007	>8.168	0.020	265.67	0.013	359.63	<0.030	>1686.6	36	9098.6
10	<0.005	>12.02	<0.0007	>8.175	0.021	265.86	0.018	359.71	<0.030	[illegible]	[illegible]	[illegible]
2	0.009	12.06	<0.0007	>8.181	0.008	266.06	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

L/S = liquid-solids ratio.

C = contaminant concentration in leachate.

Table H21

Desorption Isotherm Data for Firmex and Portland Cement

0.15 Firmex:0.15 Cement:1.0 Sediment*

L/S ml/g	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg
20	<0.005	>11.97	<0.0007	>8.168	0.022	265.63	0.011	359.67	<0.030	>1686.6	34	9139.1
20	<0.005	>11.97	<0.0007	>8.168	0.020	265.67	0.011	359.67	<0.030	>1686.6	35	9118.9
20	<0.005	>11.97	<0.0007	>8.168	0.021	265.65	0.009	359.71	<0.030	>1686.6	35	9119.0
10	<0.005	>12.02	<0.0007	>8.175	0.018	265.89	0.015	359.74	<0.030	>1686.9	63	9188.6
5	0.005	12.05	<0.0007	>8.179	0.017	265.99	0.018	359.80	<0.030	>1687.0	95	9343.7
5	0.005	12.05	<0.0007	>8.179	0.017	265.99	0.018	359.80	<0.030	>1687.0	100	9318.7
5	0.005	12.05	<0.0007	>8.179	0.016	265.99	0.018	359.80	<0.030	>1687.0	101	9313.7
2	0.008	12.06	<0.0007	>8.181	0.005	266.06	0.021	359.85	<0.030	>1687.1	248	9322.6
2	0.007	12.06	<0.0007	>8.181	0.005	266.06	0.002	359.89	<0.030	>1687.1	240	9338.6
2	0.008	12.06	<0.0007	>8.181	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H22

Desorption Isotherm Data for Lime with Fly Ash Process

0.4 Fly Ash:0.1 Lime:1 Sediment*

L/S	Arsenic		Cadmium		Chromium		Lead		Zinc		OC	
ml/g	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
100	<0.005	> 9.98	<0.0007	7.028	0.016	229.39	0.018	310.37	0.033	1460.1	9	7624.3
20	<0.005	>10.37	<0.0007	7.083	0.011	230.60	0.065	310.86	0.103	1461.3	30	7916.6
20	<0.005	>10.37	<0.0007	7.083	0.011	230.60	0.116	309.84	0.102	1461.4	33	7858.6
20	<0.005	>10.37	<0.0007	7.083	0.012	230.58	0.084	310.48	0.099	1461.4	29	7936.5
10	<0.005	>10.42	<0.0007	7.090	0.009	230.71	0.117	310.99	0.122	1462.2	53	7988.0
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

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* PC = Portland cement.

[redacted]

OC = organic carbon.

Table H23

Desorption Isotherm Data for Lime with Fly Ash Process

0.5 Fly Ash:0.1 Lime:1 Sediment*

L/S	[illegible]		[illegible]		[illegible]		[illegible]		Zinc		OC	
ml/g	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20	< 0.005	> 9.71	< 0.0007	> 6.636	0.006	216.17	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.161	1369.6	43	7550.4
2	0.013	9.79	< 0.0007	> 6.649	0.006	216.24	0.193	292.11	0.172	1370.9	148	7684.4
2	0.014	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H24

0.6 Fly Ash:0.1 Lime:1 Sediment*

	Arsenic		Cadmium		Chromium		Lead		Zinc		OC	
100	<0.005	>8.74	<0.0007	>6.187	0.008	202.86	0.037	271.53	0.065	1283.6	5	7013.5
100	<0.005	>8.74	<0.0007	>6.187	0.007	202.96	0.034	271.83	0.069	1283.3	6	6916.5
20	<0.005	>9.13	<0.0007	>6.242	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20	<0.005	>9.13	<0.0007	>6.242	0.004	203.41	0.187	271.45	0.171	1286.7	23	7047.9
20	<0.005	>9.13	<0.0007	>6.242	<0.003	>203.43	0.113	272.93	0.173	1286.6	23	7048.2
10	<0.005	>9.18	<0.0007	>6.249	0.006	203.41	0.179	273.40	0.172	1288.4	42	7088.6
10	<0.005	>9.18	<0.0007	>6.249	<0.003	>203.44	0.193	273.25	0.173	1288.3	43	7077.8
10	<0.005	>9.18	<0.0007	>6.249	0.004	203.43	0.150	273.69	0.189	1288.2	43	7078.2
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2	0.018	9.20	<0.0007	>6.255	0.004	203.44	0.186	274.81	0.217	1289.6	146	7215.6

* PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H25

Desorption Isotherm Data for Firmex Process

0.4 Firmex:1 Sediment*

L/S	Arsenic		Cadmium		Chromium		Lead		Zinc		OC	
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	246.44	<0.003	>333.85	<0.03	>1563.5	10	8109.3
100	0.011	10.04	0.0015	7.437	0.010	245.98	<0.003	>333.83	<0.03	>1563.3	10	8050.3
100	0.012	10.01	0.0015	7.447	0.007	246.34	<0.003	>333.85	<0.03	>1563.5	10	8116.4
20	0.017	10.87	0.0020	7.557	0.015	246.74	0.006	334.03	<0.03	>1565.9	37	8377.4
20	0.016	10.89	0.0018	7.561	0.022	246.60	0.006	334.03	<0.03	>1565.9	36	8397.2
20	0.017	10.87	0.0015	7.567	0.017	246.70	0.005	334.05	<0.03	>1565.9	36	8398.2
10	0.020	11.01	0.0050	7.547	0.028	246.76	0.006	334.09	<0.03	>1566.2	61	8508.3
10	0.020	11.01	0.0017	7.580	0.028	246.76	0.007	334.08	<0.03	>1566.2	60	8516.2
10	0.019	11.02	0.0010	7.587	0.027	246.77	0.005	334.10	<0.03	>1566.2	61	8506.2
5	0.028	11.07	0.0013	7.590	0.035	246.87	0.006	334.12	<0.03	>1566.4	84	8696.0
5	0.032	11.05	0.0007	7.593	0.036	246.86	0.006	334.12	<0.03	>1566.4	81	8711.6
5	0.033	11.04	0.0007	7.593	0.034	246.87	0.007	334.12	<0.03	>1566.4	84	8696.3
2	0.044	11.12	0.0009	7.595	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible] Portland cement.
L/S = liquid-solids ratio.

Table H26

0.5 Firmex:1 Sediment*

L/S	Arsenic		Cadmium		Chromium		Lead		Zinc		OC	
	C	q	C	q	C	q	C	q	C	q	C	q
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20	0.015	10.17	<0.0007	>7.083	0.023	230.32	0.005	312.06	<0.03	>1462.8	34	7836.5
10	0.019	10.28	<0.0007	>7.090	0.030	230.48	0.005	312.11	<0.03	>1463.1	58	7935.8
10	0.017	10.30	<0.0007	>7.090	0.031	230.47	0.005	312.11	<0.03	>1463.1	58	7935.4
10	0.018	10.29	<0.0007	>7.090	0.025	230.53	0.005	312.11	<0.03	>1463.1	59	7926.7
5	0.023	10.36	<0.0007	>7.093	0.030	230.63	0.006	312.13	<0.03	>1463.2	94	8045.9
5	0.024	10.35	<0.0007	>7.093	0.030	230.63	0.004	312.14	<0.03	>1463.2	94	8046.2
2	0.041	10.39	<0.0007	>7.095	0.028	230.73	<0.003	>312.15	<0.03	>1463.3	212	8092.1

* PC = Portland cement
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.

Table H27

Desorption Isotherm Data for Firmex Process

0.6 Firmex:1 Sediment*

100	0.009	8.91	<0.0007	>6.580	0.014	214.84	0.005	292.00	<0.03	>1368.2	10	6976.0
100	0.008	9.02	<0.0007	>6.580	0.001	216.15	<0.003	>292.20	<0.03	>1368.3	11	6884.4
100	0.009	8.91	<0.0007	>6.580	0.001	216.15	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	0.014	9.67	<0.0007	>6.643	0.023	216.02	0.005	292.45	<0.03	>1370.9	57	7409.8
10	0.015	9.66	<0.0007	>6.643	0.028	215.97	0.006	292.44	<0.03	[illegible]	[illegible]	[illegible]
2	0.032	9.75	<0.0007	>6.649	0.017	216.22	0.009	292.48	<0.03	>1371.2	209	7562.3
2	0.028	9.76	<0.0007	>6.649	0.015	216.22	0.006	292.49	<0.03	>1371.2	218	7543.8
2	0.026	9.76	<0.0007	>6.649	0.012	216.23	0.005	292.49	<0.03	>1371.2	205	7570.2

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* PC = Portland cement.

[illegible]

Table H28

Desorption Isotherm Data for West-P Polymer and Firmex

0.01 Polymer:0.5 Firmex:1.0 Sediment*

	Arsenic		Cadmium		Chromium		Lead		Zinc		OC	
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
100	<0.005	> 9.89	0.0082	6.220	0.005	228.55	<0.003	>309.51	<0.030	>1449.4	10	7448.4
100	<0.005	> 9.89	<0.0007	>6.974	0.004	228.65	<0.003	>309.52	<0.030	>1449.4	10	7454.4
100	<0.005	> 9.89	<0.0007	>6.973	0.005	228.55	<0.003	>309.51	<0.030	>1449.4	10	7445.4
20	0.006	10.27	<0.0007	>7.030	0.008	228.89	0.004	309.74	<0.030	>1451.8	32	7812.0
20	0.006	10.27	<0.0007	>7.030	0.009	228.87	0.006	309.70	<0.030	>1451.8	31	7831.7
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
2	0.012	10.37	<0.0007	>7.042	0.007	229.04	0.008	309.80	<0.030	>1452.4	219	8014.3
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

* PC = Portland cement.
L/S = liquid-solids [illegible] io.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H29

Desorption Isotherm Data for WEST-P Polymer and Firmex

0.03 Polymer:0.5 Firmex:1.0 Sediment*

L/S	Arsenic		Cadmium		Chromium		Lead		Zinc		OC	
ml/g	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg
100	<0.005	> 9.77	<0.0007	>6.889	0.005	225.79	<0.003	>305.77	<0.030	>1431.9	2	8151.5
100	<0.005	> 9.77	<0.0007	>6.889	0.009	225.39	<0.003	>305.78	<0.030	>1431.9	2	8152.4
100	<0.005	> 9.76	<0.0007	>6.887	0.011	225.17	<0.003	>305.77	<0.030	>1431.8	3	8045.7
20	0.008	10.11	<0.0007	>6.945	0.009	226.10	0.010	305.87	<0.030	>1434.3	26	7829.9
20	0.008	10.11	<0.0007	>6.945	0.012	226.04	ND		<0.030	>1434.3	25	7849.6
20	0.007	10.13	<0.0007	>6.945	0.012	226.04	ND		<0.030	>1434.3	24	7869.6
10	0.010	10.17	<0.0007	>6.952	0.013	226.15	ND		<0.030	>1434.6	45	7899.4
10	0.010	10.17	<0.0007	>6.952	0.012	226.16	ND		<0.030	>1434.6	46	7889.2
10	0.008	10.19	<0.0007	>6.952	0.012	226.16	ND		<0.030	>1434.6	45	7900.3
5	0.008	10.23	<0.0007	>6.955	0.015	226.21	ND		<0.030	>1434.7	88	7910.2
5	0.007	10.23	<0.0007	>6.955	0.013	226.22	ND		<0.030	>1434.7	95	7875.2
5	0.009	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
2	0.009	10.25	<0.0007	>6.957	0.009	226.27	ND		<0.030	>1434.8	249	7851.5
2	0.009	10.25	<0.0007	>6.957	0.008	226.27	ND		<0.030	>1434.8	244	7864.2

* PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H30

Desorption Isotherm Data for WEST-P Polymer and Firmex

0.05 Polymer:0.5 Firmex:1.0 Sediment*

L/S ml/g	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C	q	C	q
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
20	0.006	10.01	<0.0007	>6.849	0.008	223.01	0.004	301.78	<0.030	>1414.5	33	7574.3
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
5	0.008	10.09	<0.0007	>6.859	0.014	223.10	0.005	301.83	<0.030	>1415.0	92	7775.2
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

---

* PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H31

Desorption Isotherm Data for WEST-P Polymer and Portland Cement

[redacted]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	mg/ℓ	mg/kg	mg/ℓ	mg/kg	mg/ℓ	mg/kg	mg/ℓ	mg/kg
100	< 0.005	> 12.47	< 0.0007	> 8.719	0.010	284.80	< 0.003	> 386.27	< 0.030	> 1809.3	7	9850.5
100	< 0.005	> 12.47	< 0.0007	> 8.719	0.028	283.01	0.004	386.17	< 0.030	> 1809.3	8	9750.3
100	< 0.005	> 12.47	< 0.0007	> 8.719	0.026	283.21	0.005	386.07	< 0.030	> 1809.3	8	9750.1
20	< 0.005	> 12.87	< 0.0007	> 8.775	0.066	284.48	0.005	386.47	< 0.030	> 1811.6	48	9587.1
20	< 0.005	> 12.87	< 0.0007	> 8.775	0.051	284.78	0.012	386.33	< 0.030	> 1811.6	49	9567.9
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	> 1812.2	271	10004.4
2	0.009	12.95	0.0011	8.786	0.038	285.72	0.028	386.51	< 0.030	> 1812.2	270	10006.4

[redacted]

[redacted] concentration in solidified sediment after leaching.

OC = organic carbon.

Table H32

Desorption Isotherm Data for WEST-P Polymer and Portland Cement

0.03 Polymer:0.2 Cement:1.0 Sediment*

	Arsenic		Cadmium		Chromium		Lead		Zinc		OC	
L/S ml/g	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
20	<0.005	>12.66	<0.0007	>8.636	0.038	280.54	0.011	380.26	<0.030	>1783.1	47	9440.9
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5	0.007	12.73	<0.0007	>8.647	0.030	281.15	0.018	380.39	<0.030	>1783.6	148	9640.8
5	0.007	12.73	<0.0007	>8.647	0.030	281.15	0.002	380.47	<0.030	>1783.6	145	9655.1
2	0.011	12.74	<0.0007	>8.649	0.010	281.28	0.021	380.44	<0.030	>1783.7	307	9766.8
2	0.012	12.74	<0.0007	>8.649	0.021	281.26	0.023	380.44	<0.030	>1783.7	307	9764.9

---

* PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.
q = contaminant concentration in solidified sediment after leaching.
OC = organic carbon.

Table H33

Desorption Isotherm Data for WEST-P Polymer and Portland Cement

0.05 Polymer:0.2 Cement:1.0 Sediment*

L/S	Arsenic		Cadmium		Chromium		Lead		Zinc		OC	
ml/g	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C mg/ℓ	q mg/kg	C	q
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
10	0.006	12.50	<0.0007	>8.505	0.038	276.42	0.005	374.35	<0.030	>1754.9	79	9425.0
5	0.007	12.53	<0.0007	>8.509	0.042	276.59	0.004	374.38	0.099	1754.7	142	9504.5
5	0.008	12.52	<0.0007	>8.509	0.048	276.61	0.006	374.37	<0.030	>1755.1	142	9504.4
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
2	0.010	12.54	<0.0007	>8.511	0.025	276.75	0.009	374.38	<0.030	>1755.1	279	9656.4

---

* PC = Portland cement.
L/S = liquid-solids ratio.
C = contaminant concentration in leachate.

[redacted]

[redacted] sample analyzed.

[redacted] developed to provide a convenient framework for interpreting the desorption data. The data from the serial, graded batch leaching tests fall into five general classifications, depending on the liquid-solid ratios at which contaminants were detected. As previously discussed, the serial, graded batch [redacted] in order to obtain data for plotting a desorption isotherm. Table H34 is a summary of the results from the serial, graded batch leaching tests according to the classification scheme presented below.

36. For some of the isotherm data, the amount of contaminant released was below the detection limit for all of the liquid-solids ratios used in the series of tests. The leaching tests in which contaminant release was not measurable are termed "no release isotherms" (NRI). Most of the cadmium desorp- [redacted] stabilized Indiana Harbor sediment does not appear to have significant leaching potential for cadmium. The other contaminant desorption isotherms falling into this category are listed in Table H34.

[redacted] series, i.e., 2:1 and 10:1. Desorption isotherms characterized by aqueous phase contaminant concentrations below the detection limit for liquid-solid [redacted] desorption data for Indiana Harbor sediment solidified/stabilized with portland cement in an additive-to-sediment ratio of 0.2:1 (Table H8) is an example of a

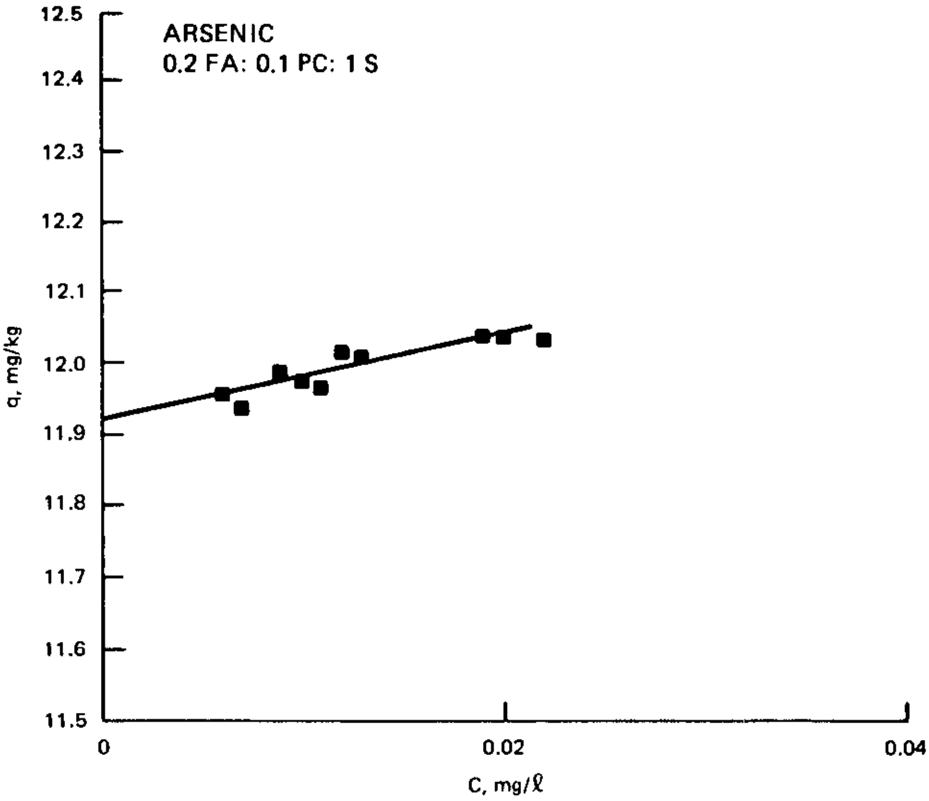
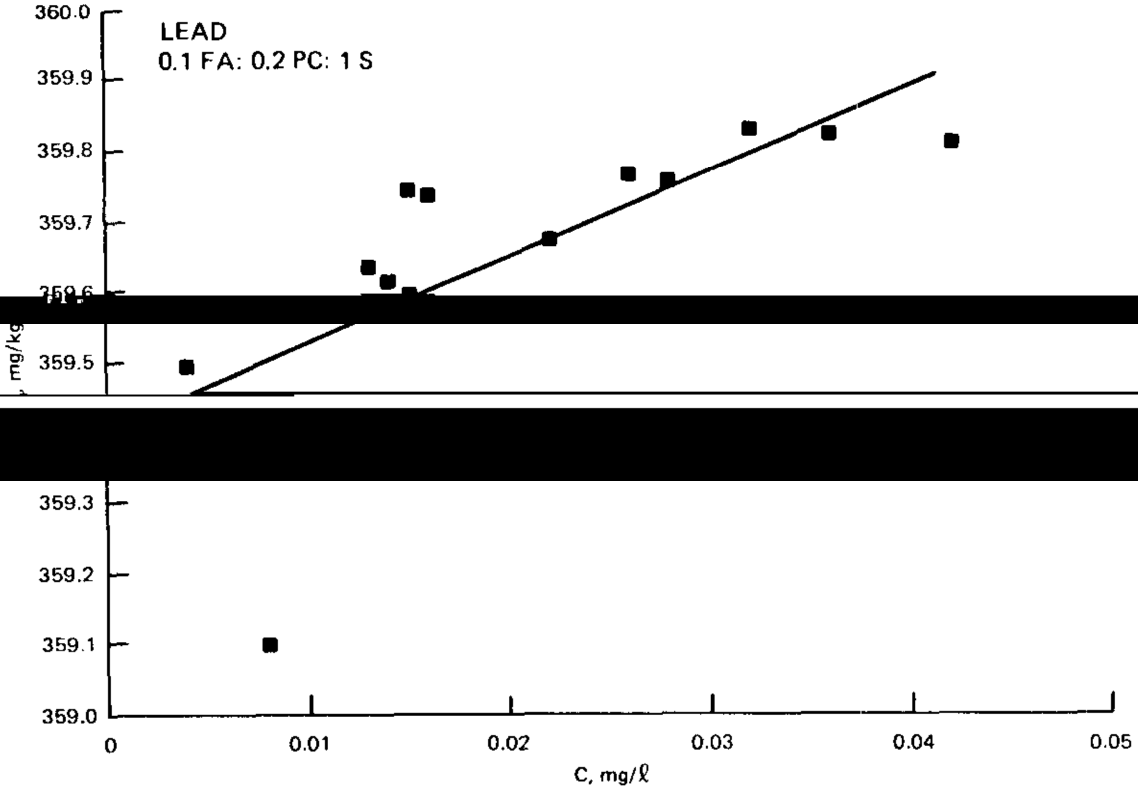


Figure H4. Arsenic desorption isotherm for 0.2 fly ash: 0.1 portland cement:1 sediment



[illegible]
0.2 portland cement:1 sediment

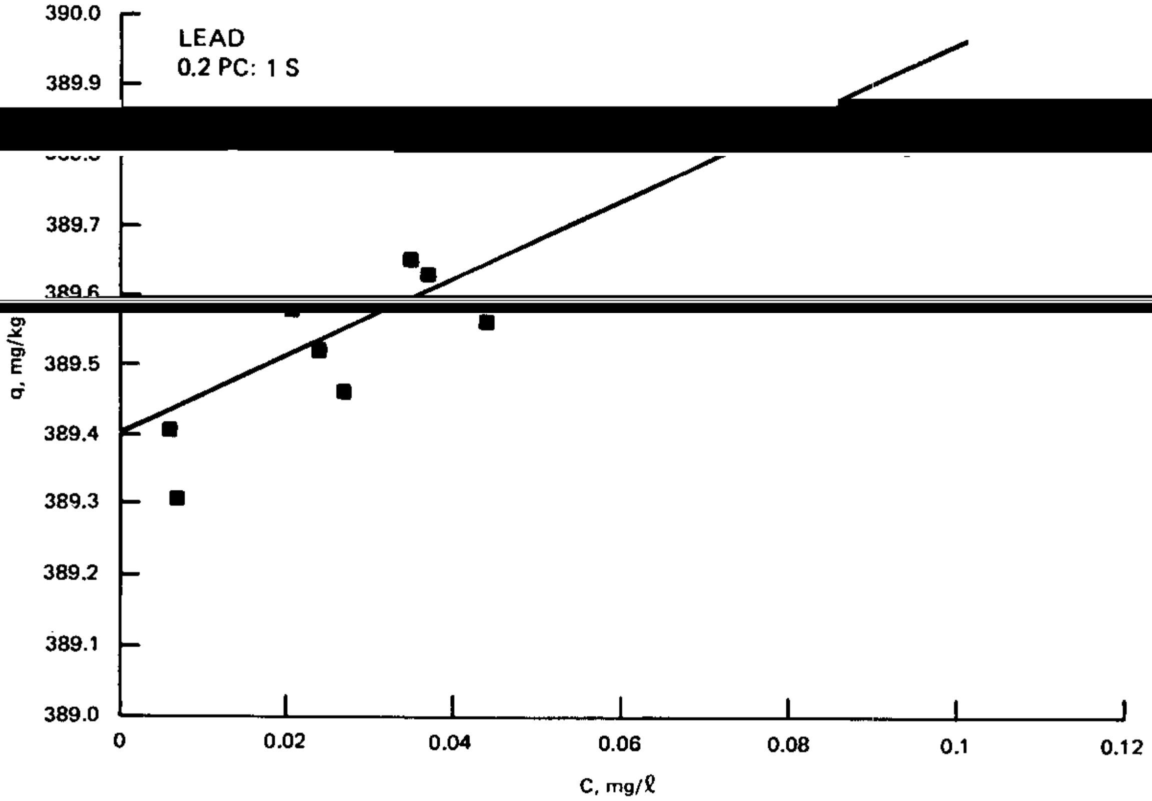
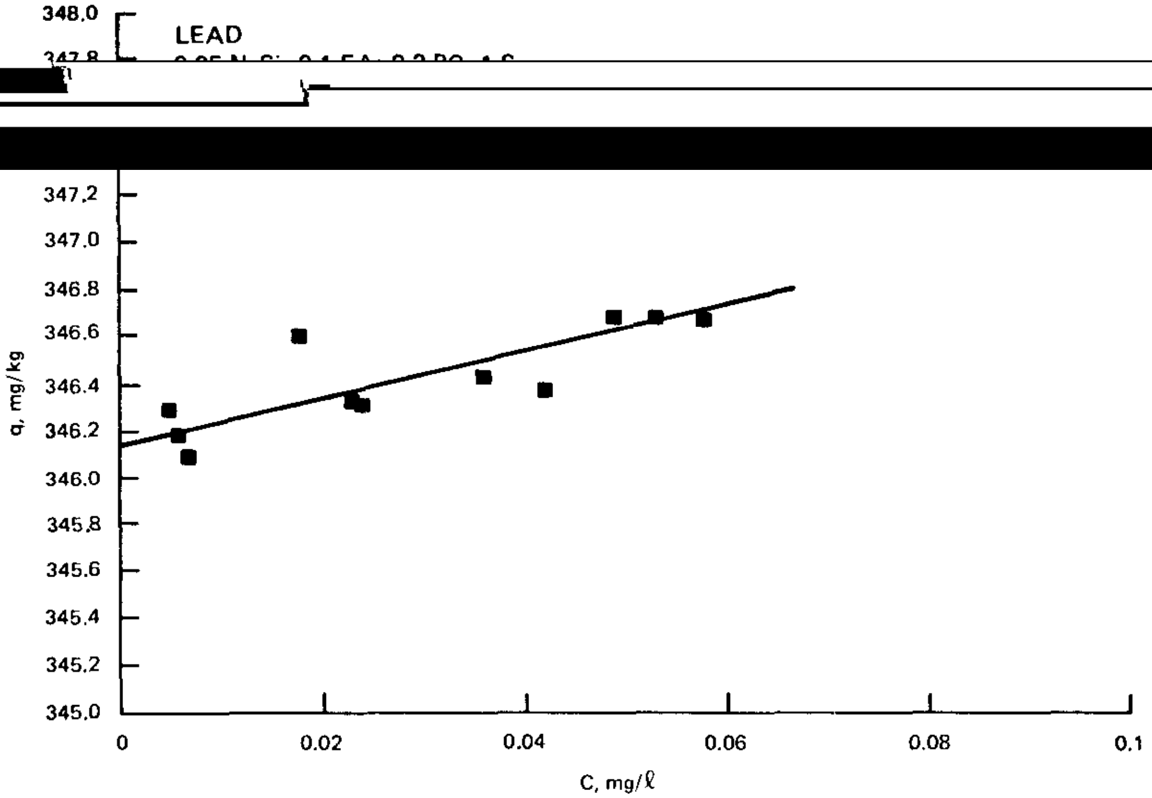


Figure U6. Lead desorption isotherm for 0.2 portland cement:
1 sediment



[redacted]
0.1 fly ash:0.2 portland cement:1 sediment

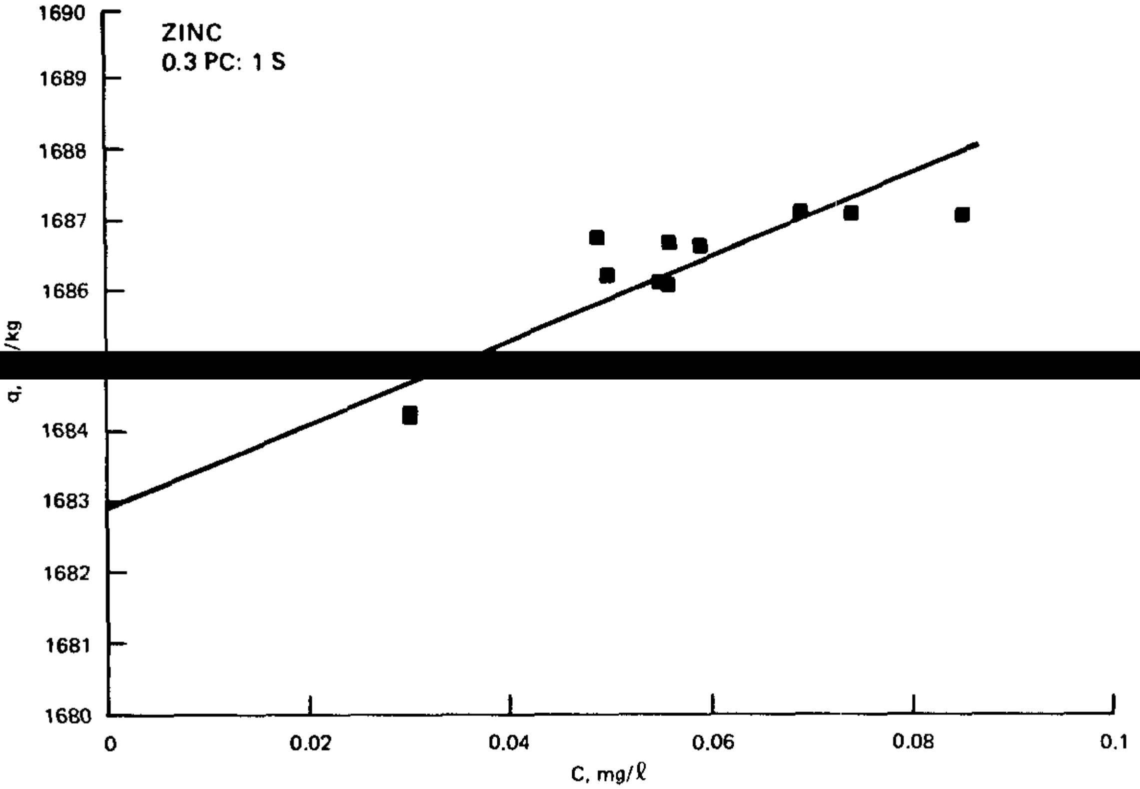
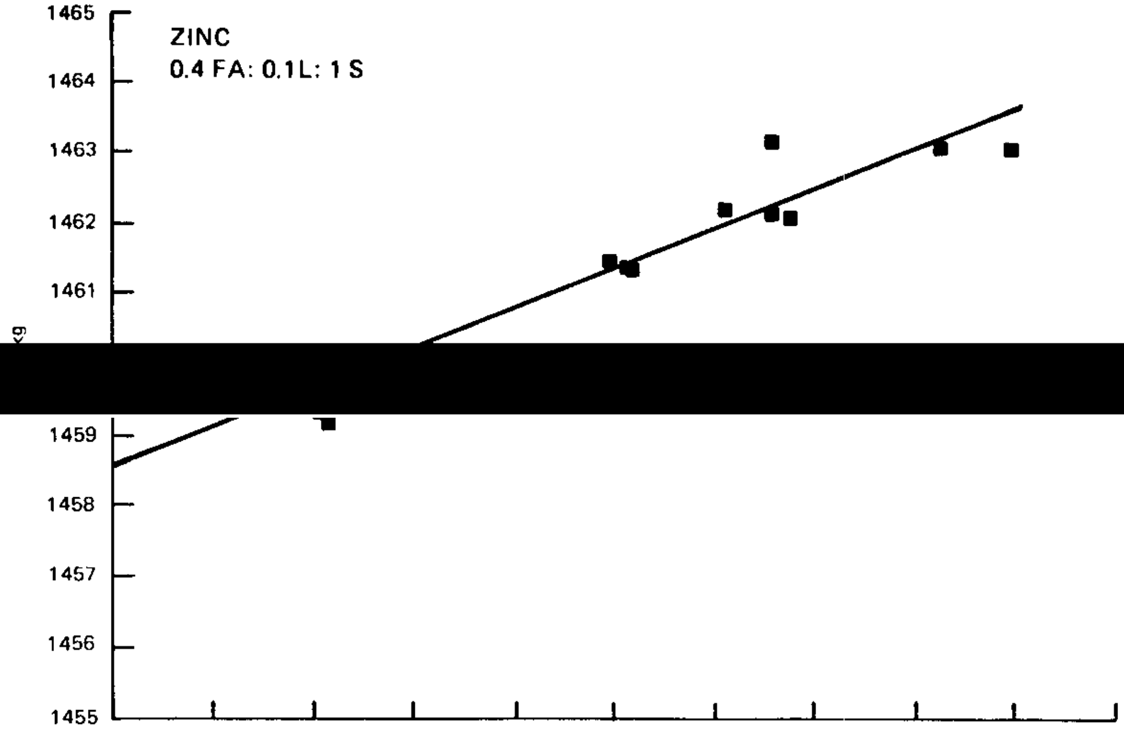


Figure no. Zinc desorption isotherm for 0.3 portland cement: 1 sediment



[redacted]

[redacted]

Figure H9. Zinc desorption isotherm for 0.4 fly ash: 0.1 lime:sediment

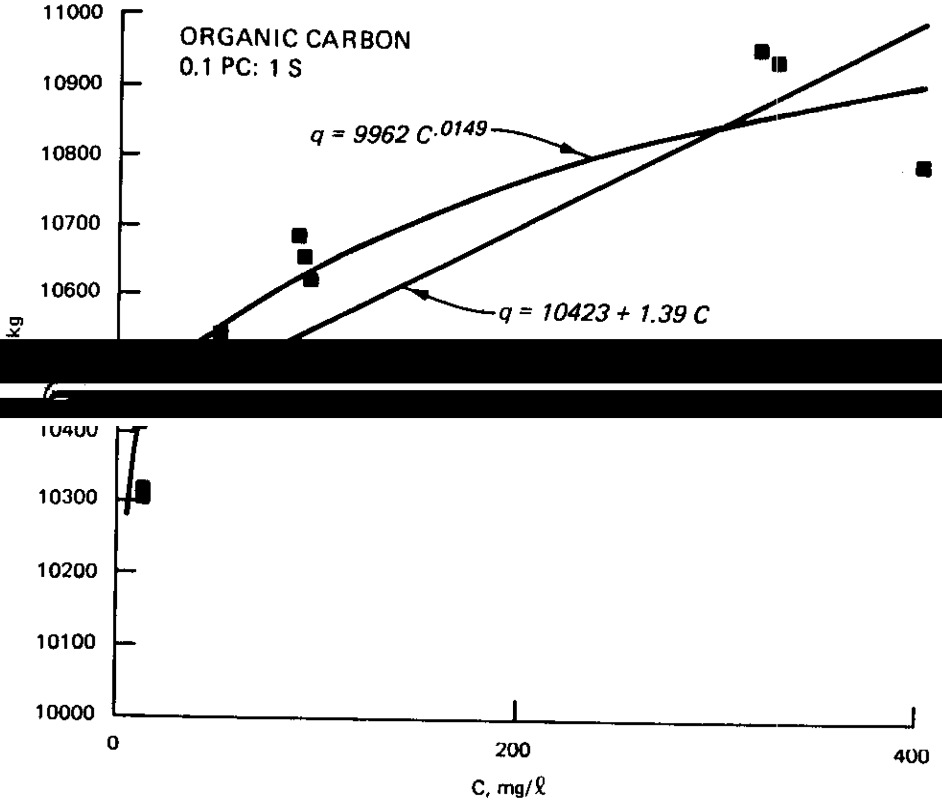


Figure H10. Organic carbon desorption isotherm for 0.1 portland cement:1 sediment

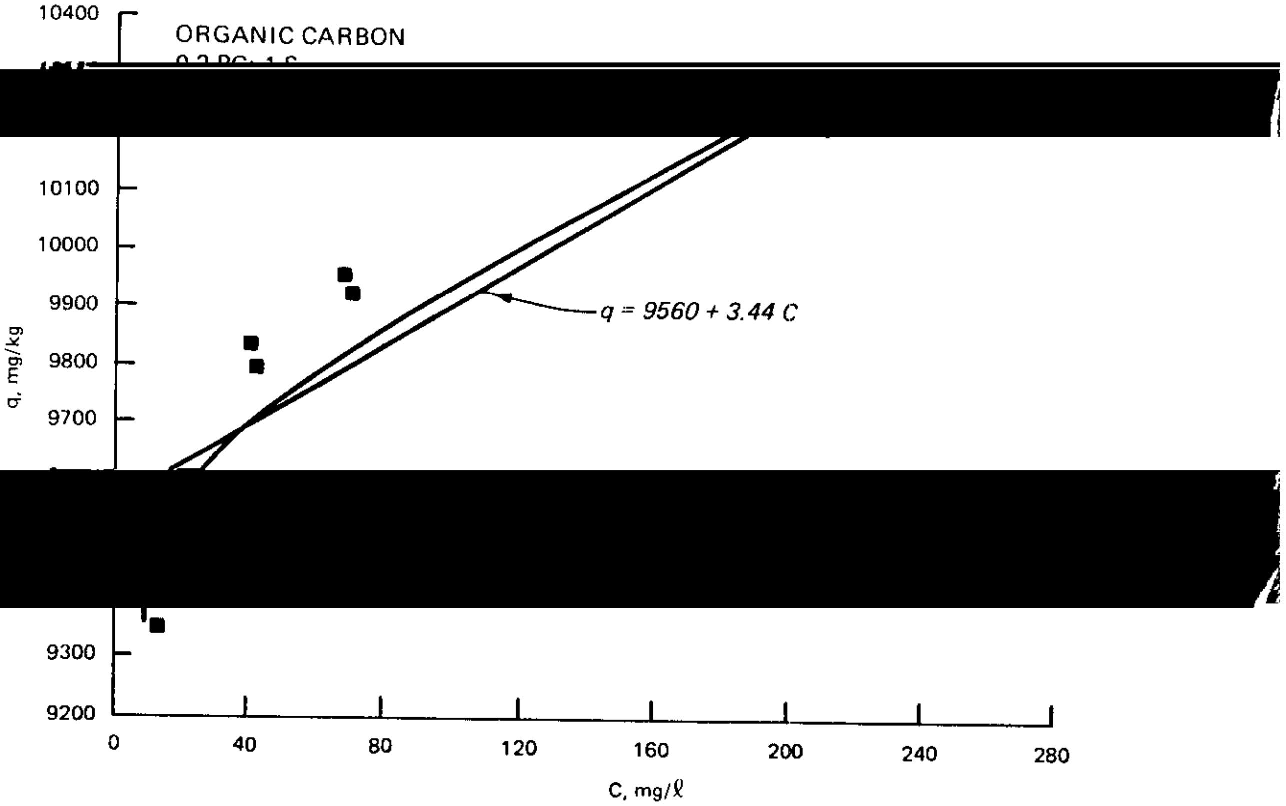


Figure H11. Organic carbon desorption isotherm for 0.2 portland cement:1 sediment

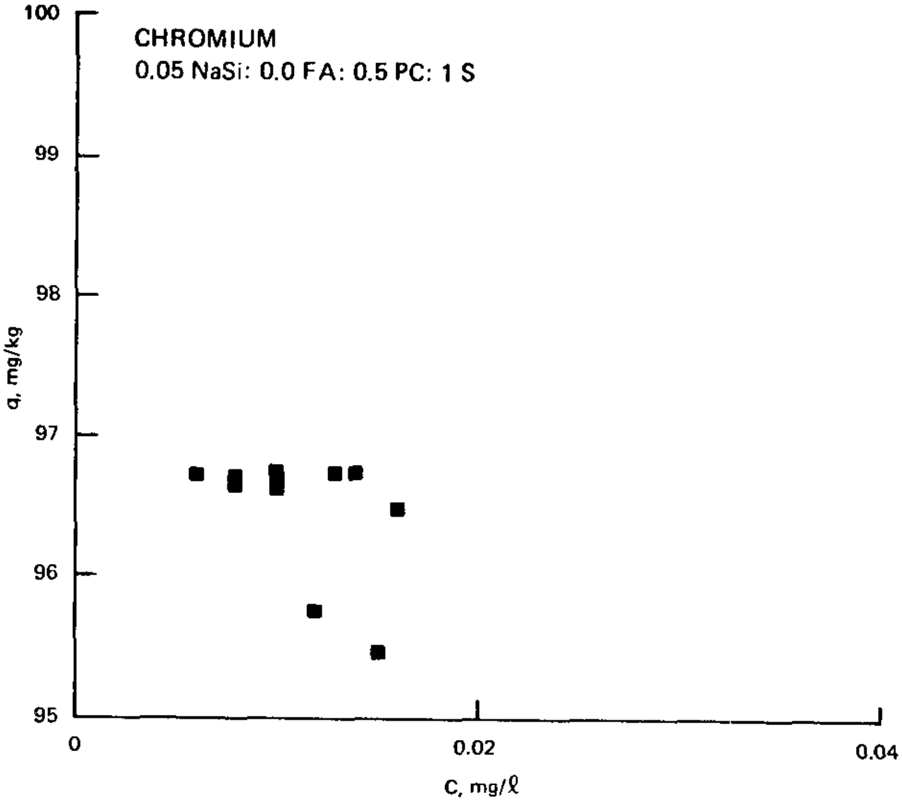


Figure H12. Chromium desorption isotherm for 0.05 sodium silicate:

[redacted]

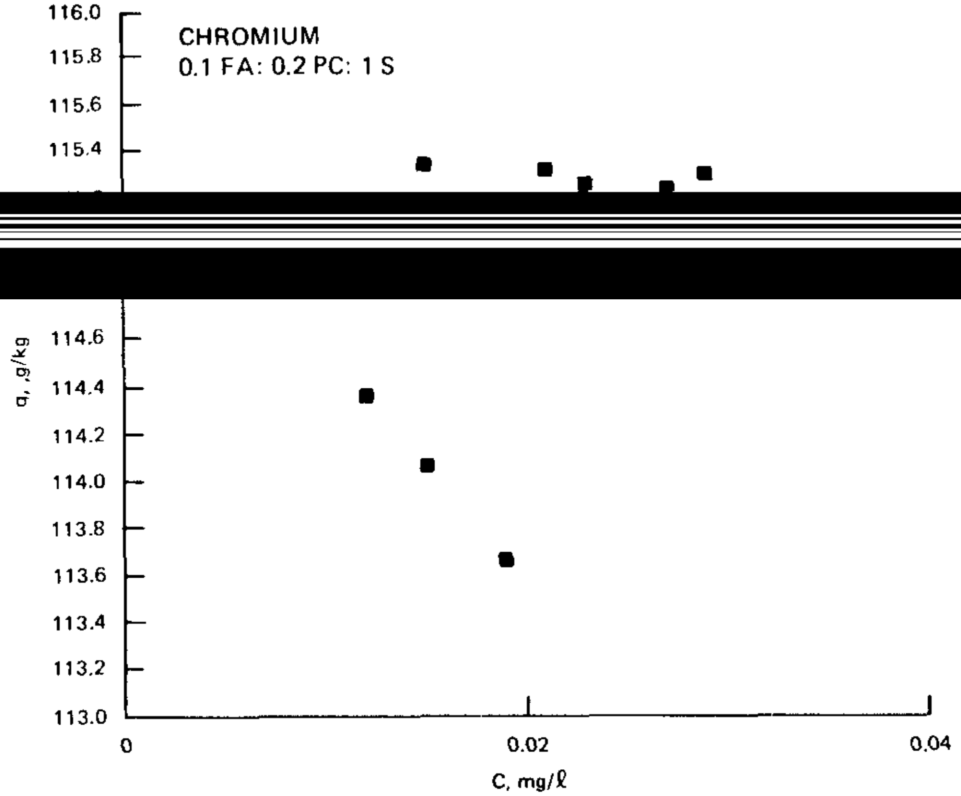


Figure H13. Chromium desorption isotherm for 0.1 fly ash: 0.2 portland cement:1 sediment

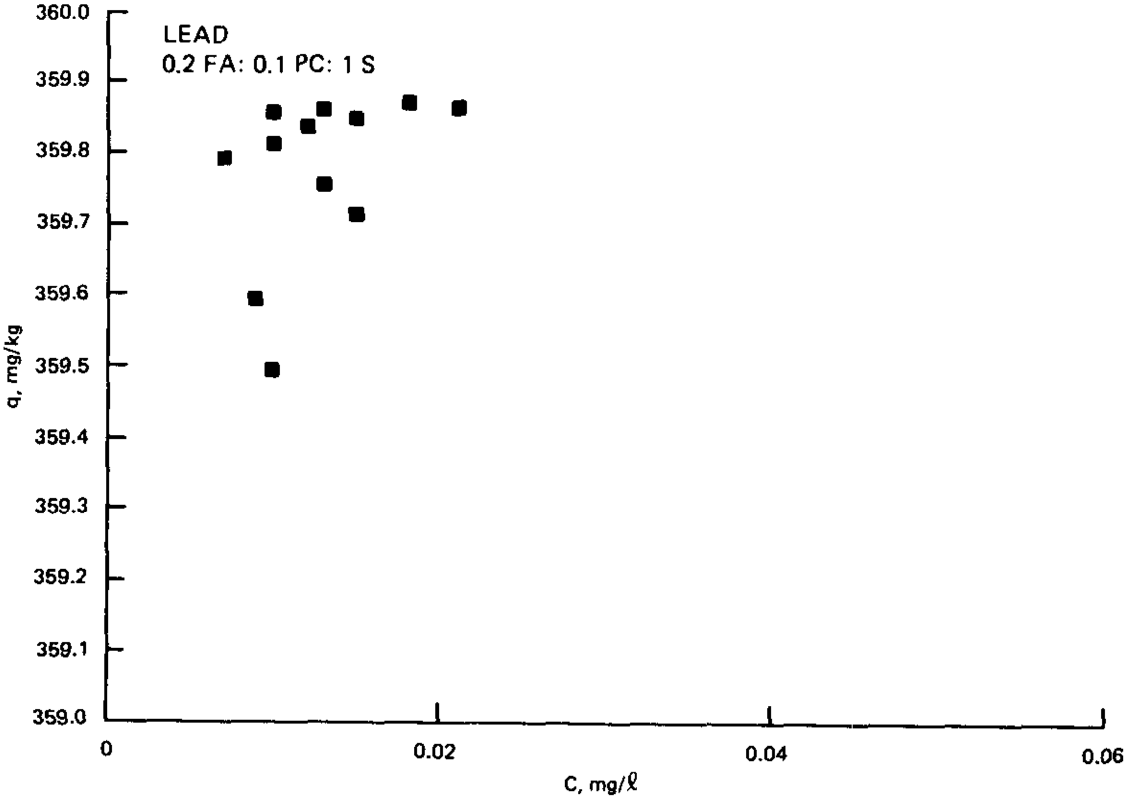


Figure H14. Lead desorption isotherm for 0.2 fly ash:
0.1 portland cement:1 sediment

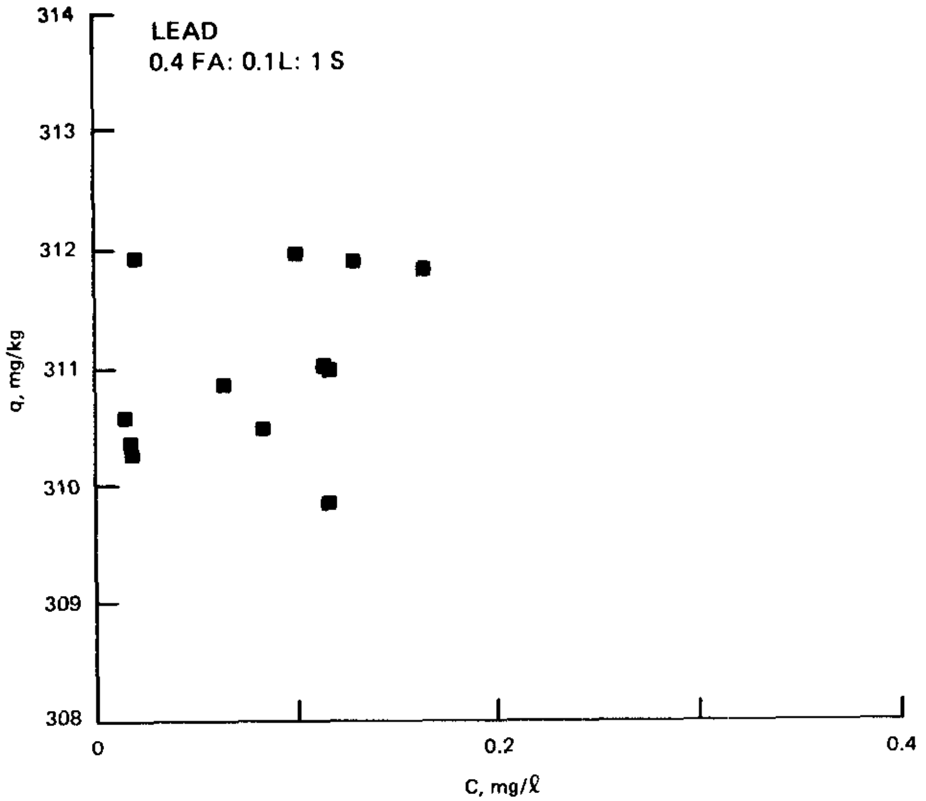


Figure H15. Lead desorption isotherm for 0.4 fly ash:
0.1 lime:1 sediment

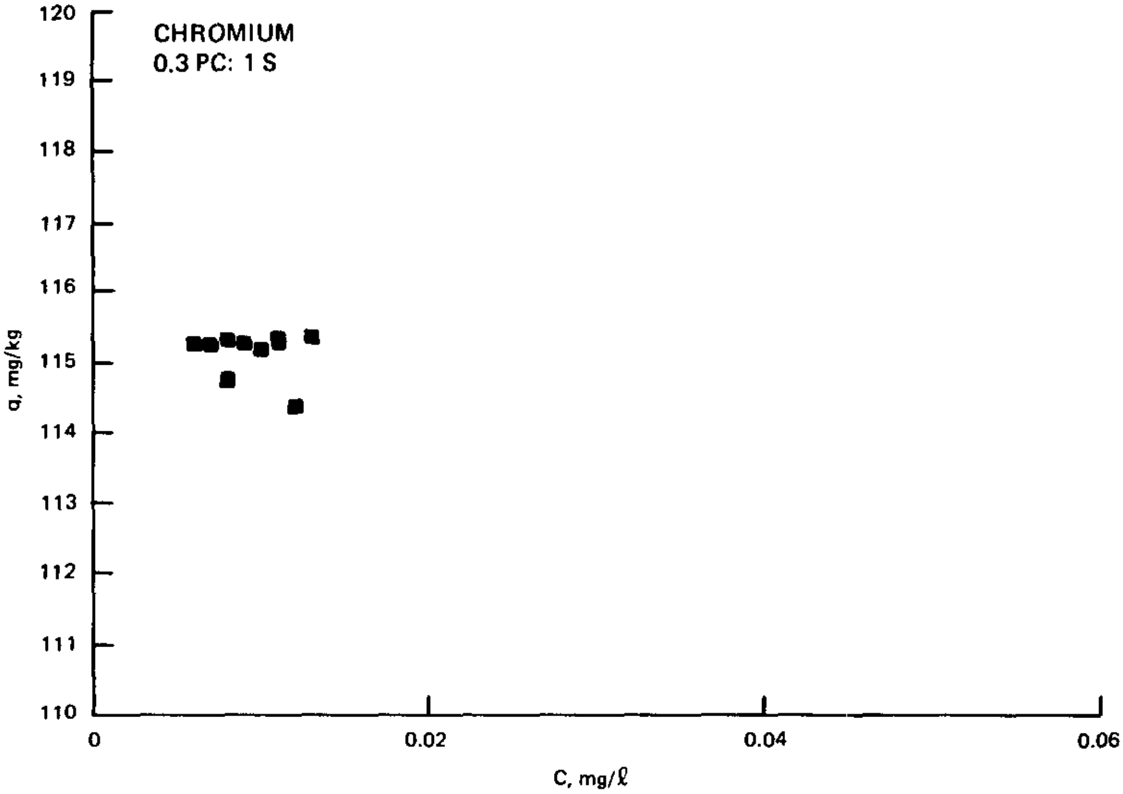


Figure H16. Chromium desorption isotherm for 0.3 portland cement: 1 sediment

Table H34

[redacted]

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Portland Cement with fly ash and/or sodium silicate						
0.05 NaSi:0.1 FA:0.1 PC:1 sediment	LRI	NRI	CI	CI	CI	ND
0.05 NaSi:0.1 FA:0.2 PC:1 sediment	LRI	NRI	CI	WDI**	LRI	ND
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
0.1 FM:0.2 PC:1 sediment	LRI	NRI	CI	WDI	NRI	WDI
0.15 FM:0.15 PC:1 sediment	LRI	NRI	CI	WDI	NRI	WDI
Fly Ash with lime						
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
0.5 FA:0.1 L:1 sediment	LRI	NRI	CI	CI	WDI	WDI
0.6 FA:0.1 L:1 sediment	LRI	NRI	CI	CI	WDI	WDI
Firmix						
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
0.5 FM:1 sediment	WDI	NRI	CI	LRI	NRI	WDI
0.6 FM:1 sediment	WDI	NRI	CI	LRI	NRI	WDI
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

LRI = low release isotherms.
WDI = well-defined desorption isotherms.
ND = no data
** Selected for presentation as a figure.

one-point LRI. The zinc desorption data for Indiana Harbor sediment solidified with portland cement in an additive-to-sediment ratio of 0.1 portland [illegible] listed in Table H34.

38. LRIs characterize contaminants that in the field situation leach in concentrations near the detection limits used in the development of the desorption isotherms. LRIs are, therefore, indicative of solidified/stabilized sediments that are not very leachable. Since most of the arsenic desorption [illegible]

39. In some of the serial, graded batch leach tests, the aqueous phase concentrations were detectable in leachates from the three lower liquid-solids ratios (20:1, 10:1, and 2:1) but not in leachates from the 100:1 liquid-solids ratio. Desorption isotherms with leachate concentrations detectable at liquid- [illegible] which contaminant concentrations were detectable at each liquid-solids ratio used in the series and the solid and aqueous phase concentrations follow a [illegible] category are listed in Table H34. [illegible]

be well above the detection limits used to develop the desorption isotherms. The initial leachate concentration is governed by the field liquid-solids [redacted] clean water percolates through the solidified/stabilized sediment is in part [redacted] the lower the initial concentration will be.

42. The desorption isotherm plots from some of the leaching tests were [redacted] that produced clusters are termed "cluster isotherms" (CI). CIs occurred more frequently in the chromium data than for any other contaminant. All of the chromium desorption isotherms were classified as CIs. The chromium desorption [redacted] isotherms shown in Figures H12 and H13 are typical CIs. Two cluster isotherms [redacted]

43. Some of the CIs had a horizontal orientation (Figure H16). A CI with a horizontal orientation indicates that there is leachable contaminant in the solidified/stabilized solids and that the leaching of this contaminant is not governed by reversible ion-exchange or sorption. In this case, the distribution coefficient K_d is zero. When K_d is zero, all of the leachable con- [redacted] between solid and aqueous phases. The solid phase concentration at the end of each test approaches q_r, the concentration that is resistant to leaching. Since the solid phase concentration of leachable contaminant is constant and neither reversible exchange nor sorption occur, the aqueous phase concentration [redacted] dilution with increasing liquid-solids ratio. Theoretically, the q versus C plot should be a horizontal line that intercepts the ordinate at q_r. The CI shown in Figure H16 is an example of a q versus C plot that closely approximates the theoretical result for K_d equal to zero.

44. If the leachable solid phase concentration is small, then the differ- [redacted]

ratio will be correspondingly small. If these differences are small relative to the combined precision of the leaching tests and chemical analytical procedures, the data will be scattered about the true result, depending on the variability associated with the leaching and chemical analysis procedures.

[redacted]

ity. In the field situation, the combination of a leachable solid phase

[redacted]

does not persist once the initial pore water has moved out.

45. Process effectiveness for contaminant immobilization. If a process provides complete immobilization for each contaminant, all of the contaminant desorption isotherms will be NRIs. None of the processes investigated in this study completely immobilized all of the contaminants in Indiana Harbor sedi-

[redacted]

cadmium and zinc. On the basis of the number of NRIs, however, no one process

[redacted]

detailed analysis is required. A contaminant specific methodology for comparing process effectiveness is outlined below that involves the distribution coefficient K_d and the amount of contaminant that is leachable q_1. The

[redacted]

for immobilizing organic carbon.

47. The distribution coefficient K_d as previously discussed, is a con-

[redacted]

represents all equilibrium-controlled interphase transfer processes. Since it is a measurement of the relative affinity of a contaminant for the solid phase versus the aqueous phase, it is an important index of contaminant immobilization. The higher the distribution coefficient, the lower the aqueous phase

[redacted]

also an important index of contaminant mobility since this quantity is the mass of contaminant available for partitioning between solid and aqueous phases. For a given distribution coefficient, the higher q_L, the higher the aqueous phase concentration.

48. The leachable contaminant concentration in the solidified sediment q_L is given by

$$q_L = q_o - q_r \tag{H4}$$

where

q_L = leachable contaminant concentration in the solidified/stabilized sediment, mg/kg

[redacted]

that is resistant to leaching, mg/kg.

49. The leachable contaminant concentration in the solidified sediment was normalized with respect to the mass of wet sediment that was processed for solidification/stabilization. Normalized leachable solid phase concentrations can be compared directly with the untreated sediment. Comparisons between processes with different additive dosages can also be made using normalized leachable solid phase concentrations. The leachable contaminant concentration normalized with respect to the mass of sediment that was processed is given by

$$q_{nL} = q_L(1 + R)(1 + w) \tag{H5}$$

where

q_{nL} = leachable contaminant concentration with respect to the mass of sediment processed by solidification, mg/kg

[redacted]

R = dosage of solidification/stabilization reagents,

[redacted]

50. The effectiveness of solidification/stabilization as a technology for immobilizing arsenic, lead, zinc, and chromium in Indiana Harbor sediment was [redacted] untreated, anaerobic sediment. The data are presented in Tables H35-38, for arsenic, lead, zinc, and chromium, respectively.

51. The data showed that in most cases solidification/stabilization reduced the mass of leachable arsenic in the sediment. This is indicated in [redacted]

were particularly effective in reducing the normalized leachable arsenic concentration q_{nL}. The portland cement process was also effective when the portland cement dosage was greater than 0.1 portland cement to 1 sediment. The process formulation with the lowest q_{nL} for arsenic was the 0.03 West-P: 0.5 Firmix:1 sediment formulation. With the exception of this one formulation, the Firmix with West-P and the Firmix processes, however, did not reduce the normalized leachable arsenic concentration, although the polymer reduced [redacted]

replacement with Firmix did not increase the normalized leachable arsenic concentration. Replacement with fly ash showed a slight increase.

52. As shown in Table H36, solidification/stabilization was also effective in immobilizing lead. Most of the processes reduced the mass of leachable [redacted]

involving fly ash did not show a comparable increase in leachable lead. The portland cement and portland cement with fly ash processes showed increased [redacted] process had higher q_{nL} than the Firmix process. In addition, the normalized leachable lead concentrations for portland cement with WEST-P were higher than [redacted]

Table H35

Summary of Arsenic Leaching Indices for Solidified/Stabilized

Indiana Harbor Sediment

Process	$_{L}q_{T}$ mg/kg	$_{UL}q_{T}$ mg/kg	$_{u}K_{d}$ ℓ/kg
[redacted]			
Portland cement			
0.1 PC:1 sediment	0.29	0.60	17.7
0.2 PC:1 sediment	<0.03	<0.07	-
0.3 PC:1 sediment	<0.05	<0.13	-
0.4 PC:1 sediment	<0.05	<0.14	-
Portland cement with fly ash			
0.2 FA:0.1 PC:1 sediment	0.15	0.37	6.06
0.1 FA:0.2 PC:1 sediment	0.07	0.17	3.10
0.15 FA:0.15 PC:1 sediment	0.09	0.22	4.53
Portland cement with fly ash			
[redacted]			
0.05 NaSi:0.25 FA:0.25 PC:1 sediment	<0.05	<0.15	-
0.05 NaSi:0.25 PC:1 sediment	<0.05	<0.13	-
0.05 NaSi:0.5 PC:1 sediment	<0.05	<0.15	-
[redacted]			
0.2 FM:0.1 PC:1 sediment	<0.05	<0.13	-
0.1 FM:0.2 PC:1 sediment	<0.05	<0.13	-
0.15 FM:0.15 PC:1 sediment	<0.05	<0.13	-
Fly ash with lime			
0.4 FA:0.1 L:1 sediment	<0.05	<0.15	-
0.5 FA:0.1 L:1 sediment	<0.05	<0.16	-
0.6 FA:0.1 L:1 sediment	<0.05	<0.16	-
Firmix			
[redacted]			

(Continued)

Firmix with WEST-P			
0.01 WP:0.5 FM:1 sediment	0.21	0.60	15.87
0.03 WP:0.5 FM:1 sediment	0.02	0.06	-
0.05 WP:0.5 FM:1 sediment	0.22	0.64	19.29
Portland cement with WEST-P			
0.01 WP:0.2 PC:1 sediment	0.08	0.18	4.65
0.03 WP:0.2 PC:1 sediment	0.09	0.21	5.92
0.05 WP:0.2 PC:1 sediment	<0.06	<0.14	-

Table H36

[redacted]

Process	[redacted] mg/kg	[redacted] mg/kg	[redacted] ℓ/kg
Untreated anaerobic sediment	2.47	2.47	2.39
Portland cement			
0.1 PC:1 sediment	0.50	1.03	2.12
0.2 PC:1 sediment	0.58	1.31	5.50
0.3 PC:1 sediment	0.98	2.44	0
[redacted]	[redacted]	[redacted]	[redacted]
Portland cement with fly ash			
0.2 FA:0.1 PC:1 sediment	0.11	0.27	0
0.1 FA:0.2 PC:1 sediment	0.48	1.17	12.1
0.15 FA:0.15 PC:1 sediment	0.35	0.85	0
Portland cement with fly ash and/or sodium silicate			
[redacted]	[redacted]	[redacted]	[redacted]
0.05 NaSi:0.25 FA:0.25 PC:1 sediment	0.43	1.25	6.05
0.05 NaSi:0.25 PC:1 sediment	1.10	2.69	4.17
0.05 NaSi:0.5 PC:1 sediment	0.63	1.83	0
Portland cement with Firmix			
0.2 FM:0.1 PC:1 sediment	0.17	0.42	0
[redacted]	[redacted]	[redacted]	[redacted]
0.4 FA:0.1 L:1 sediment	1.16	3.27	0
0.5 FA:0.1 L:1 sediment	1.38	4.15	0
[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

Process	q_L mg/kg	q_{nL} mg/kg	K_d ℓ/kg
Firmix with WEST-P			
[redacted]	[redacted]	[redacted]	[redacted]
0.05 WP:0.5 FM:1 sediment	0.05	0.15	0
Portland cement with WEST-P			
0.01 WP:0.2 PC:1 sediment	0.35	0.80	11.5
0.03 WP:0.2 PC:1 sediment	0.27	0.62	10.9
[redacted]	[redacted]	[redacted]	[redacted]

Table H37

Summary of Zinc Leaching Indices for Solidified/Stabilized Indiana Harbor Sediment

[redacted]

Process	[redacted] mg/kg	[redacted] mg/kg	[redacted] ℓ/kg
Untreated anaerobic sediment	9.4	9.4	-
Portland cement			
0.1 PC:1 sediment	0.1	0.2	-
0.2 PC:1 sediment	<0.1	<0.3	0
0.3 PC:1 sediment	1.7	2.2	16.5
[redacted]	[redacted]	[redacted]	[redacted]
Portland cement with fly ash			
0.2 FA:0.1 PC:1 sediment	0.3	0.7	-
0.1 FA:0.2 PC:1 sediment	<0.1	<0.3	-
0.15 FA:0.15 PC:1 sediment	<0.1	<0.3	-
[redacted]	[redacted]	[redacted]	[redacted]
0.05 NaSi:0.25 FA:0.25 PC:1 sediment	0.3	0.9	-
0.05 NaSi:0.25 PC:1 sediment	0.5	1.2	0
0.05 NaSi:0.5 PC:1 sediment	0.4	0.5	0
Portland cement with Firmix			
0.2 FM:0.1 PC:1 sediment	<0.1	<0.3	-
0.1 FM:0.2 PC:1 sediment	<0.1	<0.3	-
[redacted]	[redacted]	[redacted]	[redacted]
0.4 FA:0.1 L:1 sediment	4.8	13.5	27.3
0.5 FA:0.1 L:1 sediment	9.1	27.4	49.1
0.6 FA:0.1 L:1 sediment	10.2	32.6	45.8
Firmix			
0.4 FM:1 sediment	<0.1	<0.3	-
0.5 FM:1 sediment	<0.1	<0.3	-
[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

Table H37 (Concluded)

	qL	qnL	Kd
[redacted]			
0.01 WP:0.5 FM:1 sediment	<0.1	<0.3	-
0.03 WP:0.5 FM:1 sediment	<0.1	<0.3	-
0.05 WP:0.5 FM:1 sediment	<0.1	<0.3	-
Portland cement with WEST-P			
0.01 WP:0.2 PC:1 sediment	<0.1	<0.3	-
0.03 WP:0.2 PC:1 sediment	<0.1	<0.3	-
0.05 WP:0.2 PC:1 sediment	<0.1	<0.3	-

Table H38

[redacted]

Process	q_L mg/kg	q_{nL} mg/kg
[redacted]	[redacted]	[redacted]
Portland cement		
0.1 PC:1 sediment	0.96	1.98
0.2 PC:1 sediment	0.18	0.41
0.3 PC:1 sediment	0.27	0.66
0.4 PC:1 sediment	0.39	1.03
[redacted]	[redacted]	[redacted]
Portland cement with fly ash and/or sodium silicate		
0.05 NaSi:0.1 FA:0.1 PC:1 sediment	0.30	0.70
~~0.05 NaSi:0.1 FA:0.2 PC:1 sediment~~	~~0.54~~	~~1.37~~
0.05 NaSi:0.25 FA:0.25 PC:1 sediment	0.51	1.49
[redacted]	[redacted]	[redacted]
Portland cement with Firmix		
[redacted]	[redacted]	[redacted]
Fly ash with lime		
0.4 FA:0.1 L:1 sediment	0.40	1.13
0.5 FA:0.1 L:1 sediment	0.23	0.69
[redacted]	[redacted]	[redacted]
Firmix		
0.4 FM:1 sediment	0.33	0.87
0.5 FM:1 sediment	0.33	0.93
0.6 FM:1 sediment	0.26	0.78

(Continued)

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* Kd = 1.85 ℓ/kg.

Table H38 (Concluded)

Process	q_L mg/kg	q_{nL} mg/kg
Firmix with WEST-P		
0.01 WP:0.5 FM:1 sediment	0.16	0.45
0.03 WP:0.5 FM:1 sediment	0.25	0.72
0.05 WP:0.5 FM:1 sediment	0.23	0.67
Portland cement with WEST-P		
0.01 WP:0.2 PC:1 sediment	0.78	1.78
0.03 WP:0.2 PC:1 sediment	0.74	1.71
[redacted]	[redacted]	[redacted]

53. The data for zinc showed that, in general, solidification/stabilization reduced the mass of leachable zinc in the sediment. As was the case with lead, the lime in the fly ash with lime process apparently increased the [redacted] parable increases in normalized leachable zinc. The portland cement with Firmix, Firmix, and the processes involving WEST-P were particularly effective in reducing the normalized leachable zinc concentration. The zinc desorption isotherms for all the formulations for each of these processes were NRIs.

54. Table H38 lists the leachable and normalized leachable concentrations for chromium. Since all of the chromium desorption isotherms were CIs, K_d is equal to zero in every case. Some of the solidification/stabilization pro- [redacted] either inconsistent in the reduction provided or increased the normalized [redacted] relationship between solid and aqueous phase chromium concentrations makes definitive statements concerning immobilization (or the lack thereof) impossi- [redacted]

[redacted] reduced the leachability of the metals in Indiana Harbor sediment. The process formulations ranked number 1 and 2 were the 0.01 WEST-P:0.5 Firmix:1 sediment and the 0.05 WEST-P:0.5 Firmix:1 sediment formulations. Because the [redacted] lead, this process formulation was not included in the ranking. However, the [redacted]

Table H39

[redacted]

Ranking	Process	q_{nL}* (mg/ℓ)
[redacted]	[redacted]	[redacted]
5	0.4 Firmix:1 sediment	2.35
6	0.5 Firmix:1 sediment	2.35
7	0.6 Firmix:1 sediment	2.41
8	0.15 fly ash:0.15 portland cement:1 sediment	2.45
[redacted]	[redacted]	[redacted]
11	0.03 WEST-P:0.2 portland cement:1 sediment	2.84
12	0.2 Firmix:0.1 portland cement:1 sediment	2.85
13	0.2 Fly ash:0.1 portland cement:1 sediment	2.98
14	0.05 WEST-P:0.2 portland cement:1 sediment	3.01
[redacted]	[redacted]	[redacted]
	cement:1 sediment	
18	0.05 Sodium silicate:0.25 fly ash:0.25 portland	3.79
[redacted]	[redacted]	[redacted]
19	0.1 Portland cement:1 sediment	3.81
[redacted]	[redacted]	[redacted]
21	0.05 Sodium silicate:0.25 portland cement:1 sediment	5.07
22	0.3 Portland cement:1 sediment	5.43

(Continued)

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* $q_{nL} = q_{nL,As} + q_{nL,Cr} + q_{nL,Pb} + q_{nL,Zn}$

Table H39 (Concluded)

[illegible]	[illegible]	[illegible]
23	0.4 Portland cement:1 sediment	7.49
24	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

top three process formulations probably would have been Firmix with WEST-P formulations. The second best process for metal immobilization was the Firmix process. The three Firmix formulations ranked fourth, fifth, and sixth. The [redacted] numbers 19, 22, and 23. Thus, with the exception of one formulation, the portland cement process was not as effective as the other processes.

57. As previously noted, the desorption isotherms for organic carbon [redacted] usually occur in adsorption studies involving organic chemicals. Three adsorption isotherms are well known, the BET, the Langmuir, and the Freundlich isotherms. Hill, Myers, and Brannon (1986) have discussed the potential application of these isotherms to desorption data from contaminated sediment.

58. [redacted]

$$q = \frac{QbC}{(1 + bC)} \qquad \text{(H6)}$$

where

q = solid phase contaminant concentration, mg/kg
Q = sorption capacity of the solid phase, mg/kg
b = Langmuir distribution coefficient, ℓ/mg
C = aqueous phase contaminant concentration, mg/kg

Equation H6 models a contaminant that is totally leachable, i.e., q_r is equal to zero.

59. By fitting data to the linearized form of the Langmuir equation given below, the Langmuir coefficients, Q and b, can be obtained.

$$\frac{C}{q} = \frac{1}{Qb} + \frac{1C}{Q} \qquad \text{(H7)}$$

For comparison, Equation G3 and equation H7 were fitted to the organic carbon [redacted] regressed equation fits the data better.

[redacted] than the linear desorption model in every case. However, since fitting Equation H7 involves regressing C against itself, comparison of r^2 values for Equations G3 and H7 has limited meaning. An inspection of the desorption plots showed the nonlinearity of the process controlling organic carbon desorption to be unmistakable. Thus, a nonlinear model, such as the Langmuir equation, is more appropriate. In addition, the consistency of the r^2 values for the [redacted]

61. The Langmuir coefficients determined by regression of Equation H7 onto the organic carbon desorption data are presented in Table H40. The [redacted] described for normalized leachable metal concentrations, Equation H5. The [redacted] since the setting agents compete with sorbed materials for reaction sites on the sediment solids. [redacted] on the sediment solids, and, apparently, the setting agents add little or no [redacted]

63. Since the organic carbon analysis consisted of determining total [redacted]

Table H40

Langmuir Coefficients For Organic Carbon in Leachates

[redacted]

Process	r (Eq G5)	r (Eq H7)	b ℓ/kg	Q mg/kg	Q_N mg/kg
Untreated sediment	0.9175	0.9999	0.95	23400	23400
Portland cement					
0.1 PC:1 sediment	0.7799	0.9999	0.64	10900	22600
0.2 PC:1 sediment	0.7712	0.9999	0.52	10300	23200
0.3 PC:1 sediment	0.8269	0.9999	0.80	9440	23100
0.4 PC:1 sediment	0.4346	0.9999	1.21	8770	23100
Portland cement with fly ash					
0.2 FA:0.1 PC:1 sediment	0.6729	0.9999	0.46	9260	22600
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Portland cement with Firmix					
0.2 FM:0.1 PC:1 sediment	0.5595	0.9999	2.25	9380	22900
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Fly ash with lime					
0.4 FA:0.1 L:1 sediment	0.6428	0.9999	0.91	8220	23200
0.5 FA:0.1 L:1 sediment	0.1233	0.9994	0.80	7740	23300
0.6 FA:0.1 L:1 sediment	0.7445	0.9999	2.09	7220	23100
Firmix					
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Firmix with WEST-P					
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
0.01 WP:0.5 FM:1 sediment	0.4713	0.9999	1.22	8050	22800
0.03 WP:0.5 FM:1 sediment	0.2111	0.9999	-8.6	7860	22600
0.05 WP:0.5 FM:1 sediment	0.3765	0.9999	2.08	7780	22700
Portland Cement with WEST-P					
0.01 WP:0.2 PC:1 sediment	0.6314	0.9998	0.61	10000	22800
0.03 WP:0.2 PC:1 sediment	0.6574	0.9999	0.66	9790	22600
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

organic compounds such as humic and fluvic acids that are normally found in high concentration in sediments. Hence, the organic carbon desorption isotherms may reflect primarily the desorption characteristics of these substances. The ability of special solidification/stabilization agents, such as

[redacted]

[redacted]

obtained in the laboratory due to lower mixing efficiency and/or dosage con-

[redacted]

uated in a field demonstration. Temperature is another processing variable that was not investigated that can be important in the field.

65. Caution must also be exercised in extrapolating the desorption data

[redacted]

laboratory leach data are not necessarily conservative since the impact of grinding on contaminant mobility is poorly understood.

66. Chemical leach data from serial, graded batch leach tests and the

[redacted]

generation of leachate as water percolates through a porous medium, such as

[redacted]

1984), might also be applied to solidified/stabilized sediment and give reasonable results. The permeant-porous media model is probably a worst-case model, and the solid-phase diffusion model is probably a best-case model ~~(Myers and Hill 1986). The lack of detailed field records, however, makes~~ definitive statements concerning the relative merits of the two approaches impossible.

Conclusions

67. The range in 28-day UCS was 48.5 psi (334 kPa) to 682 psi (4700 kPa), [redacted] range in product strength is indicative of the versatility of solidification as a physical stabilization process for Indiana Harbor sediment. The technology has the flexibility to meet specifications for physical stability ranging [redacted] ducing a material suitable for end uses typical of soft concrete.

[redacted] lized by some processes. Because some solidification/stabilization tend to increase the leachable metal concentration, careful process selection is needed. [redacted] immobilization were Firmix with WEST-polymer and Firmix.

[redacted] evaluate the potential of solidification/stabilization technology to reduce the leachability of specific organic compounds.

APPENDIX I: FEASIBILITY STUDY OF CONTAINED AQUATIC DISPOSAL IN INDIANA HARBOR CANAL AND ENTRANCE CHANNEL

Background

[illegible] sidered for disposal of this material is capped aquatic disposal (CAD). Possible sites for the CAD include Lake Michigan, Indiana Harbor proper, the [illegible] is determined to be feasible and subsequently selected for further study, a demonstration site will first be tested to demonstrate that the CAD is an [illegible] dredged and placed in the demonstration CAD site to be monitored. If the [illegible]

Objectives of the Hydraulics Laboratory Effort

[illegible]

- a. Determine the feasibility of CAD in the Indiana Harbor Canal and Entrance Channel.
- b. If CAD is feasible, make specific siting and configuration recommendations for both the demonstration and full volume sites.
- c. Evaluate cap stability based on available data to include vessel traffic.
- d. Design a long-term program to monitor cap stability.

Approach

[illegible] integrity of nearby harbor structures, and the existence of [illegible]

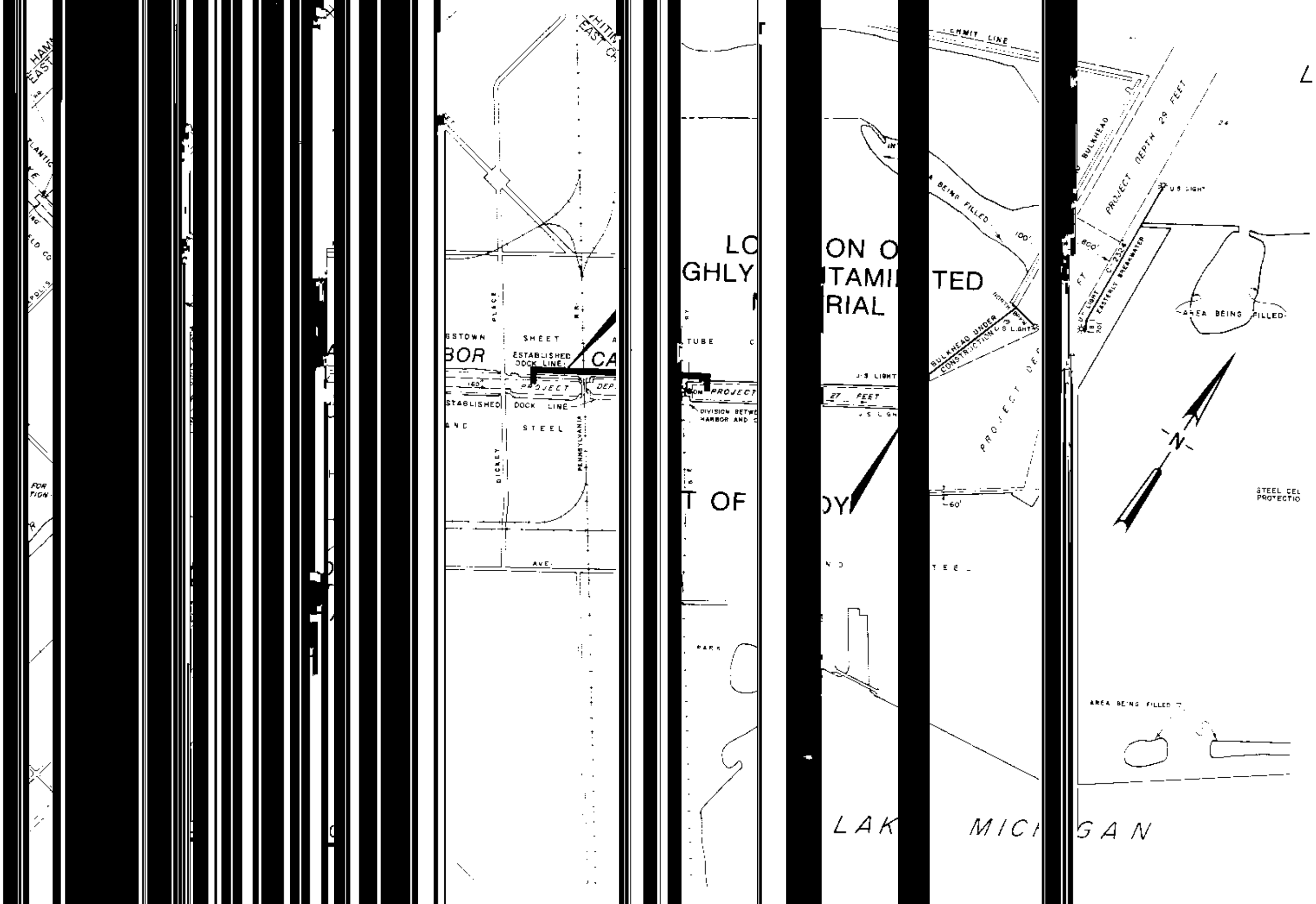

Figure II. e map

4. The second step was to site and size the required excavation for the full-volume site and to design the cap. Based on available current data (both [redacted] was not addressed. In addition to the references cited, a general bibliography containing several related subjects is included at the end of the main [redacted]

Area of Concern

[redacted] Indiana Harbor Canal, and the branches of the Federal project beyond the Forks [redacted]

6. Another area that was not considered was the Forks area since it is actively used as a turning basin and vessels' propeller wash strongly agitates bottom sediments. Other constraints considered were buried pipeline and cable [redacted]

CAD Design Considerations

7. The volume of highly contaminated material to be dredged has been [redacted] effort, it was assumed that 220,000 to 400,000 cu yd must be contained in the CAD site.

8. In order to estimate the area required for the CAD site, a cross section was developed for the smaller and less used branches of the canal. By [redacted]

study were the US turning basin and adjacent canal and the entrance channel (Figure I1).

9. There is a very limited amount of flow information available for [redacted] either in or out of the entrance channel and velocities may range from 0 to 1 fps.* A criterion of 3 fps was selected as the flow speed for incipient motion of the cap.

10. Another consideration was the physical characteristics of dredging equipment to be used. The depth of the design cross section was limited to approximately 50 ft so that most dredge types could be used.

[redacted] length over all of [illegible] to [illegible] ft and greater. These tankers and freighters have drafts up to 30 ft and propeller diameters in the range of 20 ft. Some of these vessels already operate in the entrance channel area.

[redacted]

Cap Stability

Natural flows

13. To address grain-size requirements for capping materials under [redacted] shear stress, etc., to arrive at the critical flow condition for initiation of sediment motion. By varying the average grain size (D[illegible]), the method indi- [redacted] withstand velocities of over 3 fps under normal conditions. A cap thickness of 3 ft was chosen as protection against major storm events, so that some erosion of the cap could occur without exposing the contaminated material. It also provides flexibility in replacement time whereas a thinner cap would require additional materials immediately. A thicker cap would be more costly and reduce the available containment area even more. At the Duwamish Waterway

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* [redacted]

contaminated dredge disposal site (Seattle, Wash.), a sand cap of approxi-

[redacted]

Ackers-White

14. In the development of the Ackers-White formulation (Ackers and White

[redacted]

sediment as suspended load. Sediment mobility is described by the ratio of the appropriate shear force on a unit area of the bed to the immersed weight

[redacted]

as:

[redacted]

$$F_{gr} = \frac{{}^{*}}{gD(s-1)} \quad \frac{V}{32 \log \frac{\alpha d}{D}}^{\,1-n} \qquad (I1)$$

where

v* = shear velocity based on energy grade line slope

D = sediment diameter

g = acceleration of gravity

s = mass density of sediment relative to that of water

[redacted]

A dimensionless grain diameter D_{gr} is defined as:

[redacted]

$$D_{gr} \quad \frac{g(s-1)}{v^2}^{1/3} \qquad (I2)$$

where

[redacted]

15. Once the value of D_{gr} has been derived, the value of n, the transport exponent, can be determined as follows:

for $D_{gr} \le 1.0$ $n = 1$

[redacted]

for $D_{gr} > 60$ $n = 0$

and the value of the sediment mobility number calculated from Equation I1.

[redacted]

the power per unit area of bed; and for fine sediments, it uses the product of the total shear stress and velocity. The dimensionless sediment transport rate G_{gr} is described by the equation

$$G_{gr} = C \ \frac{F_{gr}}{A} - 1 \ ^{m} \qquad \text{(I3)}$$

where

C = coefficient in sediment transport function

A = value of F_{gr} at nominal initial motion

[redacted]

for $1 < D_{gr} \le 60$ $\log C = 2.86 \log D_{gr} - (\log D_{gr})^2 - 3.53$

$A = (0.23/ D_{gr}) + 0.14$

[redacted]

for $D_{gr} > 60$ $C = 0.025$

$A = 0.17$

$m = 1.50$

17. Once the dimensionless sediment transport rate has been derived from Equation I3, the sediment transport in mass flux per unit mass flow rate X can be determined from the equation

$$X = \frac{G_{gr} SD}{d} \left(\frac{V}{v_*} \right)^n \qquad (I4)$$

18. By reworking the Ackers-White formulation with the variables of both grain size and depth as functions of flow speed, the initiation of motion, or, conversely, the cap stability was determined for capping materials. Figure I2 [redacted] senting a different depth. The graph indicates the velocity, in feet per second, at which the median sediment grain (D_{50}) begins movement at the channel depth indicated. Coarse sand mixed with fine gravel will resist natural [redacted]

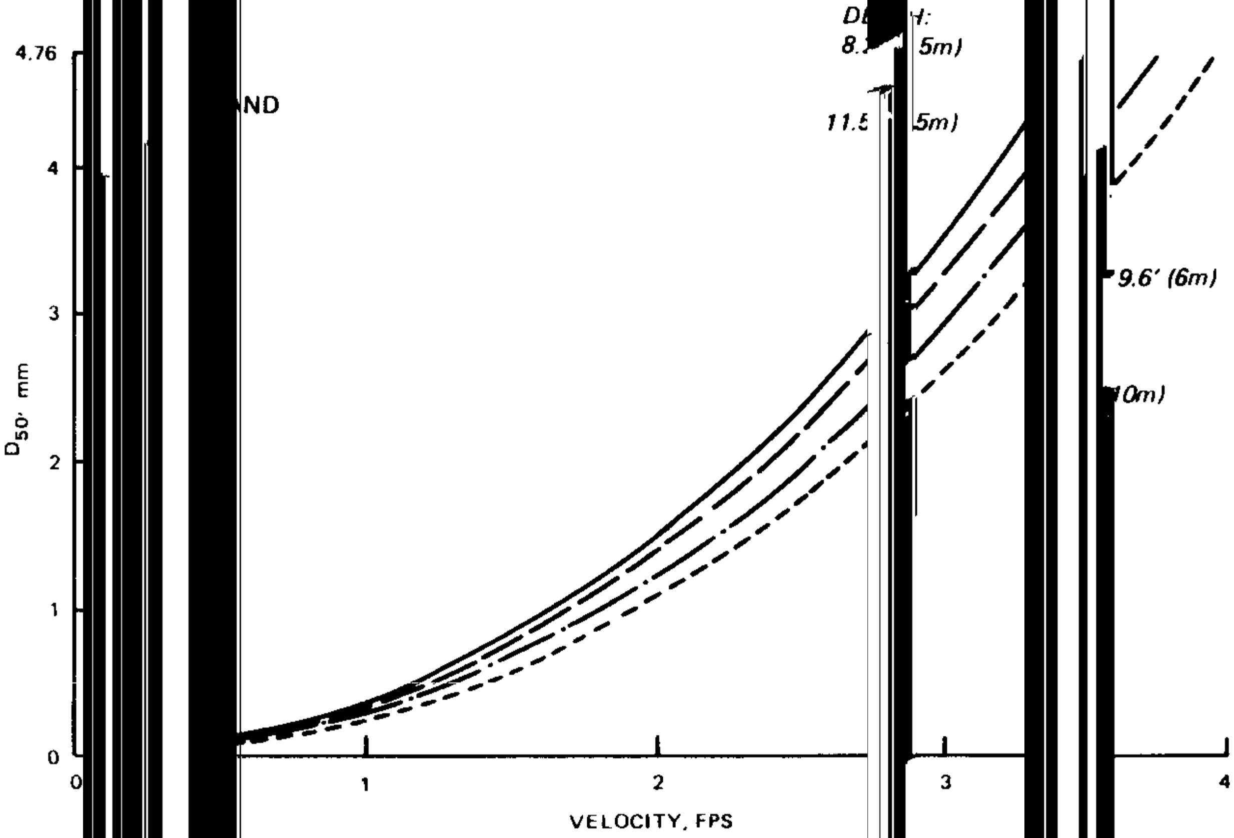
19. Two mathematical methods were compared to address the effects of ship traffic directly over the cap. The first method, Liou and Herbich (1976), is fairly involved mathematically and the authors developed a computer program to solve it. Also presented are the data of several case studies based on Corpus Christi ship channel traffic. The results appear excessively [redacted] layer and relative velocity effects.

20. The second method reviewed, Blaauw and van de Kaa (1978), is based on empirical, laboratory, and field observations. Since actual case studies were not provided, it was decided to use this method and then compare the results with those of Herbich et al.

21. The Blaauw and van de Kaa method addresses the design of bottom [redacted]

22. The value of the axial efflux velocity of propeller V_o may be determined by:

$$V_o \sim 1.60 \, n \, D_p \, K_T(\text{prop}) \qquad (I5)$$



I2. Particle movement predictions by A ers-Whi thod (Mannings n = 0.03)

where

n = number of revolutions per second of propeller

D_p = diameter of propeller

K_T(prop) = propeller thrust coefficient

23. The next value to be calculated is the initial diameter of slipstream behind the propeller D_0 :

[redacted]

24. Laboratory tests indicated that the area in which maximum scour of

[redacted]

from the propeller plane behind the vessel. Using the theory of a submerged jet, the next equation was developed to calculate the velocity distribution

[redacted]

[redacted]

where

V_x = axial velocity at a point

e = 2.718 (the base of the natural logarithm system)

25. Since the axial velocity V_x has been calculated, the bottom shear stress can be determined with Equation I8:

$$T = \frac{1}{2} C_f \rho V_x^2 \qquad \text{(I8)}$$

where

T = bottom shear stress

c_f = bottom friction factor which in general is $0.06 < c_f < 0.11$

[redacted]

26. The median size (D_{50}) of bottom protection can be computed by:

[redacted]

where

$$\Delta = \text{relative density of bottom material} = \frac{\rho_s - \rho}{\rho}$$

[redacted]

[redacted]

Harbor Canal by commercial vessel operators is to "coast" through the canal, then move through the bridges under power. However, should a vessel be in an emergency situation such as possible collision or an extreme storm event, a vessel may use full power, forward or reverse, and perhaps even drag the ves-

[redacted]

[redacted]

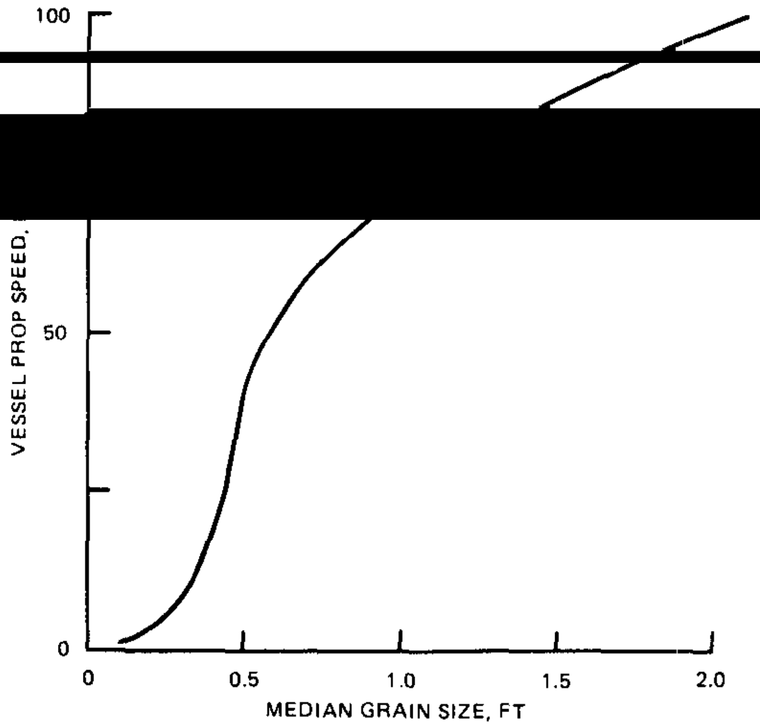
realistic 20-ft-diam propeller was selected with rotation at 50 rpm. Based on

[redacted]

At 100 rpm, still a realistic possibility, the rock size increases to just

[redacted]

passing vessel (coasting and not under power) on a channel bottom has not been considered. The dropping of an anchor or dragging anchor cannot be easily addressed but will have a major impact on any cap material. These effects were not considered further since the simple calculation showed the cap to be infeasible.



[redacted]

Figure I3. Armor stone size as a function of vessel speed

31. A comparison of these results to those of Liou and Herbich (1976) [illegible]

as needed for bottom protection. This agrees with our upper range of values. As another check, several flood control channel design handbooks dealing with bottom velocities were reviewed. Using 15 fps, these works indicate a 1.5-ft-diam or 250-lb stone would be required.

Volumetric Design with Cap and Armor

32. A second cross section was developed from the first (Figure I4) which also included a 3-ft-deep sand cap with the top of the sand 2 ft below the authorized channel depth. Note that Figure I4 is the entrance channel cross section whereas the cross section for the canal is not as wide nor deep.

33. Figure I5 shows the third cross section [illegible]

almost 30 percent. This means that 120,000 to 150,000 cu yd maximum of the 220,000 to 400,000 cu yd can be placed and another site must be located for the remainder. Beneath the armor layer, a gradation of sands and gravels prevents contaminated material movement through the armor layer. As with the cap thickness, there is no design criterion for stone armor layer thickness. As the median stone diameter increases, the relative void ratio also increases. A narrow band or "veneer" of armor would be unacceptable since the [illegible]

34. Aside from propeller wash, this channel bottom armor could, [illegible]

and armor. Maintenance dredging above the armor will have to be accomplished more cautiously, causing increased costs. Should a dredge accidentally pick up some of the armor material, there would be additional expenses in pump and equipment repair plus down time. Placement of the armor layer presents addi- [illegible]

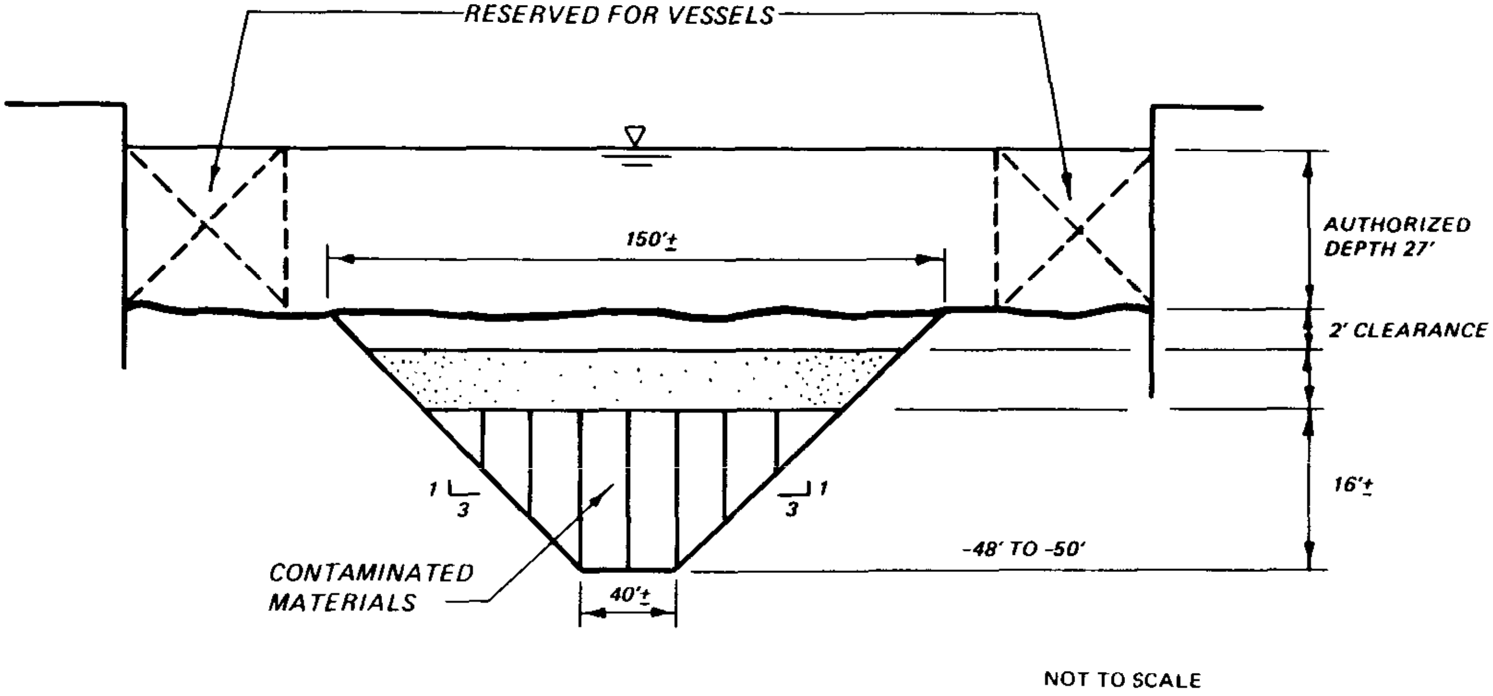


Figure I4. Trench cross section with 3-ft cap

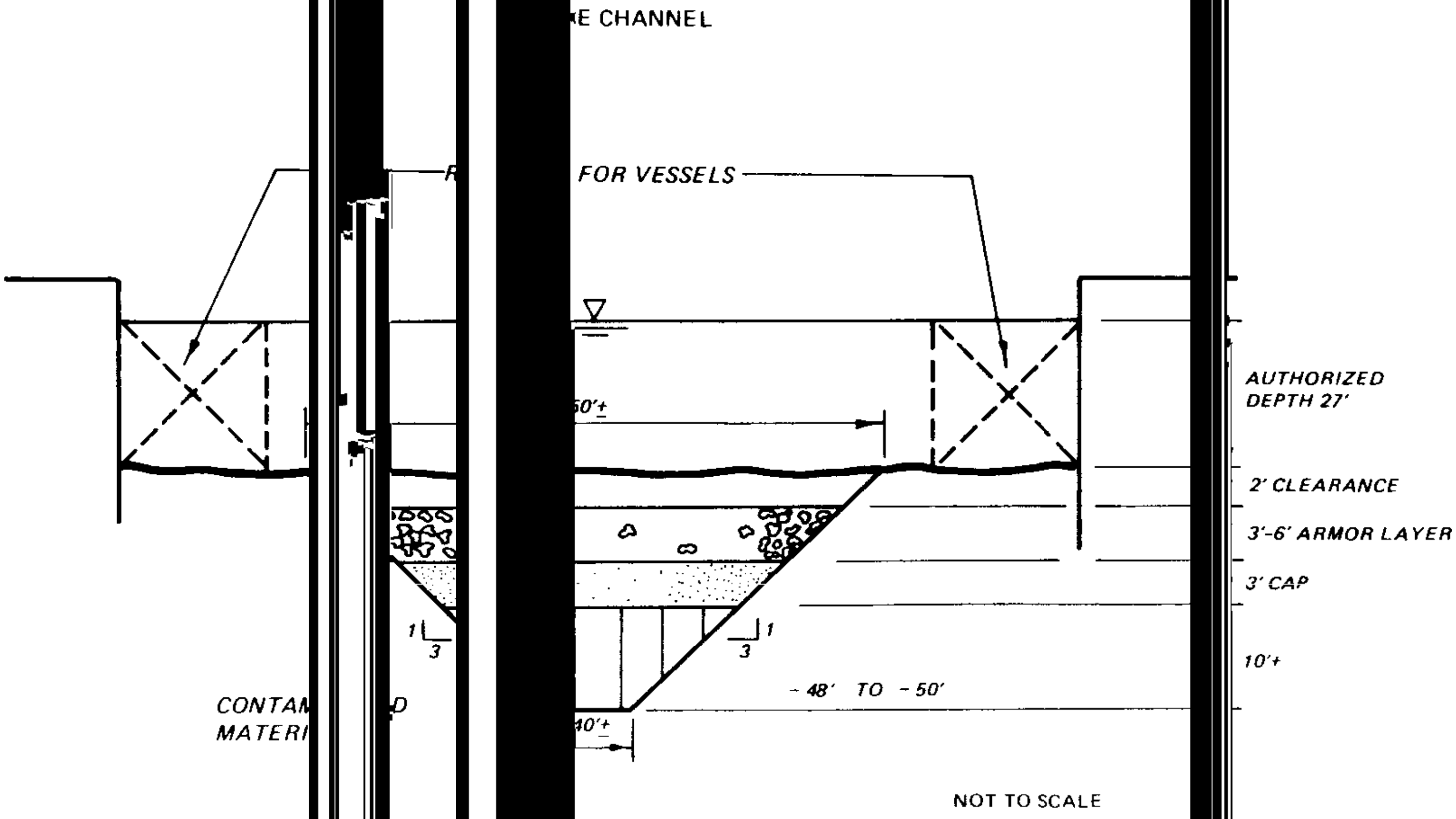


Figure 15. nch ction with 3-ft cap and 6-ft armor layer

filter cloth or netting prior to its placement over the unconsolidated or "liquefied" dredged material. These factors together with the cost of a stone armor layer greatly reduce the viability of CAD in the entrance channel and canal.

Monitoring

35. The best method of monitoring the armor layer would be side scan sonar combined with regular echo sounding. The layer would be mapped when placed and then remapped and compared periodically. Depending upon turbidity levels in the area, closed circuit television is a possibility. Due to the results of this limited study, a detailed monitoring program was not addressed [illegible]

Conclusions

36. Storage volume in the amount of 220,000 to 400,000 cu yd is needed for contaminated materials. There is 150,000 to 170,000 cu yd of storage volume available in the entrance channel and canal areas with a 3-ft sand cap and 3- to 6-ft stone armor layer. Protection of the cap against erosion by natu- [illegible] will cause operational difficulties and reduce the storage space available. Alternate sites for a CAD appear more favorable than the entrance channel and canal.

APPENDIX J: CONTAINED AQUATIC DISPOSAL: SITE LOCATION AND CAP MATERIAL INVESTIGATIONS FOR OUTER INDIANA HARBOR AND SOUTHERN LAKE MICHIGAN

Introduction

[redacted]

nated dredged sediments from the Indiana Harbor Canal. This canal connects

[redacted]

as contained aquatic disposal (CAD) sites. CAD involves placing contaminated material in an existing or dredged depression, then covering it with a layer of clean sediment (primary cap) to prevent contaminants from escaping into the

[redacted]

2. The investigations described in this report were performed in response to a study need to identify potential CAD sites and develop design guidance for erosion-resistant armor caps. Locations in southern Lake Michigan and Outer Indiana Harbor were evaluated for potential CAD usage. Bottom currents arising from a variety of forcing functions (waves, winds, seiching, and propeller wash) were calculated, and stable armor cap material was

[redacted]

Potential CAD Sites

Southern Lake Michigan

[redacted]

study. The shortest distance from Indiana Harbor to the 70-ft contour, 11 statue miles, was then used to define the maximum practical haul distance.

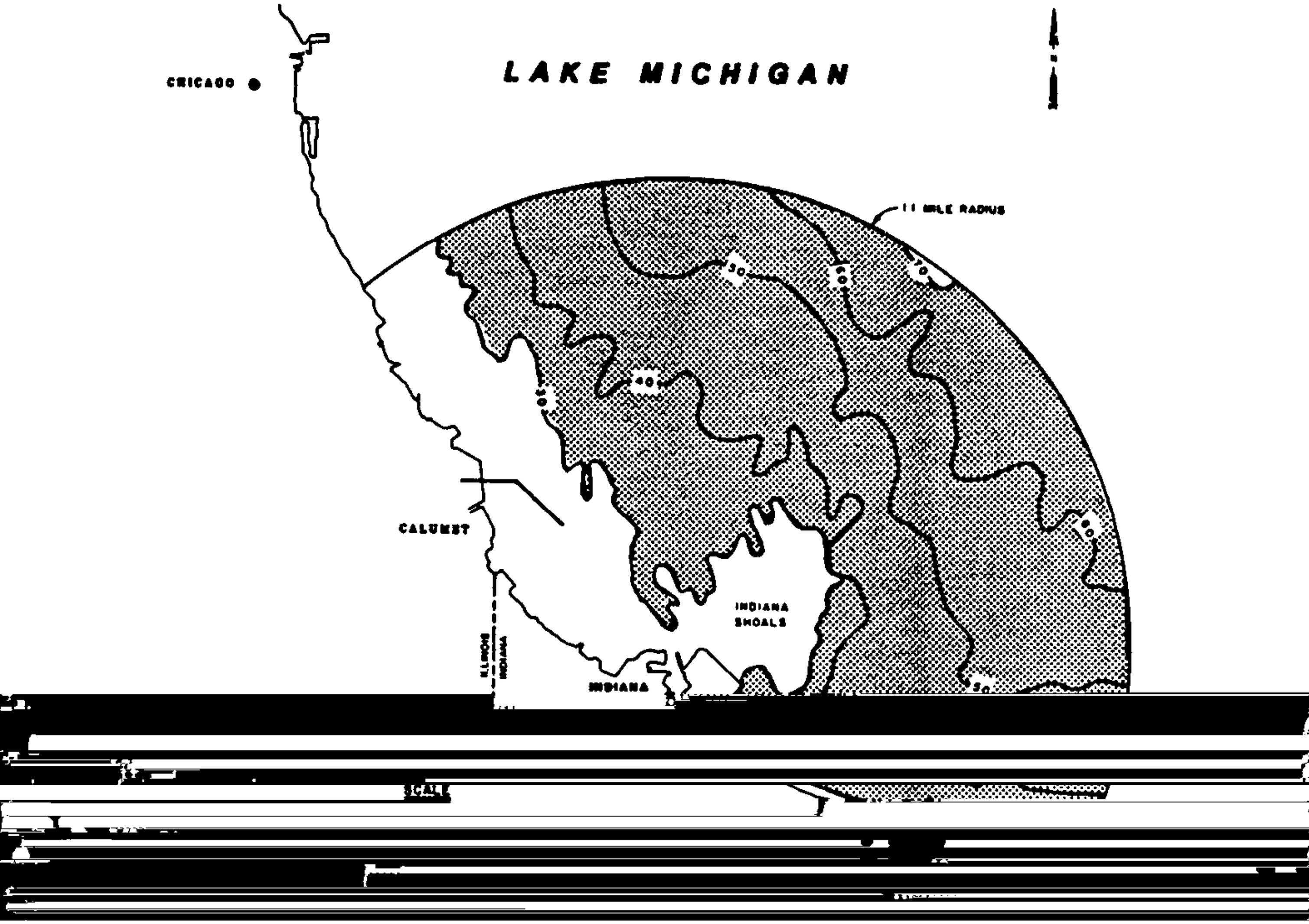


Figure J1. Eleven-mile radius of Indiana Harbor

The minimum depth was selected so as to limit the possibility of a large ship running aground on the CAD site and cutting through the primary cap. Based on recommendations in Engineer Manual (EM) 1110-2-1603 (Office, Chief of Engi- [redacted] pitch, roll, and heave of the 26-ft draft vessels that use Indiana Harbor. This minimum depth excludes Indiana Shoals, which is a large area of convoluted bathymetry extending 4 miles to the northeast of Indiana Harbor. Although large ships usually avoid this area, the shoals are regularly subjected to breaking waves, making the area unsuitable for CAD consideration.

Outer Indiana Harbor

4. The southern half of the Outer Harbor of Indiana Harbor (Figure J2) was also considered as a potential site for CAD. The trapezoidal area shown allows 200 ft of clearance between the navigation project boundaries and the edge of the potential CAD site. Calculations show that a dredged hole in this area, 15 ft deep below the authorized project depth of 28 ft with side slopes of 4 to 1, would have to capacity to hold 580,000 cu yd of contaminated sediments. This volume should be adequate to hold 200,000 cu yd of contaminated sediment with a conservative bulking factor, the primary cap, and an armor cap. Therefore, this site was initially considered as a potential site for CAD.

Ice Gouging

5. The term "ice gouging" refers to moving ice cutting furrows or tracks in the bottom of a body of water. The potential for ice gouging was examined [redacted] shore usually does not exceed 1.5 ft in thickness (National Oceanic and Atmospheric Administration (NOAA) 1983). Based upon this initial information, ice [redacted] study area. Therefore, no further study of ice gouging was conducted.

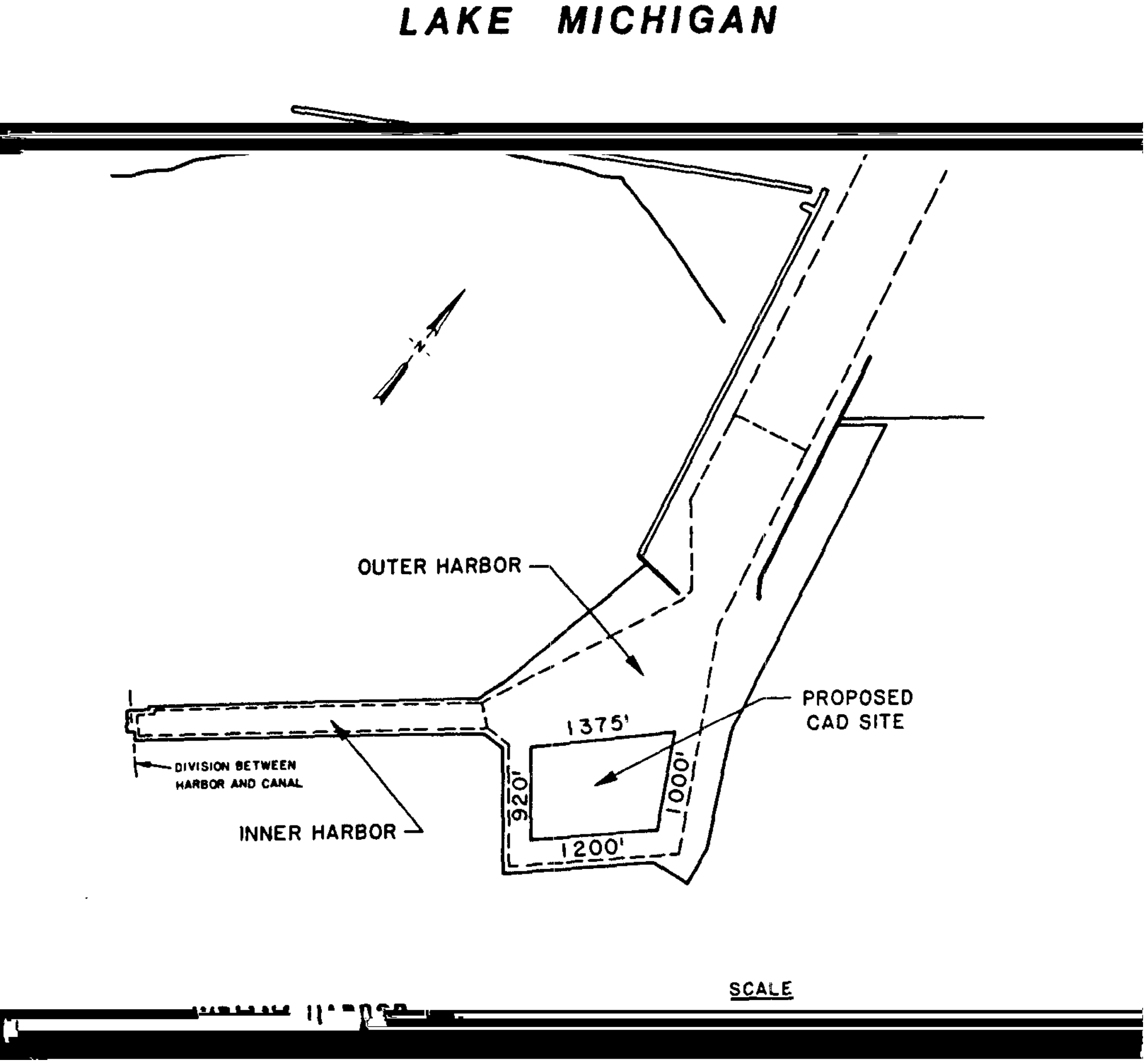


Figure J2. Indiana Harbor, Indiana

Forcing Functions

6. To initially select a stable CAD armor cap material, the maximum [redacted] function of the bottom current; consequently, those factors capable of producing significant bottom currents were examined. These included waves, winds, seiches, and propeller wash.

7. To assist the Chicago District in developing economic design alterna- [redacted] The Shore Protection Manual (SPM) (US Army Engineer Waterways Experiment Sta- [redacted] lake levels of 4.9 ft below LWD at Calumet Harbor, 6 miles northeast of Indiana Harbor. After considering this information and discussing the problem with the North Central Division (NCD) Coastal Section, of the US Army Corps of [redacted]

Waves - Deep Water

Specification of wave conditions

8. For the purposes of this study, the term "wave conditions" means a significant wave height and period with an associated frequency of reoccur- [redacted] interest to the present study consisted of three steps:

[redacted]

refraction, diffraction, dissipation, and breaking.

[redacted]

Deep-water design waves were developed in a hindcast study done by Resio and Vincent (1976). They computed design wave characteristics for 64 locations on the perimeter of Lake Michigan. Site number 29 (Burns Harbor, Indiana) was [redacted]

[redacted]

is subjected to the longest fetch in southern Lake Michigan (approximately 250 miles). Maximum deep-water wave heights for all return intervals which occurred during the winter period (January-March) were selected as most appropriate for this study. Table J1 summarizes each design deep-water wave used for subsequent calculations.

Transformation of deep-water waves to shore

9. A strict interpretation of the concept "deep-water wave" for the

[redacted]

refraction-diffraction wave transformation model. The bounds of this domain are shown in Figure J3. The point labeled "IH" is the computational site at which boundary conditions for the Outer Harbor model were obtained.

10. The computational domain contains a square grid system of 5,000-ft spacing. There are 47 steps in the offshore direction (44.5 miles in length) and 41 steps in the alongshore direction (38.8 miles in length). Bathymetry

[redacted]

slopes less than approximately 1:10. Combined refraction and diffraction

[redacted]

Beyond breaking, computations are continued by using standard depth-limited criteria, coupled with dissipation as a function of propagation distance.

12. The wave conditions from Table J1 were applied uniformly on the deep water edge of the computational domain. Computed wave heights in the interior of the domain are used in estimating CAD armor cap material sizes for poten-

[redacted]

13. Estimation of wave conditions in a harbor requires a carefully

[redacted]

Design Deep-Water Wave Conditions

Return Interval years	Sig. Wave Height ft	Sig. Wave Period sec	Direction deg true*
20	19.7	10.6	180
50	22.0	11.5	180
[redacted]	[redacted]	[redacted]	[redacted]

* Degrees relative to true north.

[redacted]

overestimate amplification factors through inadequately describing these effects. An acceptable model must also allow waves reflected back to the harbor entrance to freely leave the modeled area. These considerations led to selection of a linear wave theory, hybrid element model (HARBS) recently developed by Dr. H.S. Chen at WES. Preliminary description of this model is

[redacted]

[redacted]

is approximately 4,500 ft down-channel from the point where the offshore

[redacted]

wave height is slightly smaller than the 20- and 100-year heights. This is probably due to the coarse representation of Indiana Shoals, which is the

[redacted]

sentation caused wave breaking at a greater distance from shore for this

[redacted]

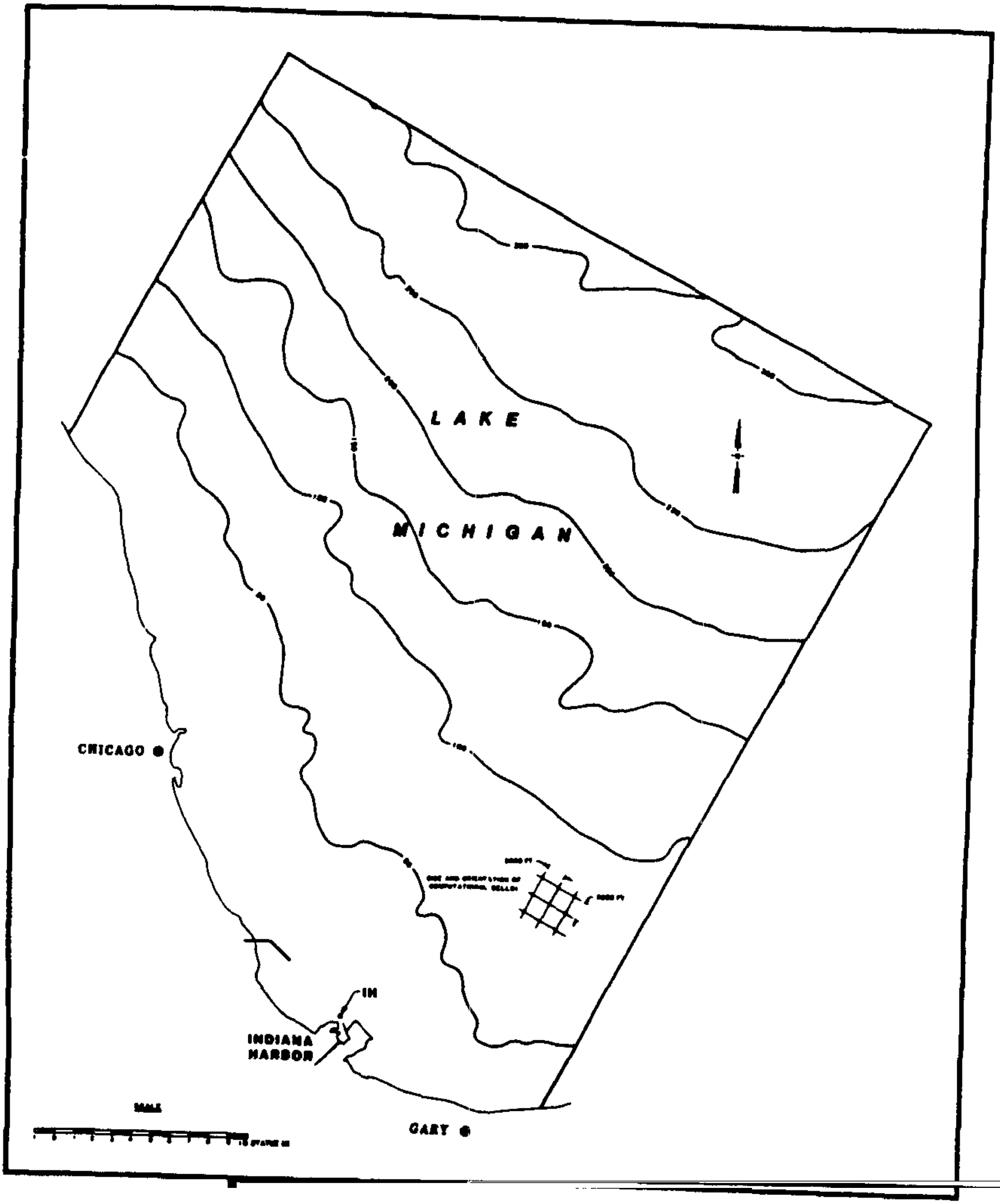


Figure J3. Wave transformation computational boundaries

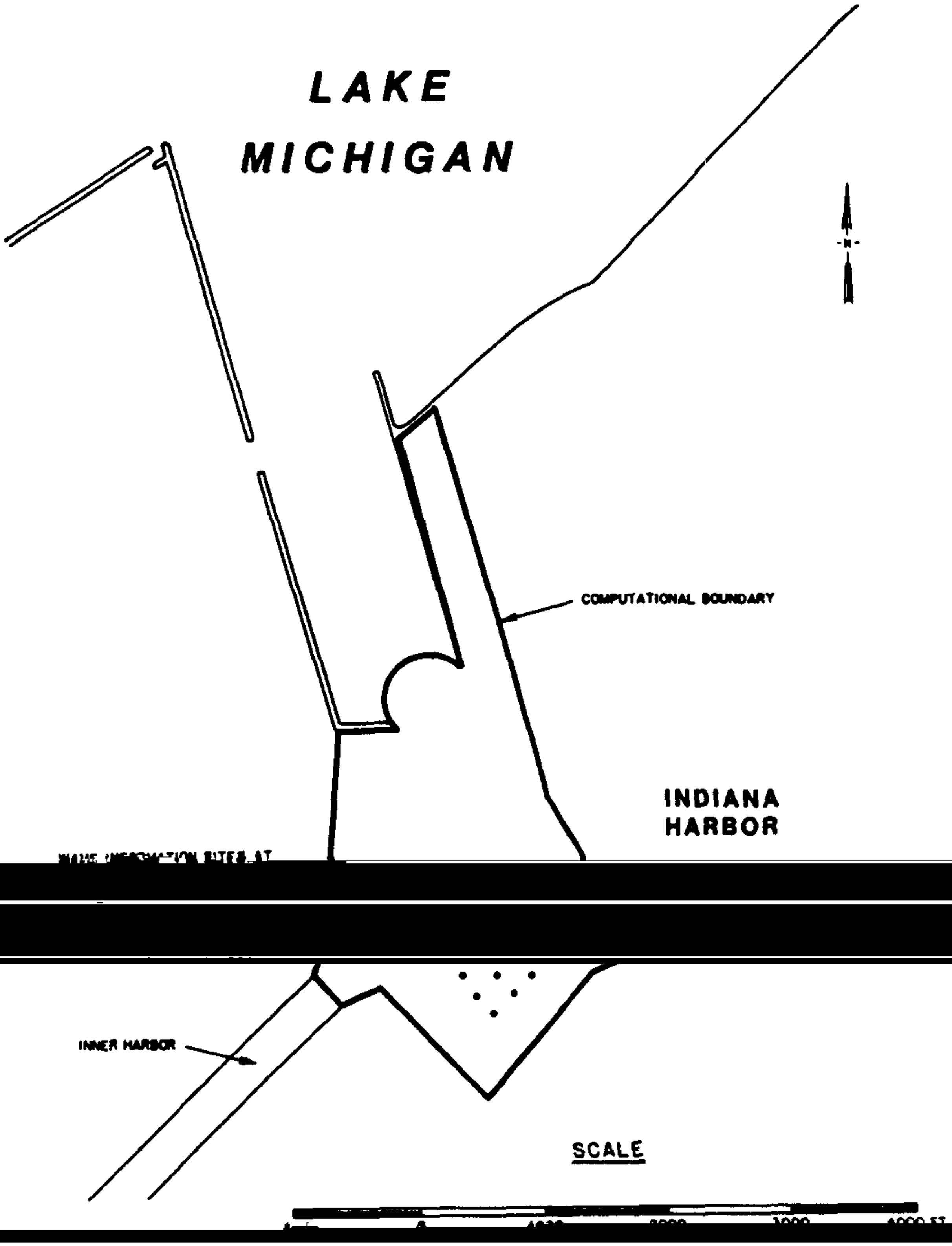

LAKE MICHIGAN
N
COMPUTATIONAL BOUNDARY
INDIANA HARBOR
WAVE INFORMATION SITES AT
INNER HARBOR
SCALE
3000

Table J2

Design Wave Conditions at Channel Entrance

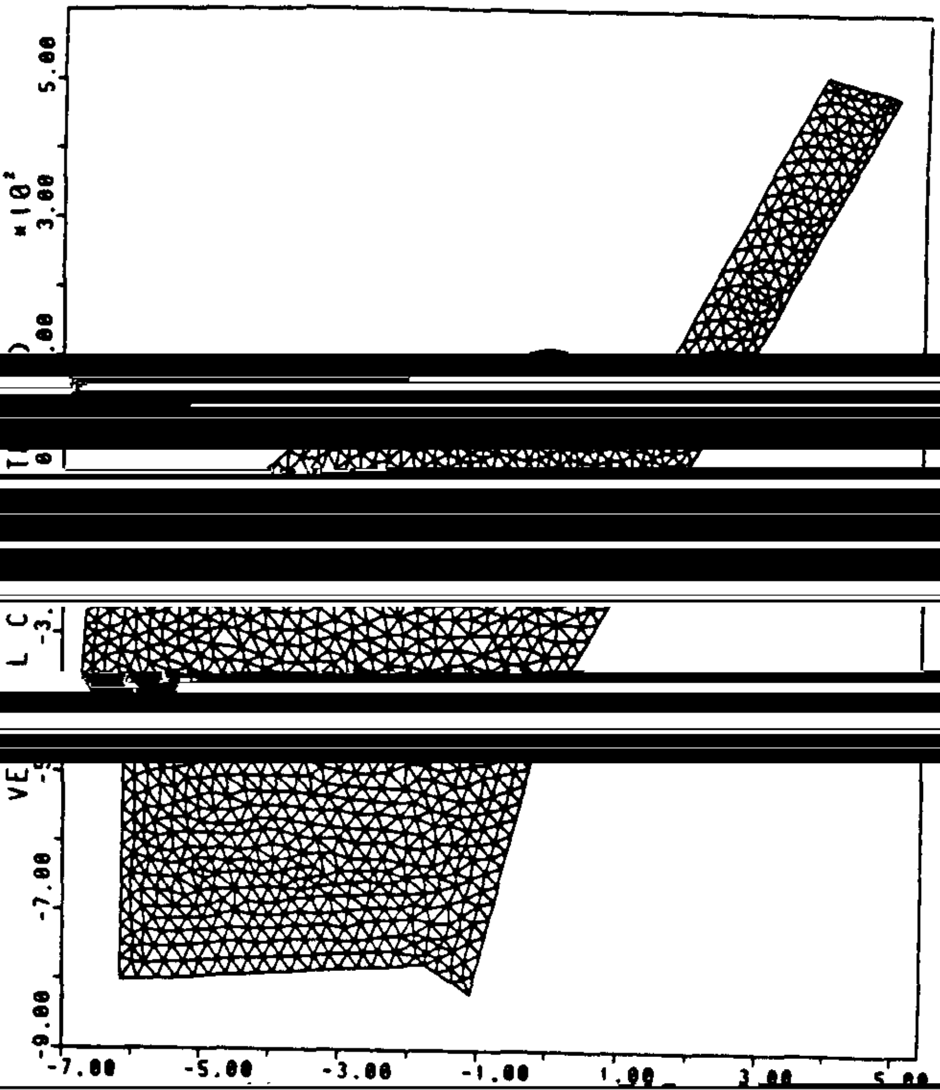
Return Interval years	Sig. Wave Height ft	Sig. Wave Period sec	Direction deg true *
[redacted]	[redacted]	[redacted]	[redacted]

[redacted]

15. A mean direction of 194 deg true was adopted for all three cases. [redacted] a propagation direction of 130 deg true. Frictional losses in propagation from the channel entrance to the model boundary were not considered.

16. The finite element model for the interior region requires at least four or five points per wavelength. The shortest period wave at the harbor entrance has a wavelength of approximately 300 ft. Thus, a maximum spatial [redacted] [redacted] for design lake level before computations were made. A reflection coefficient of 0.95 was used for solid vertical walls, and a reflection coefficient of 0.60 was used for rubble-mound structures.

17. Model output consists of an amplification factor (wave height at an interior point divided by input wave height at the radiation boundary). Values at the points indicated in Figure J4 were converted to their corre- [redacted] sponding significant height for use in armor cap material size determinations. Wave heights at the 16 points were all less than 0.2 ft. These long period [redacted]



Potential seiche modes in the Outer Harbor

for a wide range of periods, and amplification factors were recorded at sites throughout the Outer Harbor region. No resonances were detected for periods less than 2,300 sec. Since there is essentially no energy in wind wave spectra at such long periods, wind waves appear incapable of exciting seiche

[redacted]

at the bottom is:

$$u = \frac{H\pi}{T} \frac{1}{\sinh \frac{2\pi d}{L}} \qquad \text{(J1)}$$

where

H = wave height
T = wave period
d = water depth
[redacted]
L = wavelength

21. To calculate maximum bottom orbital velocities due to waves in the southern Lake Michigan study area, the wave height and length calculated by RCPWAVE were used in Equation J1 together with the depth and wave period.

[redacted]

[redacted]

wave forecasting curves. These data were then used as input to standard physical oceanography equations (Neumann and Pierson 1966) for drift and slope currents. Drift currents result from the transfer of wind stress on the water surface through the water column. Slope currents flow along the bottom away [redacted] increments. Values for the two currents were added together vectorially to give a maximum current at each depth. These total values were plotted, and a curve drawn between points. Maximum wind-induced bottom current velocities [illegible] height predicted by WIS data for Lake Michigan (Resio and Vincent 1976), determined the wind velocity and duration. For the 20-year return period, [illegible] for 11.5 hr.

24. The time limits of this study did not allow running the three-dimensional numerical model needed to accurately calculate the site-specific bottom currents due to winds associated with the 20-, 50-, and 100-year conditions. There are no quicker, less costly methods for accurately simulating [illegible] theory was used to estimate these currents. The assumptions made in applying [illegible]

25. The following discussion is based on information found in Neumann and Pierson's (1966) text on physical oceanography. The frictional drag of wind passing over water produces a surface, or drift, current. With time, due to the viscosity of water, momentum will be transferred vertically and produce currents to significant depths. Because of the Coriolis force, the current in [illegible] tion to use Eckman's equations for the velocity of these drift currents is that the wind field is uniform, constant in speed and direction everywhere, and has been blowing for a sufficient length of time to allow the currents to reach a steady-state.

26. These assumptions are conservative for the shallow depths at the [illegible] 50-year return periods even more conservative. Current forecasting curves for the open ocean (Gaythwaite 1981) predict surface currents that vary

[redacted]

wind durations.

27. The depth of the basin used in these equations is the mean depth of

[redacted]

of interest are actually occurring at much shallower depths, the shallower average depth of the lake was used.

28. Eckman's equations for a drift current in an ocean of finite depth are:

$$U_d = \alpha A - \beta B \tag{J2}$$

$$V_d = \alpha B + \beta A \tag{J3}$$

where

U_d = drift current velocity component in the direction the wind is blowing (assumed positive in the wind direction)

V_d = drift current velocity component at right angles to the

[redacted]

$\alpha = \frac{\tau_w}{\pi\nu}\left(\frac{C+E}{R}\right)$

$\beta = \frac{\tau_w}{\pi\nu}\left(\frac{C-E}{R}\right)$

τ_w = shear stress, taken from standard tables

ν = eddy viscosity = $9.5\ \tau_w + 9$ (estimated linear fit to observed data)

[redacted]

$C = \cosh p \cos p$

$E = \sinh p \sin p$

$R = \cosh 2p + \cos 2p$

$$p = \frac{ad}{\sqrt{2}}$$

$$a = (f\ \rho/\nu)^{1/2}$$

d = average basin depth

f = Coriolis force

ρ = density of seawater

and

$$B = \cosh q \sin q$$

$$A = \sinh q \cos q$$

$$D = \pi \sqrt{\frac{2\nu}{\rho f}}$$

$$q = p - \frac{az}{\sqrt{2}}$$

z = depth of the current

Slope currents

29. In addition to causing a drift current, the wind can eventually pile water up against the coast. This increase in height will produce a flow away [illegible]

30. [illegible] rents start almost immediately.

31. Eckman's equations for slope currents are:

$$U_s = \frac{-g^{S}}{\text{[illegible]}} \left[\left(\frac{\cosh m \cos n + \cosh n \cos m}{\text{[illegible]}} \right) - 1 \right] \qquad (J4)$$

[illegible]

$$V_s = \frac{+g^{S}}{f} \left(\frac{\sinh m \sin n + \sinh n \sin m}{R} \right) \qquad (J5)$$

where

U_s = slope current velocity component offshore (positive to the north)

S (surface slope) = $\frac{\tau_w}{gd}$

$m = p + \frac{az}{2}$

$n = p - \frac{az}{2}$

$R = \cosh \frac{2a}{2} d + \cos \frac{2ad}{2}$

[illegible]

[illegible] north-south due to the V-component of the drift current. However, since the [illegible]

[illegible] serve as a successful CAD site. Consequently, a preliminary investigation was

Table J3

South Lake Michigan Bottom Currents Due to Winds

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
70	2.2	-0.3	1.1	0	1.1

[redacted]

** U slope is offshore.

made into expected propeller wash velocities and the armor cap material required to withstand them.

Probability of maximum velocities

[redacted] less, and corresponding low propeller speeds. However, in extreme cases, such as high winds, loss of rudder control, avoidance of obstacles, etc., ships will use full throttle for short periods. Therefore, the possibility of large [redacted] life of a CAD site. Economics force ship owners to operate their vessels at maximum safe drafts, which means even though lake level varies, the actual minimum keel clearance should remain approximately the same.

Propeller jet theory

[redacted] work on propeller jets is based on diffusion of submerged jets.

36. Application of submerged jet theory to propeller wash has not been [redacted] investigation, model testing done in Europe and limited prototype measurements [redacted]

[redacted]

[redacted]

region.

[redacted]

tions Office at Inland Steel Corporation, the largest ships now using Indiana

[redacted]

pellers were not available, but Blaauw and Van de Kaa (1978) present typical

[redacted]

39. Blaauw and Van de Kaa show a K_T value of 0.265 for a single non-

[redacted]

$$V_o = 1.47 \left(\frac{Pd}{D^2} \right)^{1/3} \qquad \text{(J7)}$$

where Pd is the installed horsepower.

[redacted]

$$V_o = 0.95nD \qquad \text{(J8)}$$

[redacted]

Bottom Stresses

41. Shear stresses are exerted on the bottom material by currents. [redacted] design current-induced shear stress without any motion. [redacted] the scope of this report. For additional explanation of initiation of motion theory relevant to this study see Ackers and White (1973), Madsen and Grant (1976), and Hammond, Heathershaw, and Langhorne (1984). For the bottom velocities associated with the 20-, 50-, and 100-year design waves and the expected [redacted] Chief of Engineers 1970) is sufficient for the purposes of this study.

[redacted] in southern Lake Michigan averages 1 on 1,000, this is a reasonable [redacted] weight for a given velocity can be calculated directly. When the stresses caused by the bottom current are set equal to maximum stress a given size par- [redacted]

$$W = 0.0219\ V^6\ \frac{W_r}{g^3} \left(\frac{W_w}{W_r - W_w} \right)^3 \qquad (J9)$$

where

W = stable particle weight

V = bottom velocity

W_r = unit weight of particle

g = acceleration of gravity

W_w = unit weight of water

46. [illegible] Equation J9 reduces to

$$W = 2.44 \times 10^{-5} V^6 \qquad \text{(J10)}$$

This is also the empirical equation recommended by EM 1110-2-1601. This equation was used with the wave, wind, and propeller wash velocities calculated in this study. Prototype tests used to derive this equation included particles over 1.5 ft in diameter and velocities over 17 f [illegible]

Results - Translation of Velocities into Stable Material Sizes

Southern Lake Michigan

47. In the southern Lake Michigan area, the [illegible] from a low of 6.0 fps for a 17.7-ft wave with a 10.5-sec period at a depth of 64 ft (20-year wave) to a high of 12.9 fps for a 22.8-ft wave with a 12.1-sec period at a depth of 34 ft. Using Equation J10, these velocities were converted into stable material sizes for the 20-, 50-, and 100-year design waves.

48. It was not necessary to compute the particle weights at each of the 172 grid points falling within the boundaries of the study area. Instead,

[redacted]

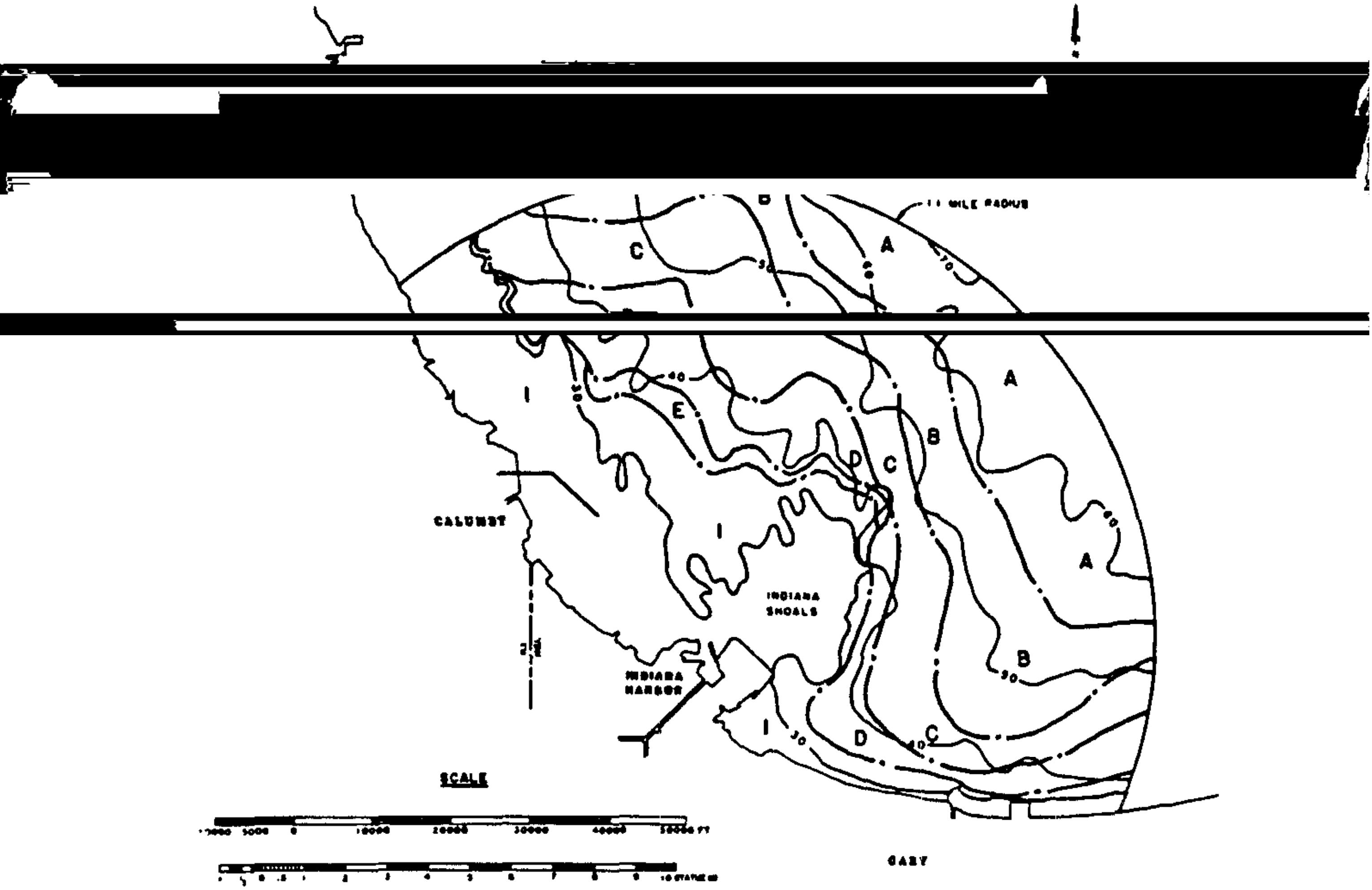
stable material east of Indiana Harbor. Areas requiring stable particle weights of 5 to 10 lb are 5 miles away, and 2- to 5-lb areas can be found [redacted]

[redacted] spondingly large particle sizes in depths of less than 50 ft to the north of Indiana Harbor and immediately east of Indiana Shoals. The best potential [redacted] Harbor. Areas requiring stable particle weights of 10 to 20 lb are 5 miles away, areas needing 5 to 10 lb material are less than 7 miles away, and areas requiring 2- to 5-lb material are over 10 miles away.

[illegible]

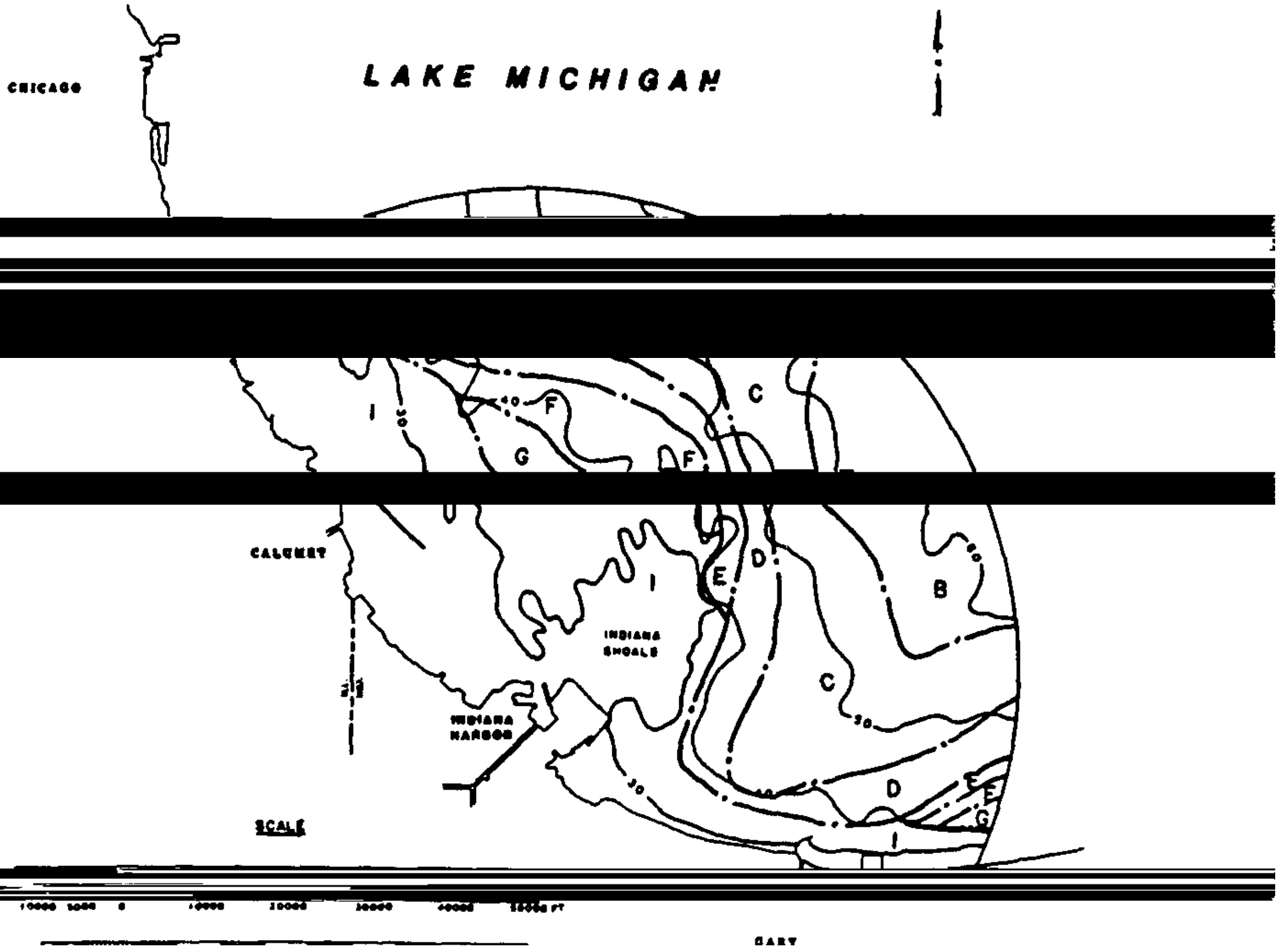
52. As discussed earlier, the amount of wave energy reaching the potential CAD site in the Outer Harbor for the 20-, 50-, and 100-year design waves [redacted] Other data indicate that significant waves are possible in the Outer Harbor under less severe lake conditions.

53. [redacted] tion 1959) with a slightly different structural configuration of the jetties [redacted] tests were a good indicator of the maximum possible waves inside the harbor. These waves are expected to occur fairly often, perhaps every few years, since they are locally generated. The "worst case" wave from the model tests, a



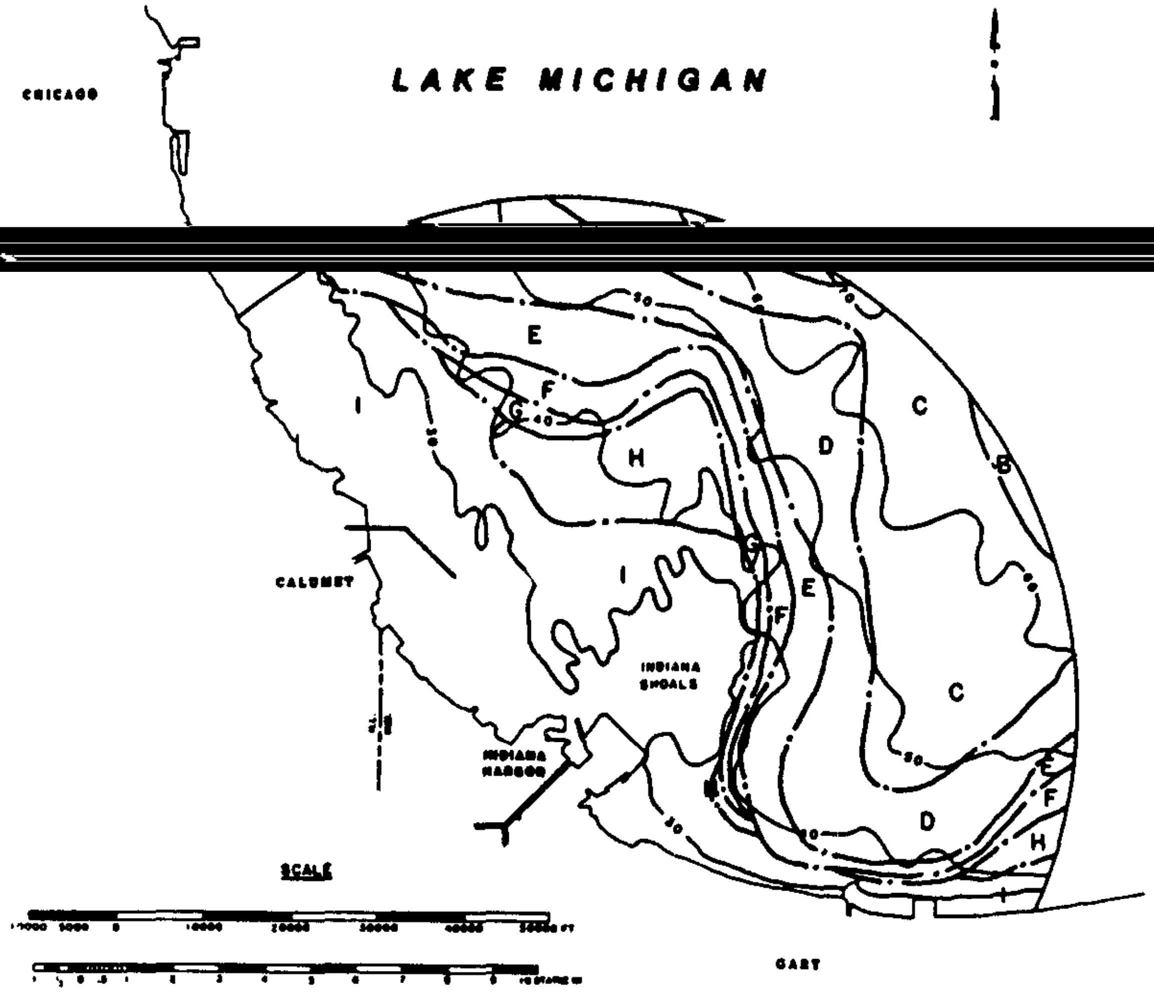
AREA	PARTICLE WEIGHT (LB)
A	1-2
B	2-5
C	5-10
D	10-20
E	20-30

Figure J6. Armor cap material sizes based on 20-year design wave



AREA	PARTICLE WEIGHT (LB)
B	2-5
C	5-10
D	10-20
E	20-30
F	30-40
G	40-60
I	AREAS OF BREAKING WAVES, SHOALS, AND SHALLOW WATER, NOT RECOMMENDED AS SITES FOR CAD

Figure J7. Armor cap material sizes based on 50-year design wave



AREA	PARTICLE WEIGHT (LB)
B	2-5
C	5-10
D	10-20
E	20-30
F	30-40
G	40-50
H	50-112
I	AREAS OF BREAKING WAVES, SHOALS, AND SHALLOW WATER, NOT RECOMMENDED AS SITES FOR CAD

Figure J8. Armor cap material sizes based on 100-year design wave

17-ft, 7.5-sec wave at the entrance channel, produced a wave 4 ft high in the potential CAD location. Experienced Inland Steel fleet operations personnel have reported approximately 3-ft waves inside the harbor, which is in reasonable agreement with the model tests.

[redacted]

conditions.

<u>Outer Harbor - propeller wash</u>

55. The velocity at the bottom is strongly influenced by the depth of water between the propeller and the bottom. From model test results (Blaauw and van de Kaa 1978, Berg and Cederwall 1981), bottom velocities of 0.5

[redacted]

$$V = V \ 2.78 \ D/X \ \exp\left(-15.43 \ Z^2/X^2\right) \qquad (J11)$$

[redacted]

V_x = bottom velocity at x distance behind the propeller

V_o = maximum axial velocity

[redacted]

[redacted]

[redacted]

maximum digging depth. Recessing the CAD armor cap below authorized project [redacted] nate the need for ship operators to reduce vessel draft to allow for a "hard" versus "soft" bottom.

Summary

[redacted] potential site is located in the Outer Harbor of Indiana Harbor, and the remainder comprise a large area in southern Lake Michigan within an 11-mile radius of Indiana Harbor at depths between 30 and 70 ft.

Southern Lake Michigan

62. The most promising areas for CAD sites appear to be 4 to 8 miles to the east of Indiana Harbor in water depths of 40 to 60 ft. Depending on the depth, location, and design wave return period, armor cap particle weights of [redacted]

Outer Harbor

63. Currents due to waves and seiching were found not to be limiting factors in the design of stable armor cap material for the Outer Harbor. For complete stability against the high propeller velocities possible from large ships during emergency maneuvers, armor cap material of 300-lb stone or larger may be needed for the Outer Harbor site. However, it should be feasible to reduce the required material armor material size considerably by employing techniques such as recessing the cap, periodic monitoring, and repair if needed. There is the possibility of objections to the Outer Harbor CAD site from ship operators due to potential for damage to ships if they hit bottom and lack of anchor holding capacity in the CAD site which would not allow ships to use their anchors during emergencies.

Recommendations

64. The studies described in this report are limited in scope. Site investigations and more detailed analyses would be needed to properly design a [redacted] should be taken during more detailed investigation of these sites.

Southern Lake Michigan

65. By making additional runs of RCPWAVE at a grid spacing of 2,500 ft [redacted] ning a wind-driven circulation model; e.g., the WES Implicit Flooding Model [redacted] estimate bottom currents.

[redacted]