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BIOACCUMULATION FROM AMAX/KITSAULT TAILINGS

By

Donald R. Guthrie
MacGuth Enterprises
2243 W. 5th Avenue

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Mr. D. Goyette
Marine Programs
Pacific and Yukon Region
Environmental Protection Service
Environment Canada
Vancouver, British Columbia
V7T 1A2

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ABSTRACT

This study examined the bioaccumulation of metals from Amax/Kitsault mine tailings over a 100-day period to determine the degree to which common marine organisms might concentrate arsenic, cadmium, chromium, cooper, molybdenum,, nickel, lead, vanadium, zinc, and iron. Species used in the tests included the marine worm Cirratulus spectabilis, the deposit-feeding clams Macoma balthica and Macoma nasuta, and the filter-feeding clams Mya arenaria and Venerupis japonica. Bioaccumulation was not closely correlated with sediment chemistry (R ranged from 0.007 for As and Venerupis to 0.797 for As and Mya), and test species often responded differently to the test metals. The clam species all indicated bioaccumulation of Pb, Mo, and Zn from the tailings. Fe and V were also accumulated from tailings by the clam species despite the lower levels in tailings. Cirratulus tended to bioaccumulate Cu, V, and Fe from the Control sediment and Mo and Pb from the tailings. Mo and Pb were concentrated from the tailings by all species tested.

RÉSUMÉ

Cette étude examine la bioaccumulation des métaux des bassins de résidus miniers de la mine Amax à Kitsault, sur une période de plus de 100 jours. On détermine jusqu'à quel degré des organismes marins communs, peuvent concentrer divers métaux; arsenic, cadmium, chrome, cuivre, molybdenum, nickel, plomb, vanadium, zinc et fer. Les espèces utilisées dans ces tests incluent le vers marins Cirratulus spectabilis, les moules détritivores Macoma balthica et Macoma nasuta et les moules filtreuses Mya arenaria et Venerupis japonica. La bioaccumulation n'était pas étroitement en corrélation avec la chimie des sédiments (r varie entre 0.007 pour As et Venerupis et 0.797 pour As et Mya). Les espèces testées souvent répondent différemment aux métaux testés. Les moules indiquent tous une bioaccumulation de Pb, Mo et Zn pour les résidus miniers. Fe et V furent aussi accumulés par les moules malgré la faible concentration dans les résidus miniers. Cirratulus semble bioaccumuler Cu, V et Fe dans les sédiments de contrôles et Mo et Pb dans les résidus miniers. Mo et Pb furent concentrés par toutes les espèces dans le résidus minier.

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

The disposal of metal-mine tailings in the marine environment has taken place in Alice Arm, B.C., since April 1981. At that time the Kitsault molybdenum mine, operated by Amax of Canada, went into production and discharged its tailings into Alice Arm through a submerged outfall (Farrell and Nassichuk, 1984). Many studies have been conducted by government agencies and by private-sector companies to increase understanding of the ramifications and consequences of that discharge.

One aspect of interest to the Environmental Protection Service has been the degree to which heavy metals in the Amax tailings might be concentrated in the tissues of marine organisms. Data from field collections in the affected areas were reported by Farrell and Nassichuk (1984), and McGreer, et al. (1980) examined the availability of such metals for uptake by marine invertebrates. Phillips (1977) and Cunningham (1979) reviewed the literature on bioaccumulation, and Phillips suggested that bivalve molluscs seemed to be the most efficient and reliable group of invertebrates for use as biological indicators.

Bioaccumulation in the field situation depends upon the nature of the sediments, temperature, and salinity (McGreer et al., 1980), on the physiological state of the organism (Cunningham, 1979; Martin et al., 1984), and on the physico-chemical state of the sediment (Stukas, 1983). Thus, variability in field studies would be expected to be high.

This study was designed to examine directly the specific question of bioaccumulation of heavy metals from the Amax tailings. The test organisms provide a direct assessment of the potential for bioaccumulation from Amax sediments under controlled conditions.

2.0 MATERIALS AND METHODS

The objective of the experiment was to determine the extent to which local species would concentrate heavy metals from the Amax mine tailings under controlled laboratory conditions. This design should reduce variability by controlling many of the variables which are known to affect bioaccumulation in the natural environment. All experiments were conducted at the West Vancouver laboratories.

2.1 Apparatus

Tanks used for the bioaccumulation study were made of blue fibreglass and were supported in aluminum frames. The tanks were tub-shaped and were 75.6 cm in length. The water level was maintained at a depth of 40.64 cm, providing a volume of 133 litres (0.13 cu. m.) in each tank. A drain pipe was centrally located with side overflow drain holes 42 cm above the tank bottom. Clean, unfiltered seawater was supplied by a pipe that extended down the inside of the tank to just above the water level. The intake for the seawater was located at a depth of 10 meters; thus the seawater was taken from the euphotic zone adjacent to the West Vancouver Laboratory.

2.2 Experimental Animals

Experimental animals were selected from those available in the Vancouver area, but which were also found normally in the area affected by the Alice Arm tailings deposits. Collections were made as follows:

Species	Date	Location
Japanese littleneck clam *Venerupis japonica*	4 June 1982	Saltspring Is.
Mud or soft-shell clam *Mya arenaria*	2 Oct. 1982	Bedwell Bay
Bent-nose clam *Macoma nasuta*	8 Oct. 1982	White Rock
Macoma balthica	8 Oct. 1982	White Rock
Marine worm *Cirratulus spectabilis*	8 Oct. 1982	Laboratory

In addition, some oysters (*Crassostrea gigas*) and some Terrebellid polychaetes were collected and kept in test containers, but were not used in the experiment.

2.3 Experimental Procedures

Test organisms were transferred, within 24 hours of collection, from the collection containers to the control tank. They remained in the control tank until the experiment began.

On 6 June 1982, five (5) littleneck clams were cleaned and frozen in individual whirl-pac containers for later analysis. On 1 September 1982, five (5) additional littleneck clams were taken from the control tank and cleaned. These were submitted, with the sample from 6 June, for chemical analysis to test for any changes caused by the control conditions.

The experiment began on 22 October 1982 with the addition of Amax/Kitsault mine tailings to the experimental tank. Specimens of all experimental species were transferred from the control tank to the experimental tank. Sufficient numbers of animals were used to ensure that 10-15 of each species would survive the experiment, assuming relatively normal mortalities would occur. During the experiment, containers were checked regularly to ensure that water was flowing properly and that experimental conditions were maintained. No operational problems were recorded.

At the beginning of the experiment (22 October 1982) and at the termination (6 February 1983) samples of the four main species (Cirratulus spectabilis ,Mya arenaria, Macoma nasuta, and Venerupis japonica) were taken and cleaned for chemical analysis. To avoid any variation in laboratory procedures between October and February, the October samples were frozen in whirl-pac containers and submitted for analysis with the February samples. To ensure that chemical analyses were not biased by gut contents, all experimental animals were placed in clean tanks and purged for 24 hours prior to preparation for the chemical analysis.

Water samples and sediment samples were taken from the Control Tank and the Experimental Tank on 17 October 1982 and again on 1 February 1983. These samples were analyzed at the end of the experiment in March 1983.

2.4 Chemical Analysis

Samples were analyzed for trace metals at the West Vancouver Laboratory according to procedures outlined by Swingle and Davidson (1979). Tissue samples were thawed, treated in a tissue homogenizer, freeze-dried, and oxidized in a low temperature asher. The ash containing the metallic salts was then dissolved in warm concentrated nitric acid. Samples were analyzed by the Inductively-Coupled Argon Plasma method (ICAP). Tissue samples for lead and cadmium that were below the ICAP detection limit were also analyzed by the Jarrell Ash 850 AAS with a FLA 100 graphite tube furnace to lower the detection limits.

2.5 Quality Control

The EPS Laboratory quality control program consists of running standard reference samples to check techniques and to establish confidence intervals of less than 10% variation. The standard reference materials used were BCSS-1 and MESSI for sediments, and NBS1577 bovine liver and NB1566 oyster tissue. These standards were obtained from the National Research Council of Canada, Division of Chemistry, Marine Analytical Chemistry Standards program; and from the U.S. National Bureau of Standards.

2.6 Statistical Analysis

The data were entered into data files on an Apple //e microcomputer. Statistical analyses were conducted using the commercial statistics package "Stats Plus", produced by Human Systems Dynamics (9010 Reseda Blvd.; Northridge, California). The t-tests used were tests for two independent sample means. Comparison tests were conducted with a program developed by the writer (D.R. Guthrie) to confirm the accuracy of the commercial program. The commercial program results seemed to be identical to those obtained using a pooled sums-of squares method (Ostle, 1963). The same program was used to perform regression analysis and determine correlation coefficients.

In all statistical analyses the 5% level is used in determining significance.

3.0 RESULTS

The data are presented for each species and treatment, with mean, standard deviation, and maximum and minimum values.

3.1 Cirratulus spectabilis

Data for the marine worm Cirratulus spectabilis are presented in Tables 1-3 and are represented graphically in Figures 1-10. Significant differences are indicated on the graphs by an asterisk.

3.2 Macoma balthica

Data for Macoma balthica are shown in Table 4 and are represented graphically in Figures 11-20. Although it was intended to have final sample sizes of 10-15 animals, only 5 specimens of this species were available for each treatment at the end of the experiment. The five specimens were combined into a composite sample for each of the treatments rather than being analyzed separately. Thus, it was not possible to conduct statistical tests on this species. Accordingly, no significant differences are indicated on Figures 11-20.

3.3 Macoma nasuta

Data for the bent-nose clam, Macoma nasuta, are presented in Tables 5-7. Graphic representations of the data are in Figures 21-30.

3.4 Mya arenaria

Data for the soft-shell or mud clam, Mya arenaria, are presented in Tables 8-10, with graphic representations in Figures 31-40.

3.5 Venerupis japonica

Data for the Japanese little-neck clam, Venerupis japonica, are contained in Tables 11-15. The data are shown in graphic form in Figures 41-50. These animal were held in the laboratory for a longer period to test for any effects that might occur due to the laboratory conditions. Thus, there are two additional data sets for this species. The June data indicate the condition immediately after collection, and the September data provide an examination of the condition between collection and the initiation of the experiment in October.

3.6 Sediment analysis

Table 16 contains the results of analyses on the Amax tailings and on the Control sediment. Figure 51 shows the average value for Amax tailings expressed as a percentage of the average value for the Control sediment. This graph was truncated at 500% to maintain a suitable scale for the smaller values. The true value for Cadmium was 4000% of control, and the true value for Molybdenum was 2520% of control value.

3.7 Water analysis

The data for the water samples is in Table 17.

TABLE 1 DATA FOR CIRRATULUS - OCTOBER 1982

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	5	93.000	18.600	5.683	9.000	23.000
CD	5	1.070	.214	.075	.100	.300
CR	5	11.500	2.300	.725	1.500	3.300
CU	5	142.200	28.440	7.229	20.000	37.400
MO	5	2.700	.540	.336	.200	.900
NI	5	17.000	3.400	.548	3.000	4.000
PB	5	12.470	2.494	.473	2.000	3.000
V	5	5.400	1.080	.471	.500	1.800
ZN	5	499.900	99.980	9.322	86.300	110.000
FE	5	3735.000	747.000	187.294	592.000	994.000

CIRR/OCT

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	22	.23	1.5	20	.4	3	2.29	.9	110	655
2	23	.1	3.3	24.5	.2	4	2	1.8	86.3	900
3	18	.25	2.6	34.4	.9	4	2.18	1.1	107	594
4	21	.19	2.4	37.4	.3	3	3	1.1	99.9	994
5	9	.3	1.7	25.9	.9	3	3	.5	96.7	592

TABLE 2 DATA FOR CIRRATULUS - CONTROLS

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	17	198.000	11.647	4.242	5.000	20.000
CD	17	12.340	.726	.322	.230	1.400
CR	17	79.700	4.688	2.578	1.200	13.000
CU	17	1094.500	64.382	26.373	12.900	106.000
MO	17	19.100	1.124	.360	.600	2.000
NI	17	99.000	5.824	2.099	2.000	12.000
PB	17	141.300	8.312	4.586	2.000	19.000
V	17	62.400	3.671	2.106	.600	9.000
ZN	17	1916.700	112.747	20.019	71.400	153.000
FE	17	43308.000	2547.529	1208.939	736.000	5520.000

CIRR/CON

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	10	.5	3	39	1	5	5	3	86.2	1990
2	10	1	5	89	1	5	7	5	131	2670
3	10	.5	5	106	1	5	19	4	111	2550
4	10	.7	5	54	1	7	8	4	116	3020
5	20	.7	6	59	1	7	8	3	136	2960
6	10	1	5	84	1	6	7	5	118	3620
7	10	.5	5	46	1	5	6	5	103	3390
8	10	.7	4	80	2	5	7	2	106	2500
9	10	1.1	6	78	1	5	8	5	112	2890
10	5	.3	1.2	33.9	1.4	2	2	.6	97.6	804
11	20	1.2	4	59	1	5	9	3	103	1870
12	9	1.4	13	105	1	12	18	9	120	5520
13	12	.51	1.8	37.7	.6	4	3.3	.9	71.4	736
14	10	.7	6	74	1	8	11	6	127	3800
15	10	.8	4	88	1	7	10	3	93.5	2380
16	20	.5	3	49	2	5	10	3	153	1740
17	12	.23	2.7	12.9	1.1	6	3	.9	132	868

TABLE 3 DATA FOR CIRRATULUS - TAILINGS

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	18	133.000	7.389	3.466	5.000	20.000
CD	18	14.700	.817	.603	.100	2.200
CR	18	60.000	3.333	1.744	1.100	9.500
CU	18	506.700	28.150	10.612	8.600	50.000
MO	18	48.400	2.689	2.389	.800	11.000
NI	18	87.100	4.839	3.035	2.000	13.000
PB	18	199.800	11.100	9.627	2.000	38.000
V	18	20.500	1.139	.731	.500	3.000
ZN	18	1895.500	105.306	28.658	70.100	189.000
FE	18	24966.000	1387.000	848.594	501.000	3990.000

CIRR/TAIL

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	8	.5	3.8	21.2	1.9	4	9	.9	109	1480
2	5	1	2.9	32.5	1.6	2	4	.9	118	850
3	9	.7	3	21	2	5	7	2	135	1610
4	7	.75	3.4	41.6	1.9	5.1	6.8	.5	98.8	885
5	20	1.3	4	50	3	13	38	2	110	2400
6	5	.2	1.1	20.3	1.1	2	2	1	90.6	683
7	9	1.8	4	38	5	10	15	2	123	2010
8	7	.3	2.8	20.9	2.4	3	6	.6	76.3	965
9	6	.8	2.2	24.3	1.9	3	12	.9	76.8	1170
10	9	2.2	4	35	5	7	24	3	189	3990
11	7	.6	1.8	22.7	1.4	3	5	.5	81.5	1030
12	7	.45	2.3	21	.9	2	4	.8	80.4	568
13	5	.1	3.5	8.6	1.4	4	3	.5	97.3	1080
14	5	.4	2.5	43.2	3	3	13	2	125	2230
15	7	.7	2.9	35.4	1.9	6	15	.6	106	1130
16	5	.6	2.5	28.4	.8	2	4	.8	70.1	501
17	5	.4	3.8	25.1	2.2	5	6	.5	84.7	874
18	7	1.9	9.5	17.5	11	8	26	1	124	1510

FIG. 1 Mean level of Arsenic in Cirratulus for October, Controls, and Tailings (ug/g)

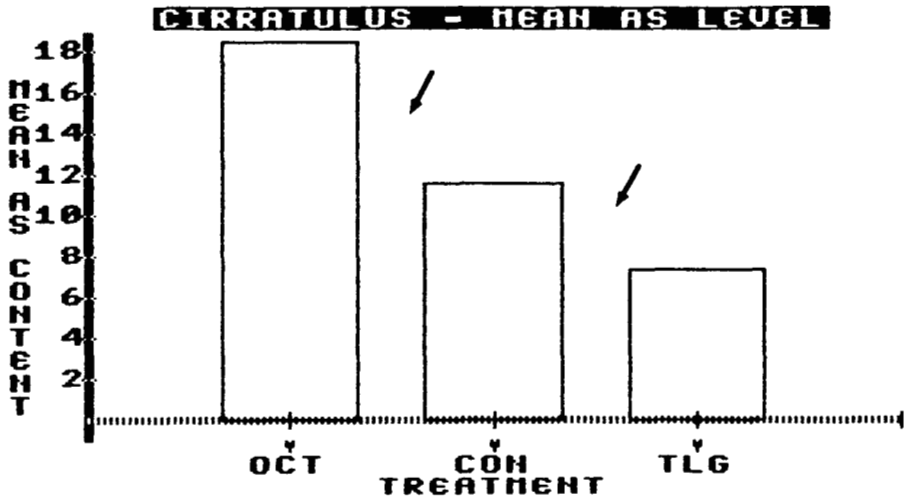


FIG. 2 Mean level of Cadmium in Cirratulus for October, Controls, and Tailings (ug/g)

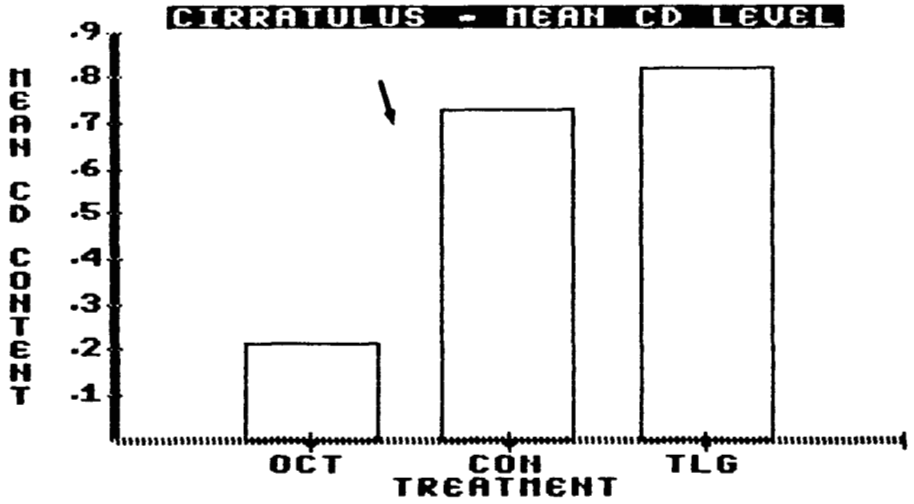


FIG. 3 Mean level of Chromium in Cirratulus for October, Controls, and Tailings (ug/g)

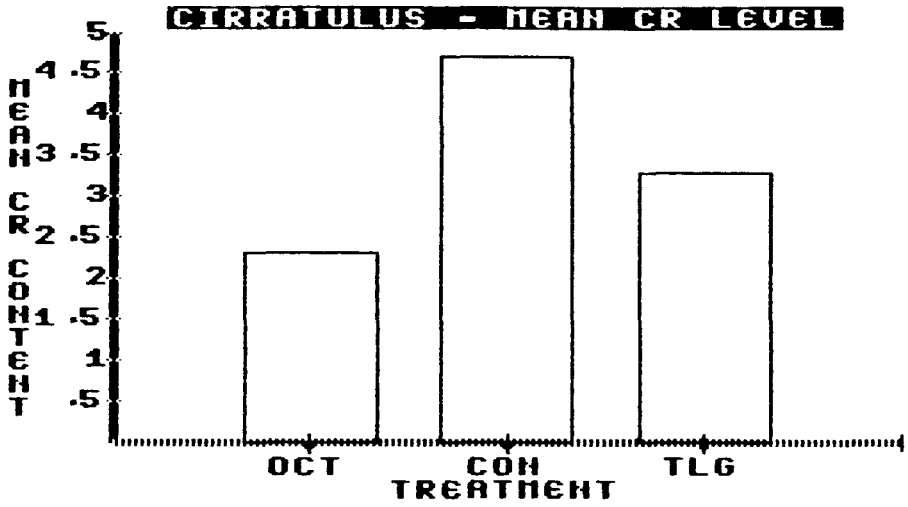


FIG. 4 Mean level of Copper in Cirratulus for October, Controls, and Tailings (ug/g)

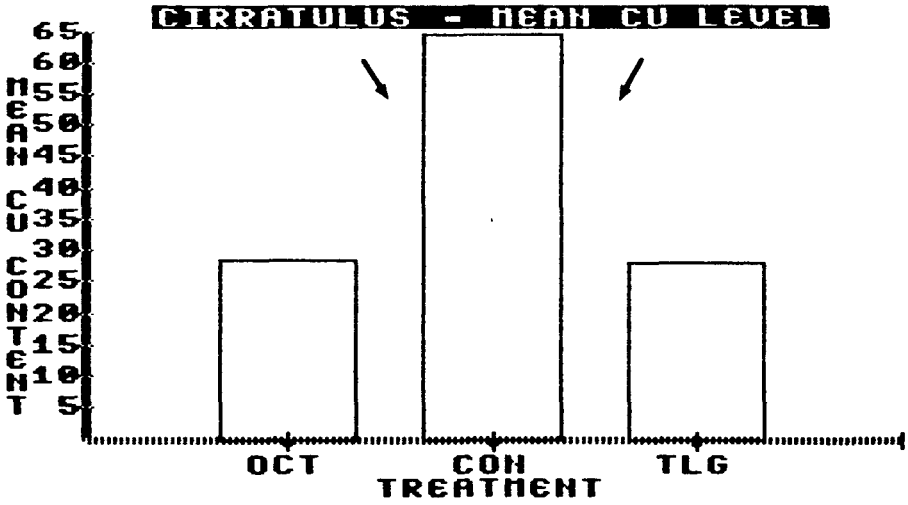


FIG. 5 Mean level of Molybdenum in Cirratulus for October, Controls, and Tailings (ug/g)

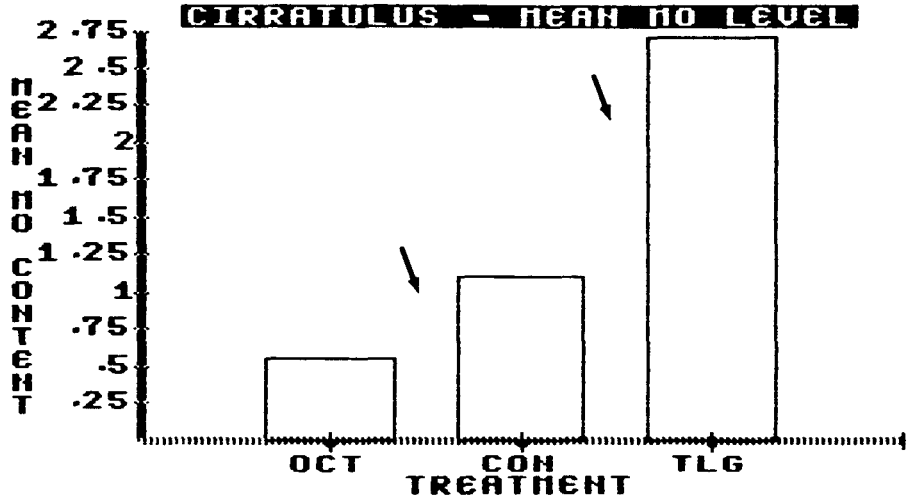


FIG. 6 Mean level of Nickel in Cirratulus for October, Controls, and Tailings (ug/g)

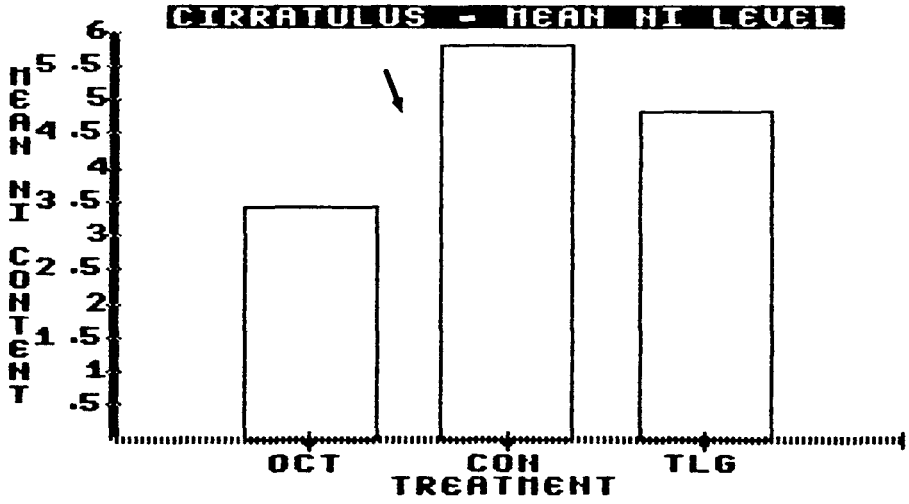


FIG. 7 Mean level of Lead in Cirratulus for October, Controls, and Tailings (ug/g)

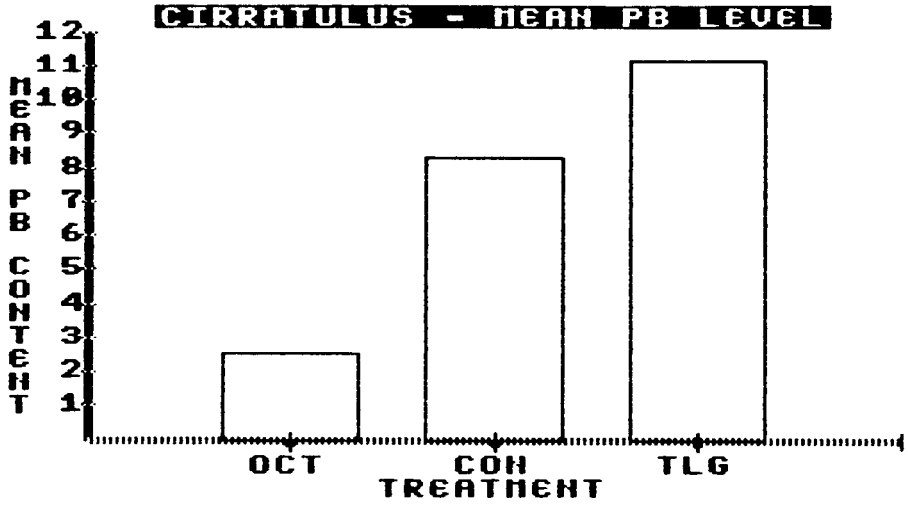


FIG. 8 Mean level of Vanadium in Cirratulus for October, Controls, and Tailings (ug/g)

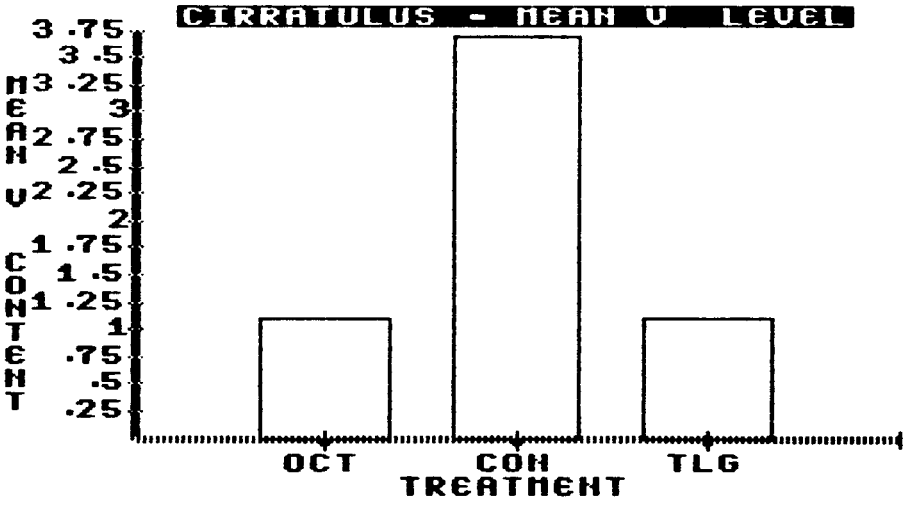


FIG. 9 Mean level of Zinc in Cirratulus
for October, Controls, and Tailings (ug/g)

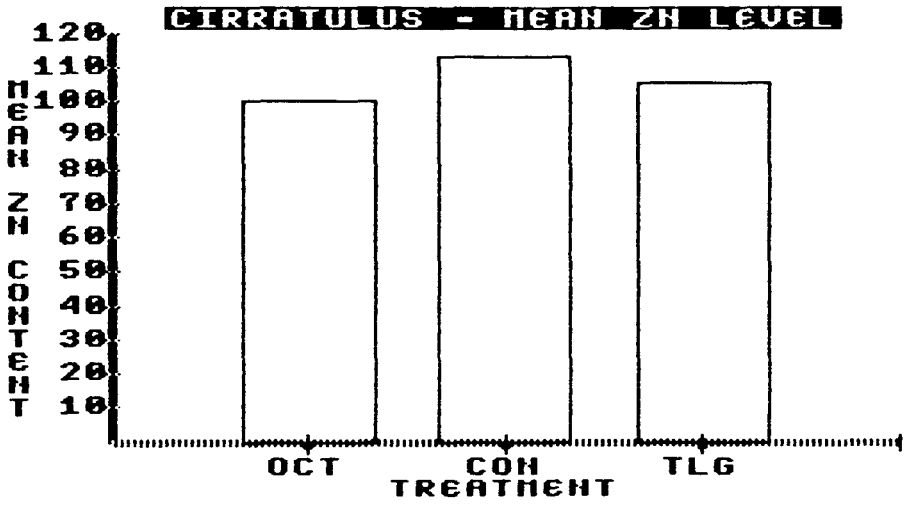


FIG. 10 Mean level of Iron in Cirratulus
for October, Controls, and Tailings (ug/g)

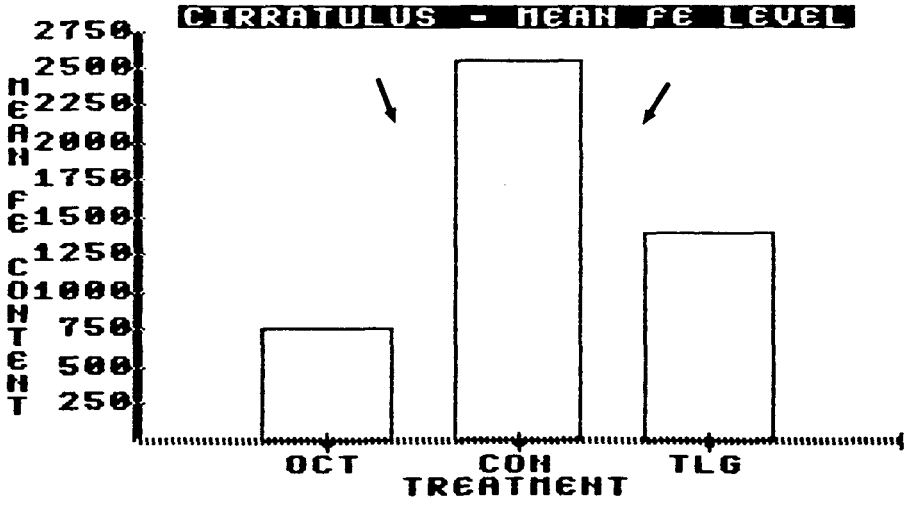


Table 4 Values for *Macoma balthica*

	As	Cd	Cr	Cu	Mo	Ni	Pb	V	Zn	Fe
October	11	.9	5.6	264	2.7	5.0	11	1.0	950	860
Control	15	.6	2.4	204	2.5	3.0	5	1.0	882	703
Tailings	13	1.3	3.5	117	4.1	3.0	45	3.0	774	2160

Note: Each treatment had 5 animals. The 5 animals were combined into a single composite sample. Thus, no statistics are given.

FIG. 11 Level of Arsenic in M. balthica
for October, Controls, and Tailings (ug/g)

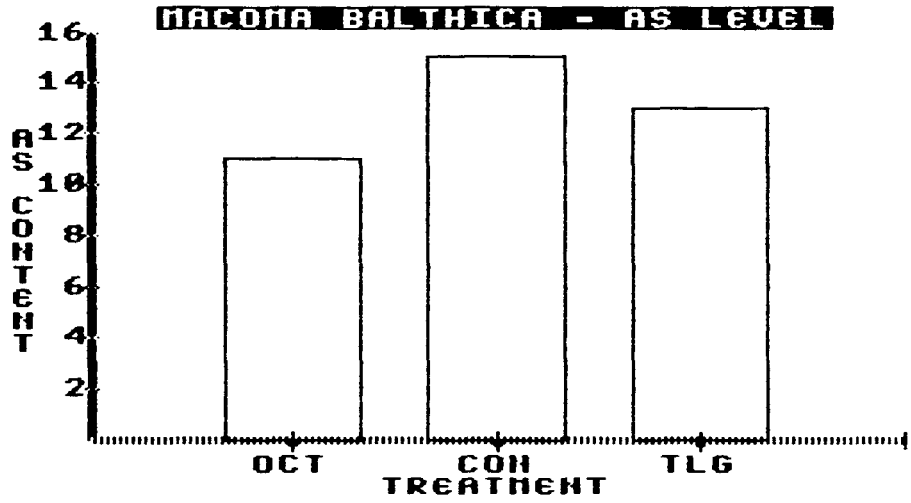


FIG. 12 Level of Cadmium in M. balthica
for October, Controls, and Tailings (ug/g)

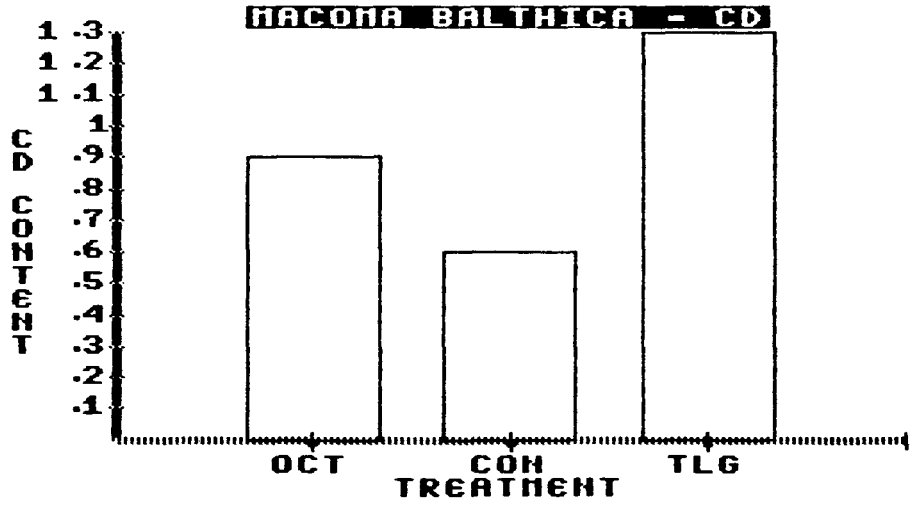


FIG. 13 Level of Chromium in M. balthica
for October, Controls, and Tailings (ug/g)

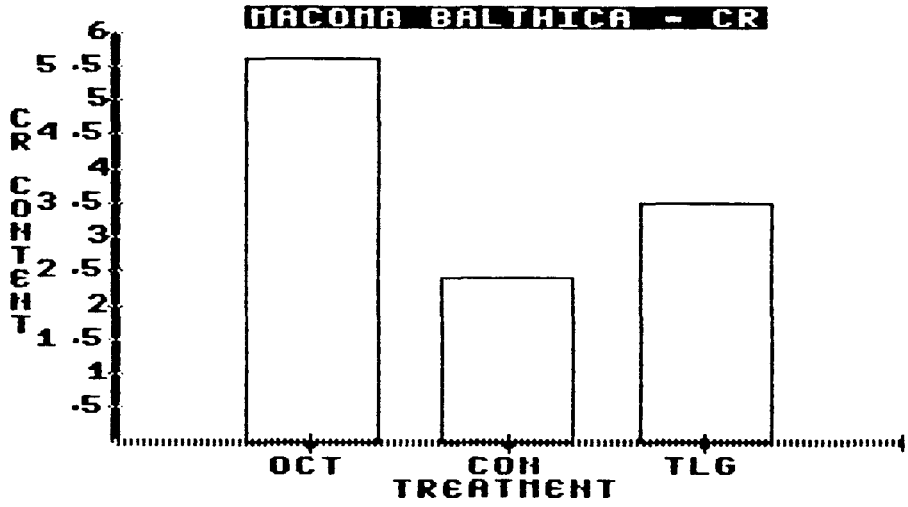


FIG. 14 Level of Copper in M. balthica
for October, Controls, and Tailings (ug/g)

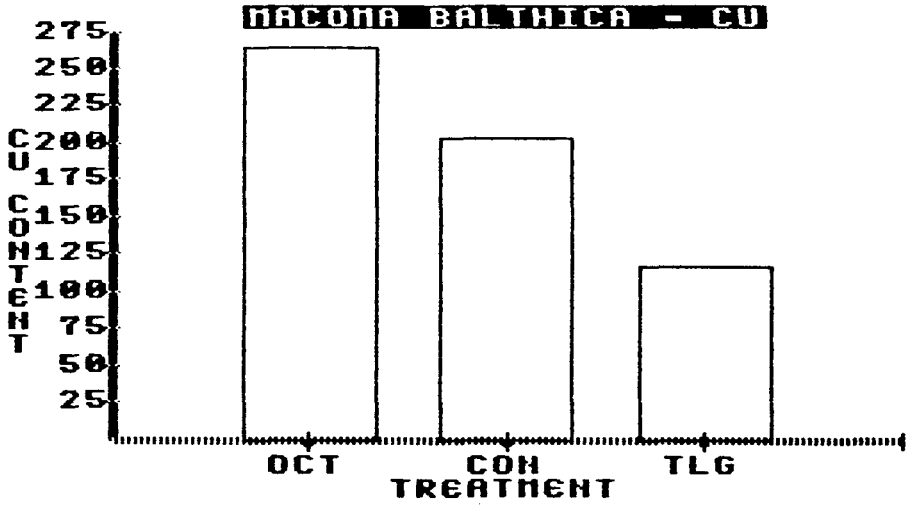


FIG. 15 Level of Molybdenum in M. balthica for October, Controls, and Tailings (ug/g)

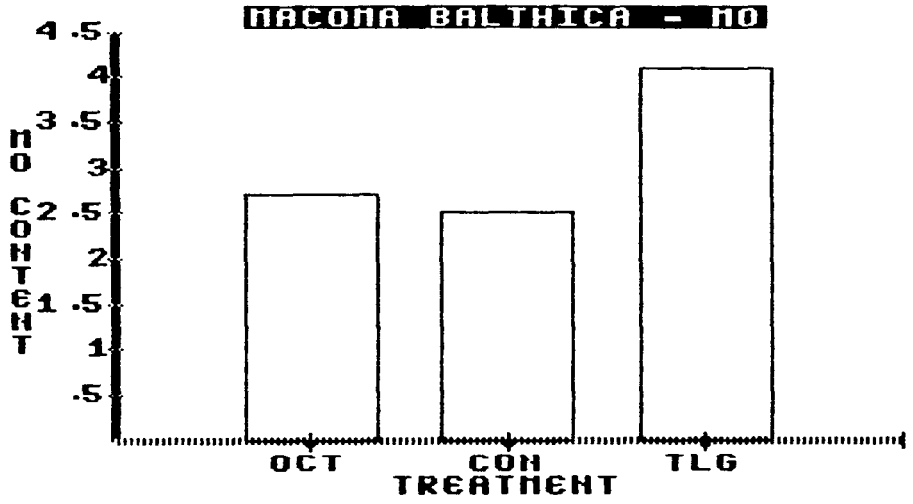


FIG. 16 Level of Nickel in M. balthica for October, Controls, and Tailings (ug/g)

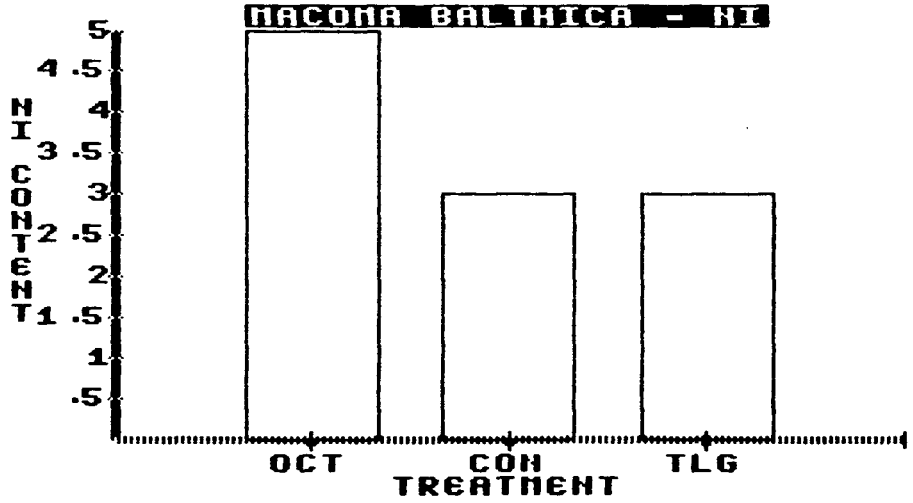


FIG. 17 Level of Lead in M. balthica
for October, Controls, and Tailings (ug/g)

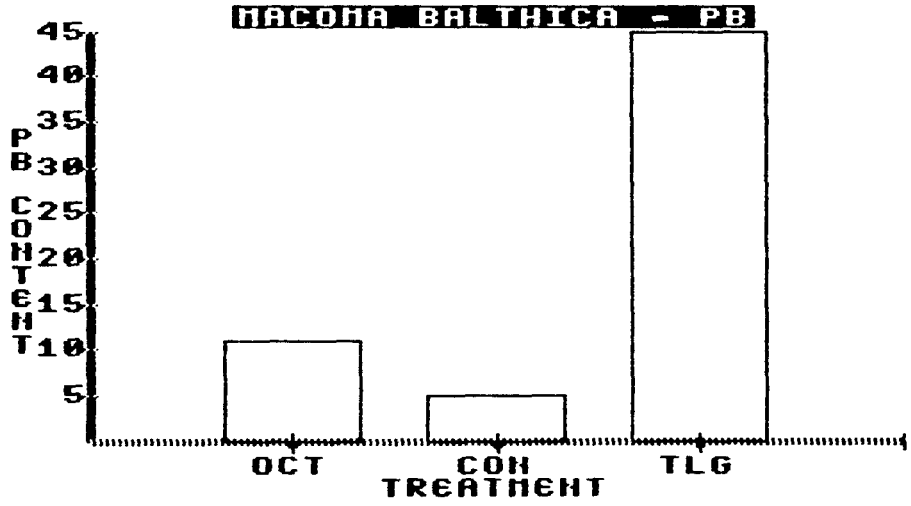


FIG. 18 Level of Vanadium in M. balthica
for October, Controls, and Tailings (ug/g)

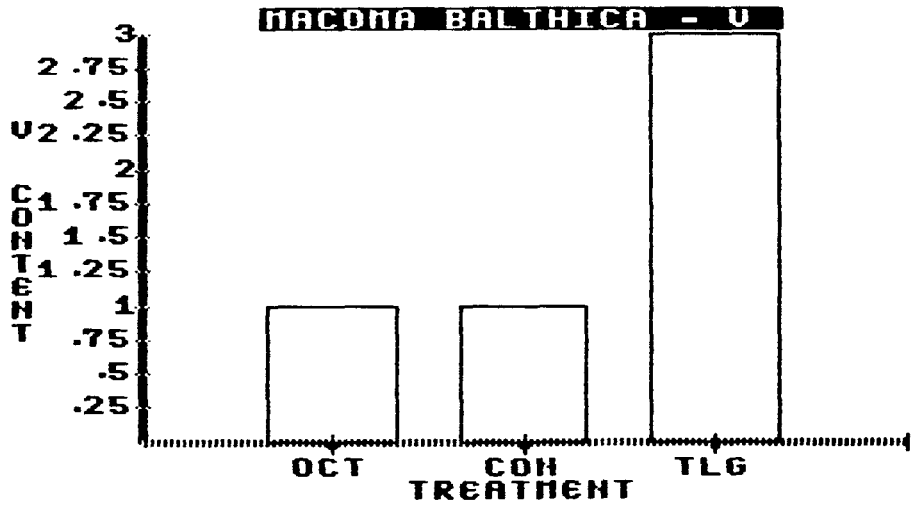


FIG. 19 Level of Zinc in M. balthica
for October, Controls, and Tailings (ug/g)

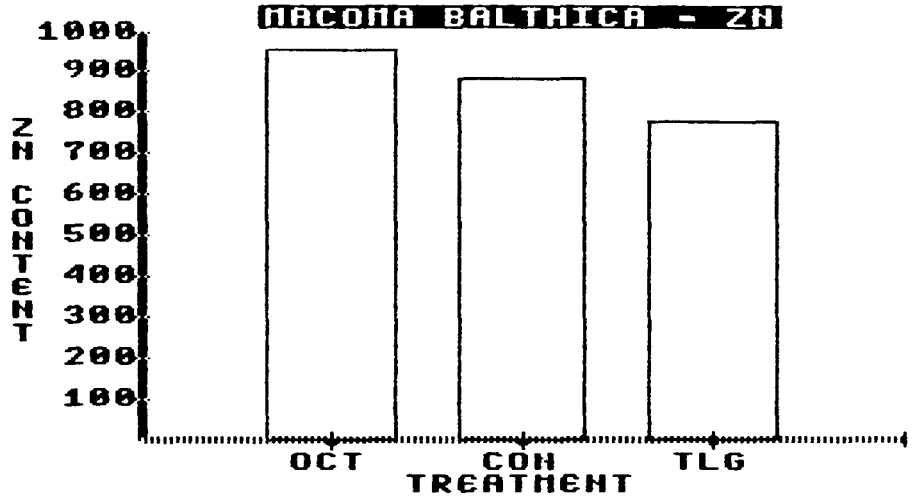


FIG. 20 Level of Iron in M. balthica
for October, Controls, and Tailings (ug/g)

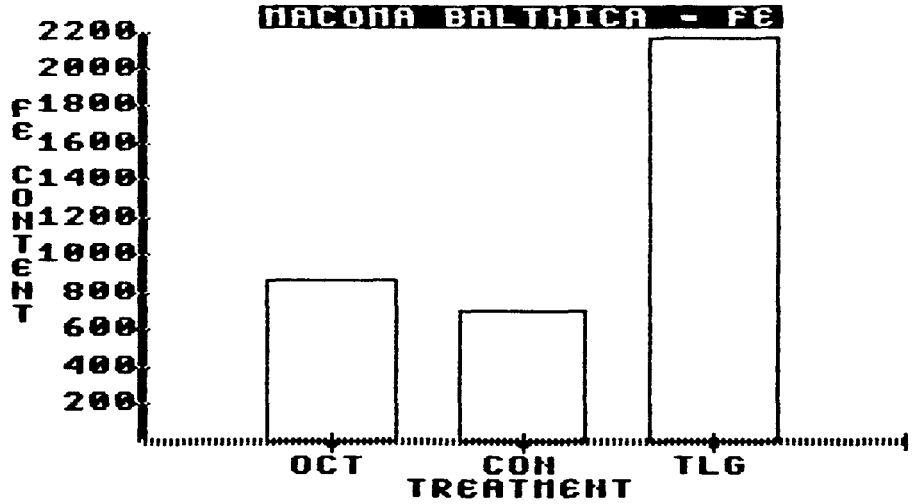


TABLE 5 DATA FOR MACOMA NASUTA - OCTOBER

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	16	271.000	16.938	8.567	8.000	39.000
CD	16	4.940	.309	.167	.190	.900
CR	16	49.300	3.081	2.833	1.000	13.400
CU	16	334.900	20.931	8.437	13.500	48.300
MO	16	44.000	2.750	1.508	1.100	7.200
NI	16	42.000	2.625	.885	1.000	4.000
PB	16	70.000	4.375	1.360	3.000	8.000
V	16	21.100	1.319	.647	.100	2.300
ZN	16	1727.400	107.963	36.500	69.000	184.000
FE	16	11484.000	717.750	295.207	225.000	1320.000

MACOMA

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	23	.30	3.1	24.2	2.4	4.0	8.0	2.3	167	1320
2	10	.3	3.0	25.0	2.0	4.0	6.0	2.0	82.3	494
3	12	.2	2.9	13.6	1.1	3.0	3	2.1	91	1150
4	13	.3	2.5	17.8	2.0	3.0	4.0	2.0	93.6	757
5	14	.3	2.7	19.5	1.6	3.0	4.0	1.6	89	847
6	8	.9	13.4	48.3	3.4	4.0	4.0	.1	72.9	807
7	14	.3	3.7	25.9	2.8	3	5	2	184	1070
8	11	.22	1.9	14.8	2	2	3	.8	69	562
9	11	.28	2.5	20.5	2.6	2	4	1.2	121	932
10	11	.25	2.9	13.5	1.4	2	4	1.4	81.8	764
11	17	.3	1.9	24.6	2.3	2	6	1	91.6	529
12	14	.19	1	15.7	2.5	1	3	.5	95.7	225
13	18	.4	1.6	13.5	2.2	2	3	.6	78.5	422
14	39	.2	2.3	17.6	3.5	3	4	1.3	103	628
15	32	.2	1.7	20.1	7.2	2	5	.9	162	434
16	24	.3	2.2	20.3	5	2	4	1.3	145	543

TABLE 6 DATA FOR MACOMA NASUTA - CONTROLS

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	12	280.000	23.333	10.680	8.000	50.000
CD	12	5.900	.492	.250	.200	1.000
CR	12	21.800	1.817	.988	1.000	4.000
CU	12	213.500	17.792	8.958	9.200	37.000
MO	12	36.100	3.008	2.006	1.000	8.900
NI	12	26.000	2.167	1.267	1.000	5.000
PB	12	58.700	4.892	1.639	2.000	8.000
V	12	12.300	1.025	.483	.600	2.000
ZN	12	1544.200	128.683	38.574	79.000	185.000
FE	12	4760.000	396.667	309.070	145.000	1220.000

MACOMA/CONTROL

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	20	.8	2.1	15.4	1.8	3	8	1	169	381
2	8	.5	3.5	31.7	1.8	3	5	2	183	1220
3	10	1	4	37	1	5	6	2	166	620
4	22	.4	1.2	13.5	1.7	1	3	.7	88.5	145
5	24	.3	2	26.7	3.1	1	6	.8	96.3	677
6	25	.2	1	9.2	2.3	1	2	.6	118	233
7	19	.5	1.9	13.5	2.7	3	6	1	127	337
8	32	.8	1.6	11.7	2.9	2	4	1.1	185	230
9	21	.3	1.1	12.2	3.2	1	3.7	.7	104	202
10	22	.5	1.2	15.7	3.4	3	5	.7	136	226
11	27	.3	1.1	10.8	3.3	1	4	.7	92.4	176
12	50	.3	1.1	16.1	8.9	2	6	1	79	313

TABLE 7 DATA FOR MACOMA NASUTA - TAILINGS

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	12	474.000	39.500	19.920	10.000	63.000
CD	12	25.140	2.095	2.204	.130	6.800
CR	12	18.900	1.575	.676	1.000	3.000
CU	12	268.300	22.358	7.939	10.000	39.000
MO	12	77.300	6.442	3.090	2.000	12.900
NI	12	25.600	2.133	1.451	1.000	5.000
PB	12	553.600	46.133	38.355	7.000	137.000
V	12	17.700	1.475	1.607	.500	6.000
ZN	12	2475.000	206.250	87.995	94.000	379.000
FE	12	16086.000	1340.500	1299.861	207.000	5101.000

MAC-TAILINGS

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	10	.8	3	10	2	5	10	3	191	207
2	24	6.8	1.7	27.9	4.4	2	51	6	379	897
3	14	.6	1.3	29.6	4.2	2	52	.6	155	648
4	26	5.3	2.8	39	4.9	5	137	2	364	1740
5	18	4.2	1.3	20.8	2.8	2	93	.9	251	1640
6	43	.13	1	13.9	6.7	1	10	.5	94	311
7	61	1.3	1.1	21.3	9.7	1	29	.9	185	1030
8	63	1.51	1.9	21	5.9	2.6	45.6	1.3	232	1670
9	52	1	1.1	28.1	8.5	1	38	.6	157	905
10	46	2.8	1	23.7	12.9	1	64	.5	190	1470
11	61	.5	1.4	16.7	7.1	2	17	.7	139	5101
12	56	.2	1.3	16.3	8.2	1	7	.7	138	467

FIG. 21 Mean level of Arsenic in Macoma nasuta for October, Controls, and Tailings (ug/g)

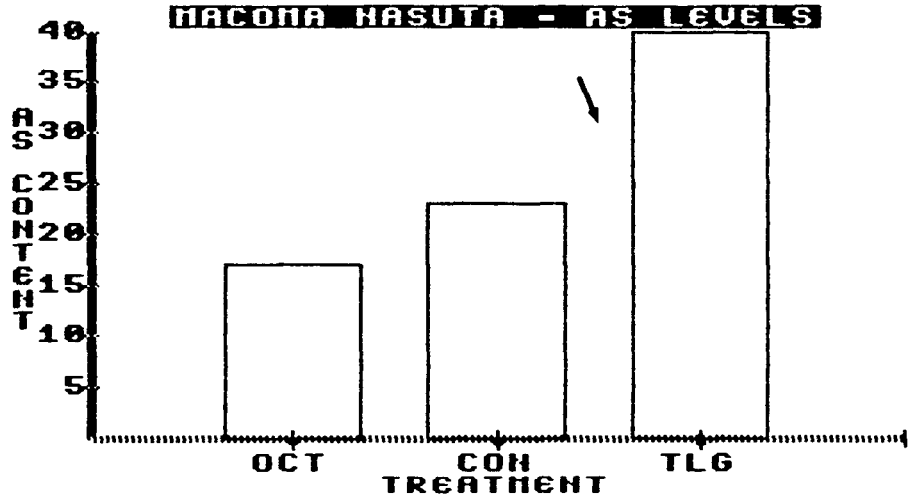


FIG. 22 Mean level of Cadmium in Macoma nasuta for October, Controls, and Tailings (ug/g)

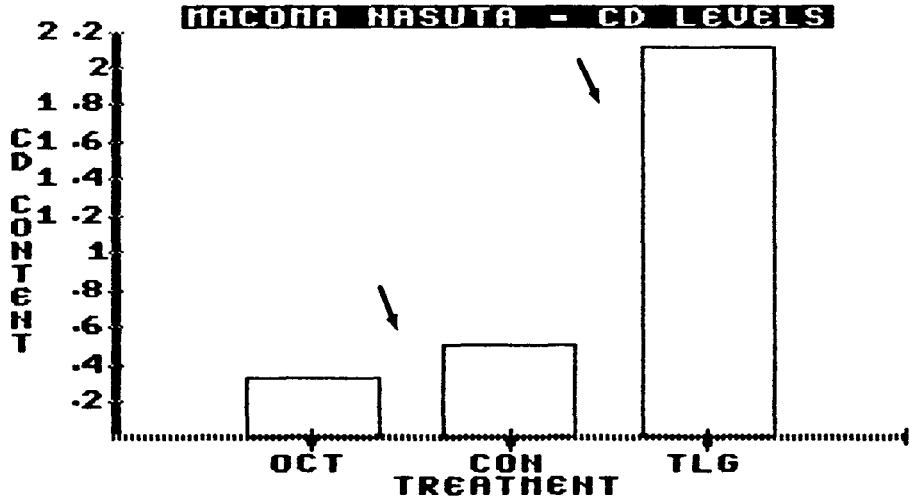


FIG. 23 Mean level of Chromium in Macoma nasuta for October, Controls, and Tailings (ug/g)

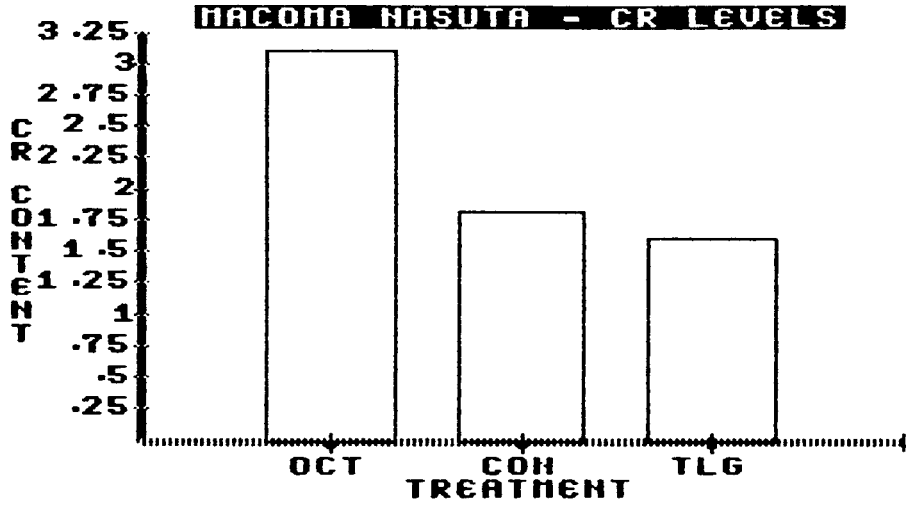


FIG. 24 Mean level of Copper in Macoma nasuta for October, Controls, and Tailings (ug/g)

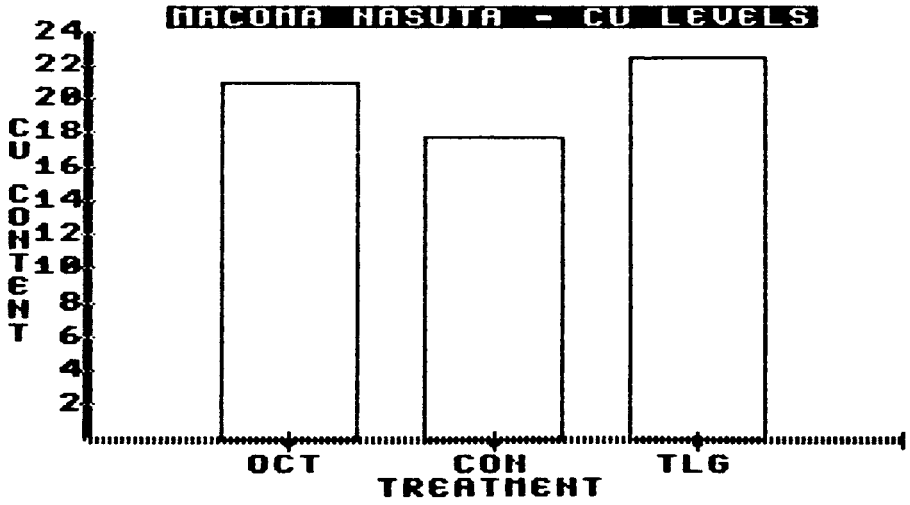


FIG. 25 Mean level of Molybdenum in Macoma nasuta for October, Controls, and Tailings (ug/g)

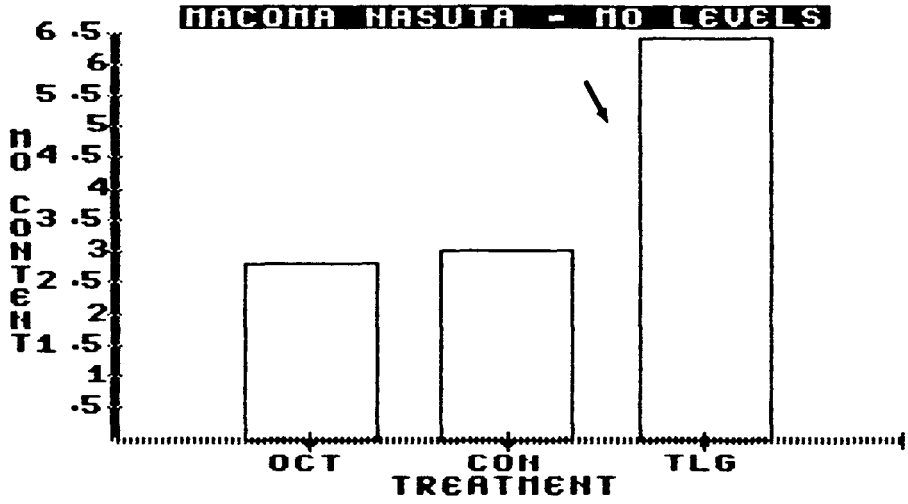


FIG. 26 Mean level of Nickel in Macoma nasuta for October, Controls, and Tailings (ug/g)

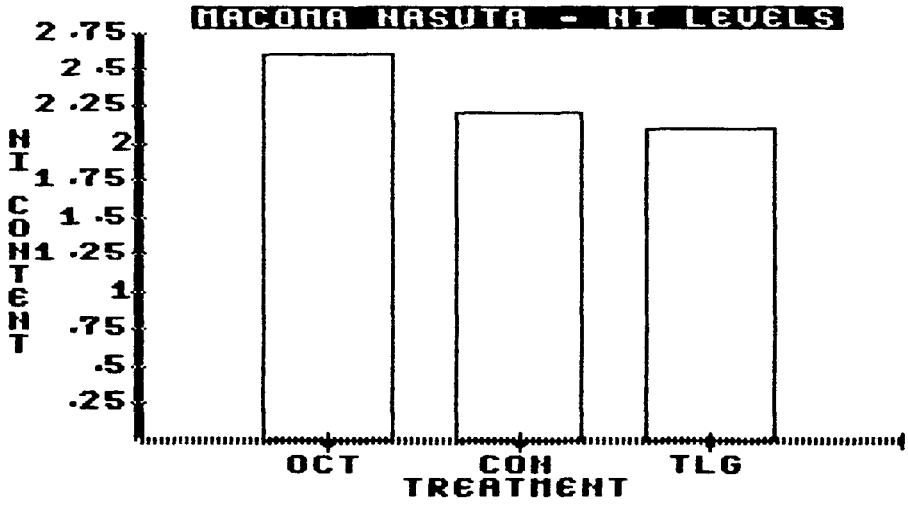


FIG. 27 Mean level of Lead in Macoma nasuta for October, Controls, and Tailings (ug/g)

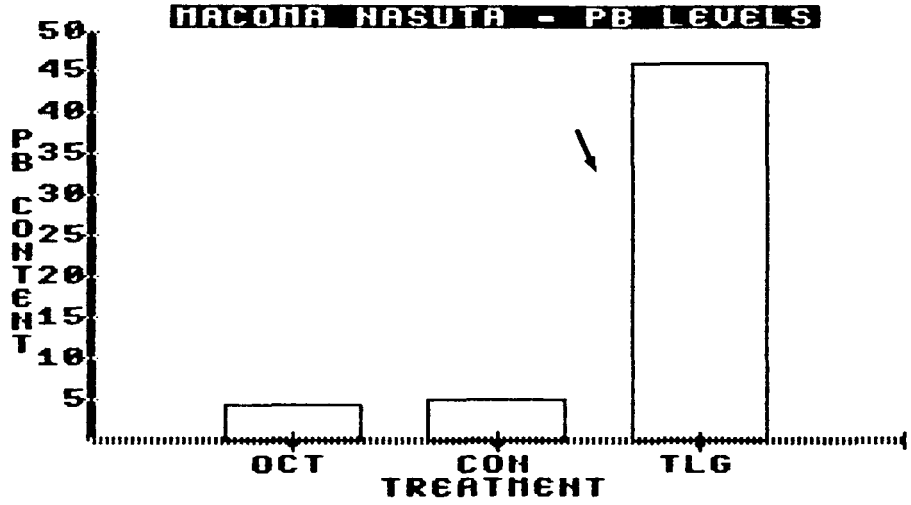


FIG. 28 Mean level of Vanadium in Macoma nasuta for October, Controls, and Tailings (ug/g)

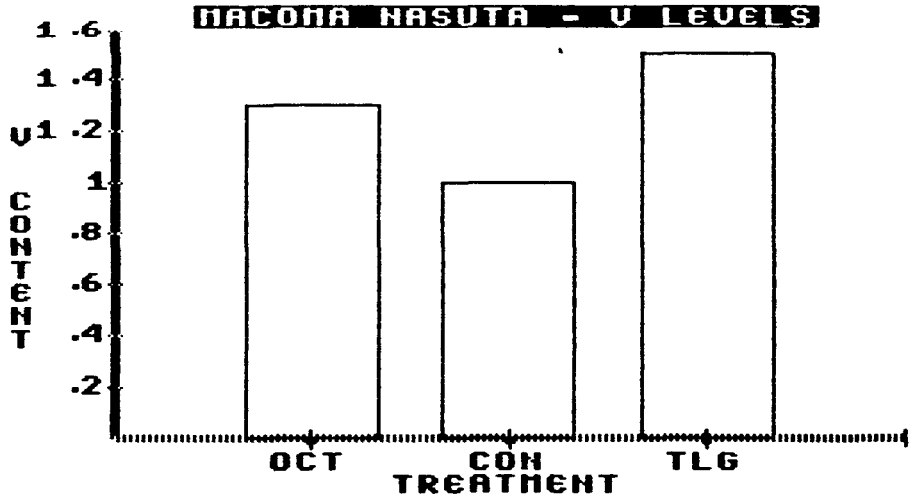


FIG. 29 Mean level of Zinc in Macoma nasuta for October, Controls, and Tailings (ug/g)

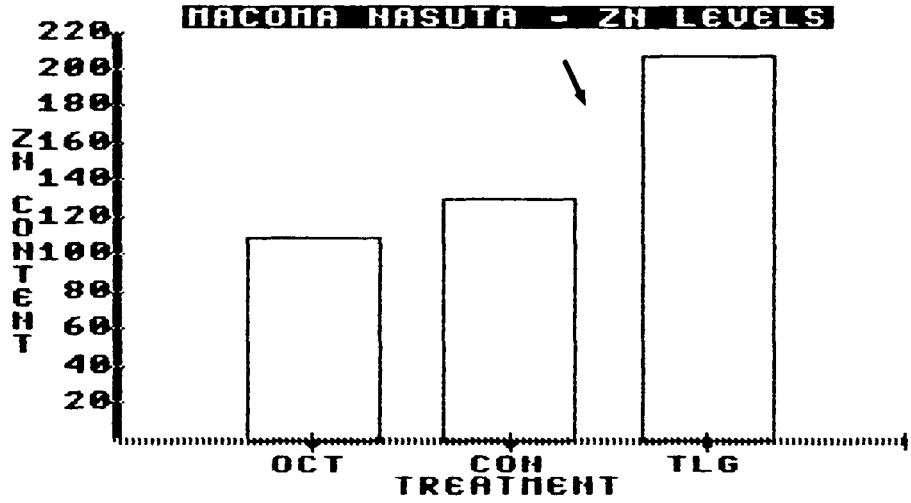


FIG. 30 Mean level of Iron in Macoma nasuta for October, Controls, and Tailings (ug/g)

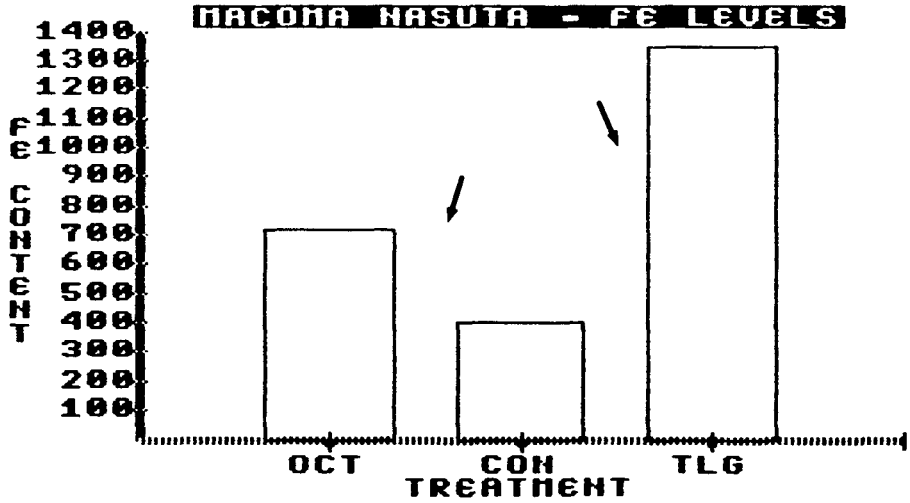


TABLE 8 DATA FOR MYA ARENARIA - OCTOBER

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	13	130.000	10.000	6.671	4.000	20.000
CD	13	10.220	.786	.268	.400	1.500
CR	13	29.500	2.269	1.169	1.400	5.700
CU	13	218.200	16.785	2.597	12.300	20.900
MO	13	17.000	1.308	.715	.300	2.900
NI	13	36.100	2.777	.947	2.000	5.100
PB	13	58.920	4.532	1.199	2.020	6.000
V	13	12.500	.962	.393	.500	1.600
ZN	13	1631.000	125.462	49.075	64.900	234.000
FE	13	7827.000	602.077	182.163	381.000	894.000

MYA/OCT

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	20	.6	1.7	16.8	.3	3	6	1.3	112	778
2	6	.92	5.7	16.6	1.4	5.1	3.9	.5	113	420
3	4	.9	2.2	20.7	1	4	4	.7	78.7	552
4	4	1.5	1.5	13.6	.8	3	5	.6	84.4	484
5	4	.6	1.8	15.7	.8	2	4	1.4	112	894
6	5	.8	2.8	20.9	1.2	3	5	1.6	140	852
7	4	.8	3	17	1	2	6	1	106	681
8	4	.9	2.8	13.8	.8	3	6	1.4	64.9	752
9	13	.8	1.4	17	2.5	2	4	.6	209	397
10	18	.5	1.8	12.3	1.2	3	5	.9	118	514
11	16	.8	1.7	18.1	1.7	2	5	1.3	234	701
12	20	.4	1.7	16.4	2.9	2	3	.7	156	421
13	12	.7	1.4	19.3	1.4	2	2.02	.5	103	381

TABLE 9 DATA FOR MYA ARENARIA - CONTROLS

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	10	69.000	6.900	4.677	3.000	18.000
CD	10	11.100	1.110	.482	.300	1.900
CR	10	12.400	1.240	.350	.900	2.100
CU	10	178.300	17.830	6.609	8.400	27.900
MO	10	9.800	.980	.339	.400	1.600
NI	10	14.000	1.400	.699	1.000	3.000
PB	10	14.930	1.493	.808	.280	3.000
V	10	5.600	.560	.107	.500	.800
ZN	10	933.400	93.340	24.167	58.800	139.000
FE	10	3135.000	313.500	133.329	128.000	582.000

MYA/CON

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	18	.9	1	19.2	1.6	1	.28	.5	116	264
2	3	.9	1.1	15.6	1.1	1	2	.5	82.3	288
3	4	.9	1.1	17.3	.9	1	.81	.5	75.5	306
4	7	1	1.3	22.4	1	2	.89	.6	92	311
5	4	1.2	1.3	27.9	1.1	2	3	.5	139	343
6	7	1.8	1.5	25.6	.8	1	.72	.8	85.1	485
7	5	1.4	.9	9.7	1	1	1.98	.5	83.6	225
8	5	.8	1	20.7	.6	1	1.78	.5	58.8	203
9	12	1.9	2.1	11.5	.4	3	1.68	.5	81.1	582
10	4	.3	1.1	8.4	1.3	1	1.79	.7	120	128

TABLE 10 DATA FOR MYA ARENARIA - TAILINGS

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	11	207.000	18.818	4.792	11.000	25.000
CD	11	12.800	1.164	.353	.700	1.800
CR	11	19.400	1.764	.607	1.000	2.800
CU	11	168.000	15.273	6.426	5.600	27.400
MO	11	80.800	7.345	6.611	1.200	23.000
NI	11	23.000	2.091	1.136	1.000	5.000
PB	11	234.000	21.273	21.462	3.000	58.000
V	11	15.400	1.400	1.072	.500	3.600
ZN	11	1330.000	120.909	32.175	72.100	171.000
FE	11	13612.000	1237.455	1109.964	280.000	3480.000

MYA/TAIL

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	21	1.5	2.8	19.5	12.2	2	44	3.6	162	3480
2	25	.9	2.1	14.1	7.4	2	58	2	95.2	1620
3	22	1.4	1.6	10.8	23	2	44	1.8	72.1	1800
4	24	1.8	2.7	27.4	12.3	5	45	2.9	171	2920
5	12	1.1	1	9.4	4	1	7	.5	115	305
6	18	1	1.7	22.9	1.2	2	5	1	156	692
7	11	1.2	1.2	17.8	2.1	2	12	.5	93.4	286
8	17	.7	1.4	16.6	1.9	2	4	.5	109	557
9	14	1	1.1	5.6	3.3	1	4	.5	115	280
10	22	.7	2.1	9.7	9.9	3	8	1.4	99.3	1170
11	21	1.5	1.7	14.2	3.5	1	3	.7	142	502

FIG. 31 Mean level of Arsenic in Mya arenaria for October, Controls, and Tailings (ug/g)

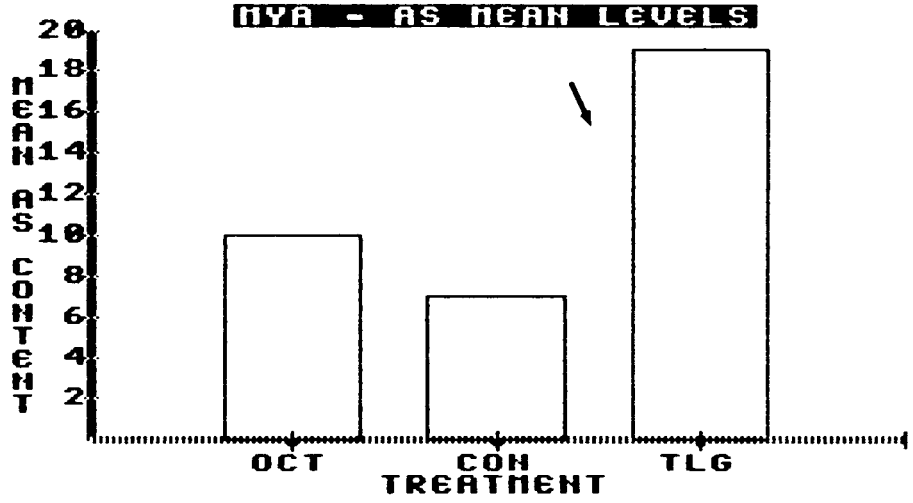


FIG. 32 Mean level of Cadmium in Mya arenaria for October, Controls, and Tailings (ug/g)

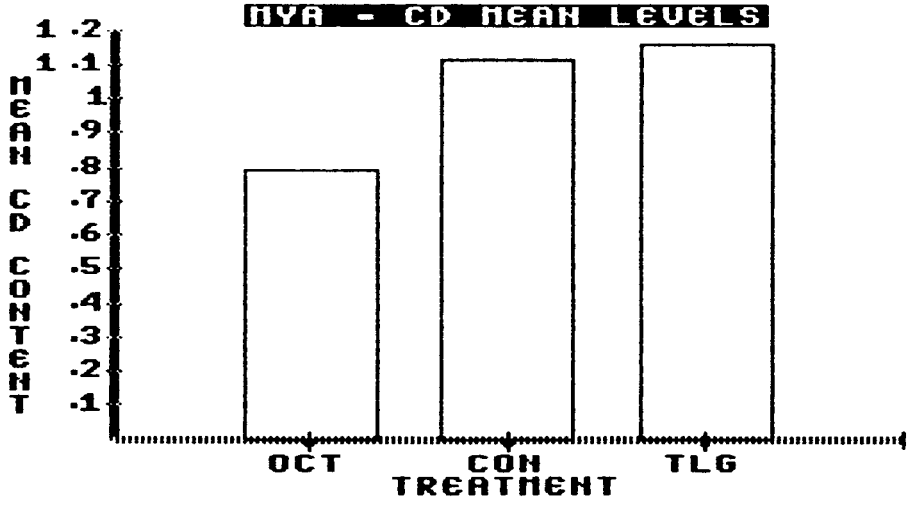


FIG. 33 Mean level of Chromium in Mya arenaria for October, Controls, and Tailings (ug/g)

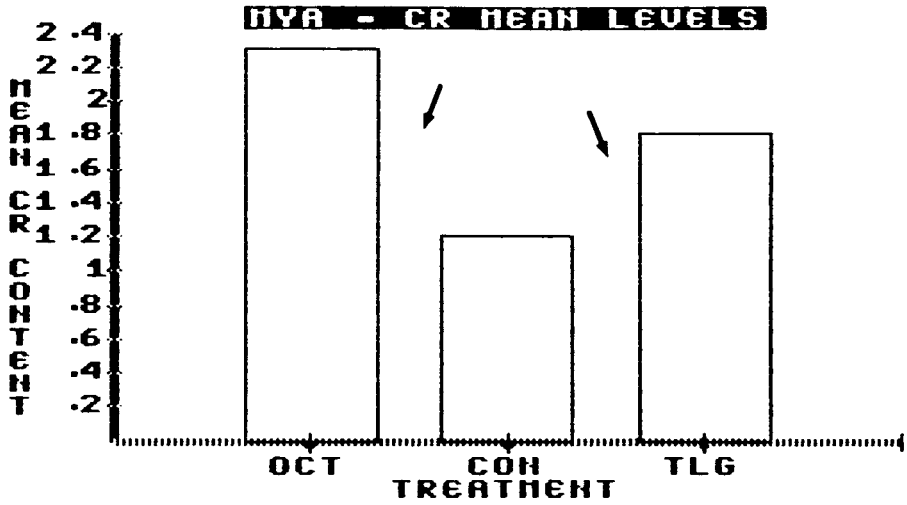


FIG. 34 Mean level of Copper in Mya arenaria for October, Controls, and Tailings (ug/g)

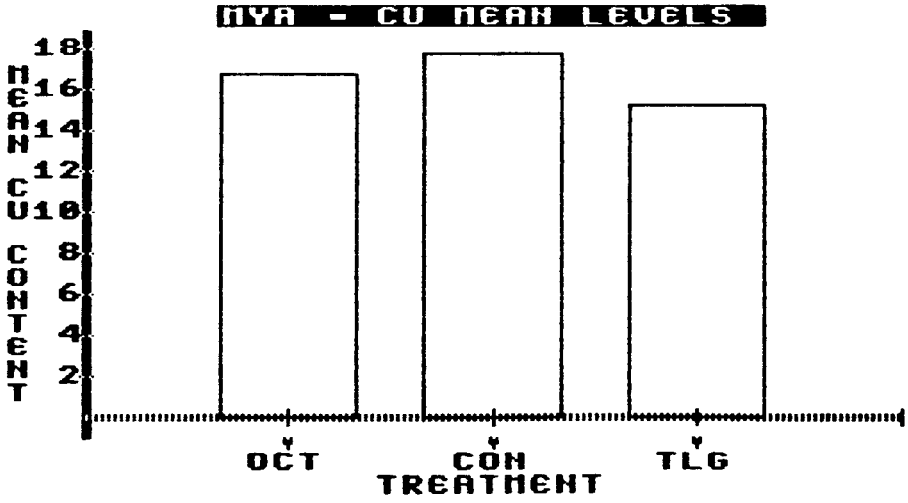


FIG. 35 Mean level of Molybdenum in Mya arenaria for October, Controls, and Tailings (ug/g)

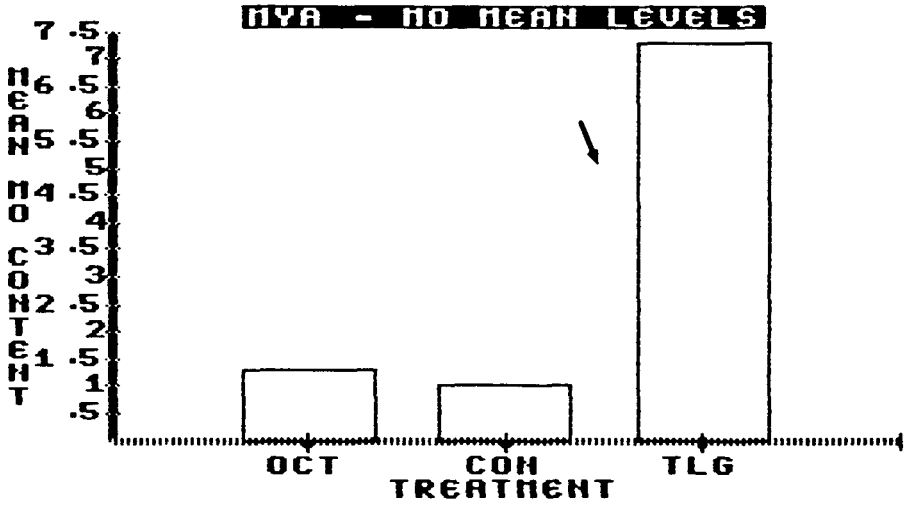


FIG. 36 Mean level of Nickel in Mya arenaria for October, Controls, and Tailings (ug/g)

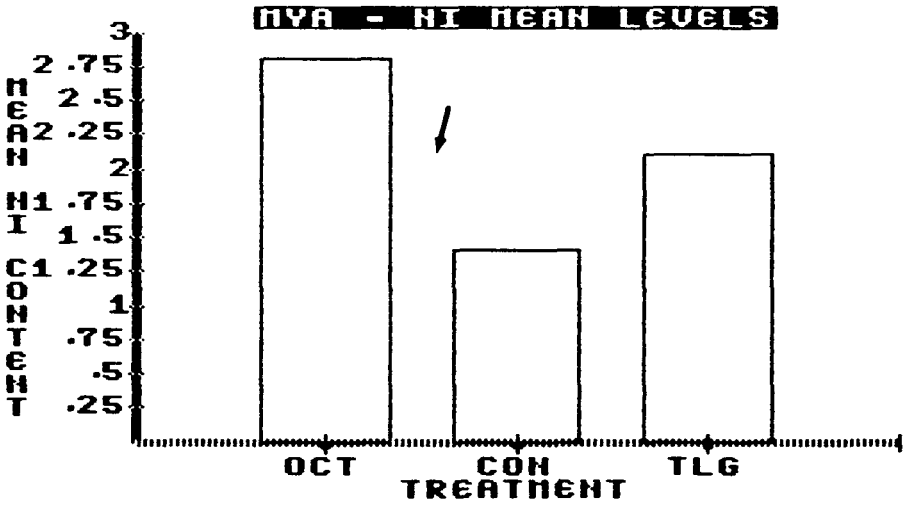


FIG. 37 Mean level of Lead in Mya arenaria for October, Controls, and Tailings (ug/g)

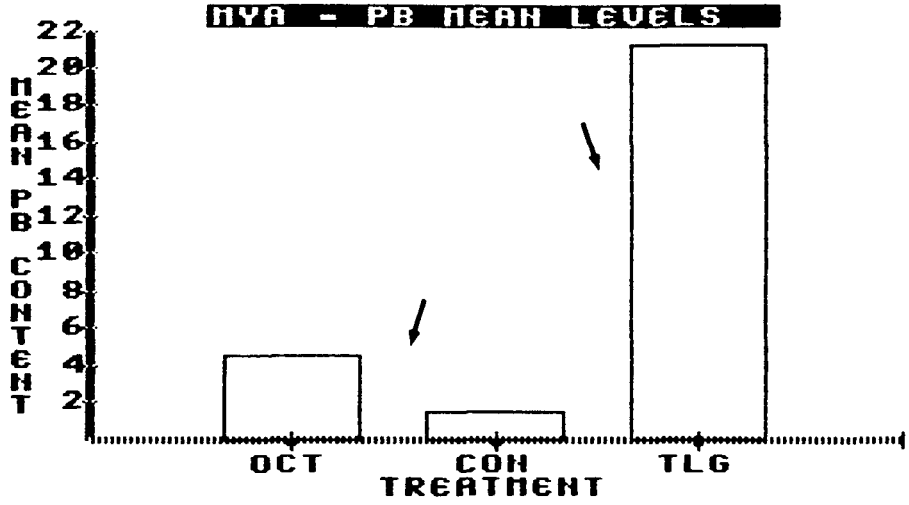


FIG. 38 Mean level of Vanadium in Mya arenaria for October, Controls, and Tailings (ug/g)

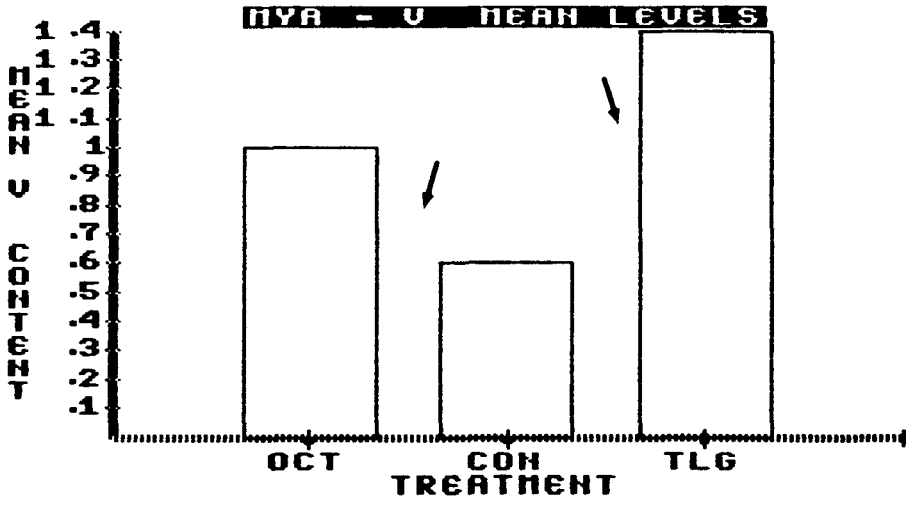


FIG. 39 Mean level of Zinc in Mya arenaria
for October, Controls, and Tailings (ug/g)

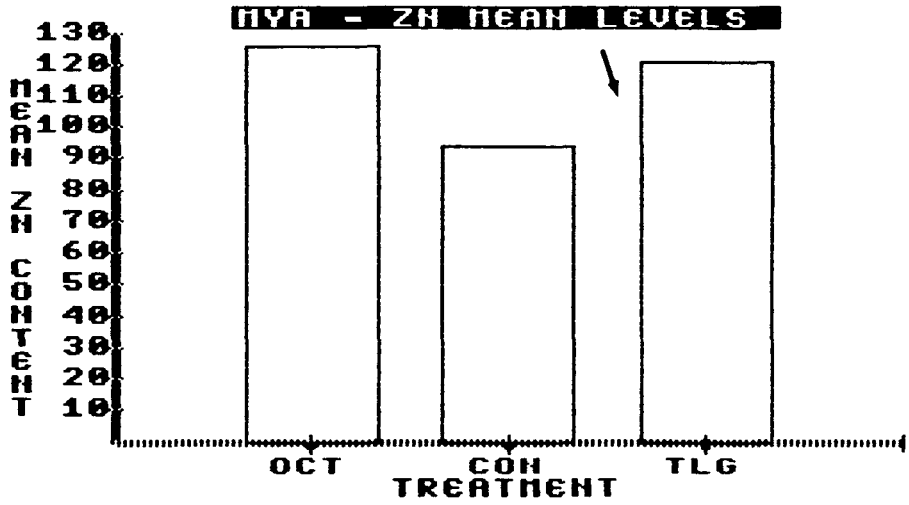


FIG. 40 Mean level of Iron in Mya arenaria
for October, Controls, and Tailings (ug/g)

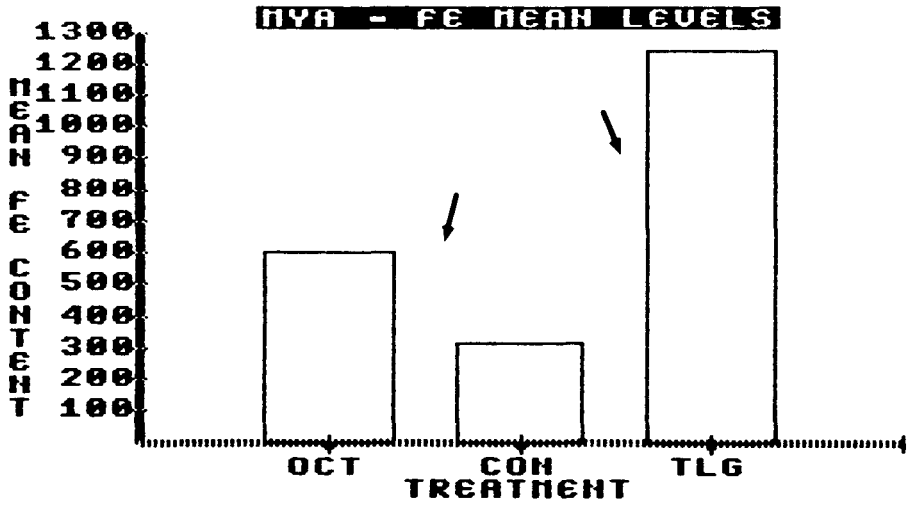


TABLE 11 DATA FOR VENERUPIS JAPONICA - JUNE

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	5	106.000	21.200	2.168	18.000	24.000
CD	5	8.800	1.760	.365	1.500	2.400
CR	5	9.500	1.900	.274	1.600	2.300
CU	5	65.600	13.120	3.136	10.500	17.400
MO	5	1.600	.320	.179	.200	.600
NI	5	38.000	7.600	2.881	4.000	12.000
PB	5	6.430	1.286	.289	.880	1.660
V	5	2.700	.540	.089	.500	.700
ZN	5	646.000	129.200	15.595	109.000	151.000
FE	5	2226.000	445.200	86.803	371.000	590.000

V/JUN

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	18	1.6	1.7	10.5	.4	7	.88	.5	109	371
2	22	1.5	1.6	10.7	.2	4	1.29	.5	127	407
3	21	1.7	1.9	11.5	.2	8	1.66	.5	136	458
4	21	1.6	2	15.5	.6	12	1.42	.5	123	400
5	24	2.4	2.3	17.4	.2	7	1.18	.7	151	590

TABLE 12 DATA FOR VENERUPIS JAPONICA - SEPTEMBER

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	5	167.000	33.400	7.197	24.000	40.000
CD	5	9.100	1.820	.286	1.500	2.200
CR	5	9.900	1.980	.164	1.800	2.200
CU	5	56.400	11.280	1.608	9.000	13.000
MO	5	2.300	.460	.207	.300	.800
NI	5	33.000	6.600	1.140	5.000	8.000
PB	5	4.250	.850	.294	.590	1.340
V	5	2.500	.500	.000	.500	.500
ZN	5	703.000	140.600	28.228	112.000	181.000
FE	5	1163.000	232.600	26.245	208.000	273.000

V/SEP

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	40	1.6	1.9	9	.3	6	.76	.5	128	208
2	28	2.2	1.8	11.9	.4	5	.88	.5	112	244
3	24	2	2.2	10.3	.3	7	.68	.5	124	222
4	40	1.8	2.1	13	.5	8	1.34	.5	181	273
5	35	1.5	1.9	12.2	.8	7	.59	.5	158	216

TABLE 13 DATA FOR VENERUPIS JAPONICA - OCTOBER

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	21	791.000	37.667	10.679	22.000	66.000
CD	21	41.000	1.952	.475	1.300	3.300
CR	21	49.200	2.343	.314	1.900	3.100
CU	21	268.200	12.771	1.907	9.200	16.300
MO	21	11.200	.533	.271	.200	1.000
NI	21	184.000	8.762	2.095	6.000	14.000
PB	21	33.430	1.592	.466	.870	2.400
V	21	12.400	.590	.134	.500	.900
ZN	21	2711.600	129.124	25.147	90.100	191.000
FE	21	8417.000	400.810	111.692	182.000	609.000

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	66	2.7	3.1	11.8	1	14	1.39	.7	107	364
2	34	1.8	2.5	12.3	.3	9	1.99	.8	156	609
3	26	2.5	2	12	.6	6	1.23	.8	94	282
4	24	1.9	2.3	13.6	.5	9	1.54	.6	135	437
5	32	1.8	2.1	14.7	.9	8	2	.5	122	357
6	33	1.7	2.4	14.3	.5	8	1.8	.5	136	443
7	41	2	2.3	13.7	.9	12	.87	.5	191	343
8	39	2	2.2	14.1	.2	10	1.96	.5	154	498
9	45	1.8	2.2	9.4	.7	9	1.19	.5	102	288
10	36	2.3	2.4	14.9	.6	7	1.42	.7	138	517
11	28	1.9	2.6	12.9	.3	9	1.9	.5	90.1	460
12	28	1.5	1.9	9.2	.9	7	1.16	.5	106	182
13	40	1.8	2.4	11.6	.2	7	2.4	.5	90.5	444
14	34	1.3	2.1	12	.7	9	1.76	.5	159	293
15	39	1.5	2.6	16.3	.2	7	2	.6	139	550
16	39	2.5	2.2	13	.3	7	2.37	.9	126	450
17	45	1.7	2.3	12.5	.4	8	.99	.5	135	374
18	60	1.8	3	16	.2	13	1.78	.8	130	582
19	40	1.8	2	10.4	.8	7	1.04	.5	129	288
20	22	1.4	2	11.4	.3	10	1.75	.5	128	317
21	40	3.3	2.6	12.1	.7	8	.89	.5	144	339

TABLE 14 DATA FOR VENERUPIS JAPONICA - CONTROLS

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	21	322.000	15.333	4.431	4.000	27.000
CD	21	51.900	2.471	.787	.900	5.100
CR	21	49.500	2.357	.517	1.200	4.000
CU	21	254.000	12.095	2.725	7.600	19.600
MO	21	8.300	.395	.169	.300	1.100
NI	21	172.900	8.233	2.684	1.000	15.000
PB	21	33.100	1.576	.695	.240	2.620
V	21	11.400	.543	.098	.500	.900
ZN	21	2038.800	97.086	19.769	67.200	135.000
FE	21	8051.000	383.381	108.327	166.000	551.000

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	4	.9	1.2	19.6	1.1	1	1	.5	104	166
2	16	2.8	2.5	15.1	.4	8	2.18	.9	90.5	517
3	13	2.2	2	9.8	.3	8	1.22	.5	99.4	300
4	19	2.6	2.1	8.4	.3	8	.24	.5	74.7	311
5	13	2.8	2.5	15.6	.3	9	1	.6	79.8	420
6	15	2.2	2	10.2	.3	8	1.24	.5	102	286
7	12	2.1	2.5	14.3	.3	6	2	.5	68.8	471
8	13	2.1	2.3	10.5	.4	8	1.91	.5	87.8	291
9	13	2.5	2.5	12.5	.3	7	1.42	.5	79.7	376
10	27	5.1	4	7.6	.4	15	.49	.5	108	473
11	22	3.1	2.5	11.3	.4	10	1.22	.5	110	373
12	15	2.7	2.3	13.3	.3	5	2.49	.7	93.4	551
13	17	2.1	2.7	10.5	.4	10	1.04	.5	67.2	400
14	16	2.6	2.5	13.1	.3	11	2.2	.5	135	503
15	15	2.4	2.3	10.6	.4	8	1.68	.5	89.5	304
16	17	3.1	2.4	12	.4	8	2.57	.6	127	477
17	19	2.2	2.7	11	.4	11	1.34	.5	129	325
18	12	1.4	1.7	11	.4	7	1.04	.5	74.6	244
19	16	2.5	2.1	14	.4	6.9	1.6	.5	107	266
20	15	2.4	2.6	13.6	.4	10	2.62	.5	92.4	473
21	13	2.1	2.1	10	.4	8	2.6	.6	119	524

TABLE 15 DATA FOR VENERUPIS JAPONICA - TAILINGS

SAMPLE	N	SUM	MEAN	S.D.	MIN	MAX
AS	21	321.000	15.286	2.348	9.000	19.000
CD	21	54.100	2.576	.529	1.500	3.600
CR	21	55.000	2.619	.371	1.600	3.200
CU	21	286.900	13.662	1.984	8.800	16.400
MO	21	11.000	.524	.130	.300	.800
NI	21	188.000	8.952	1.596	6.000	12.000
PB	21	58.160	2.770	1.064	.500	5.000
V	21	14.600	.695	.183	.500	1.100
ZN	21	2167.200	103.200	13.830	71.200	131.000
FE	21	11308.000	538.476	159.489	281.000	842.000

	AS	CD	CR	CU	MO	NI	PB	V	ZN	FE
1	16	2.4	2.5	14.3	.6	9	.5	.5	96.3	447
2	13	3.2	2.9	13.8	.6	8	2	.6	103	552
3	14	2.3	2.3	13.6	.4	9	2	.5	92.3	417
4	14	2.5	2.2	8.8	.3	7	1.79	.5	109	354
5	16	2.6	2.7	12.1	.7	8	4	.5	88.7	442
6	11	2.3	2.4	14.3	.6	7	3	.8	92.2	558
7	14	2.2	2.3	12	.5	9	2.38	.6	122	396
8	16	2.4	3	16.4	.6	12	3	.9	120	735
9	16	2.3	3.2	14.5	.3	11	4	.9	100	784
10	15	3.6	2.9	15.8	.6	10	3	.7	103	712
11	18	2.1	3	16.2	.6	11	4	1.1	113	842
12	17	3.6	3	16.3	.4	8	3	.5	131	555
13	14	2.3	2.7	14.3	.5	7	5	.9	94	674
14	16	2.9	2.9	15.1	.4	11	3	.8	87.4	637
15	17	2.8	2.8	14.9	.6	9	4	.9	105	728
16	17	2.6	2.3	12	.6	9	1.22	.5	115	281
17	16	1.9	2.7	13.6	.6	9	3	.6	98.1	494
18	15	3.2	2.3	13.6	.4	8	2	.7	118	445
19	18	2.4	2.6	13.2	.8	9	2.2	.8	108	457
20	19	3	2.7	12.1	.5	11	3	.8	100	481
21	9	1.5	1.6	10	.4	6	2.07	.5	71.2	317

FIG. 41 Mean level of Arsenic in Venerupis japonica for June, September, October, Controls, and Tailings (ug/g)

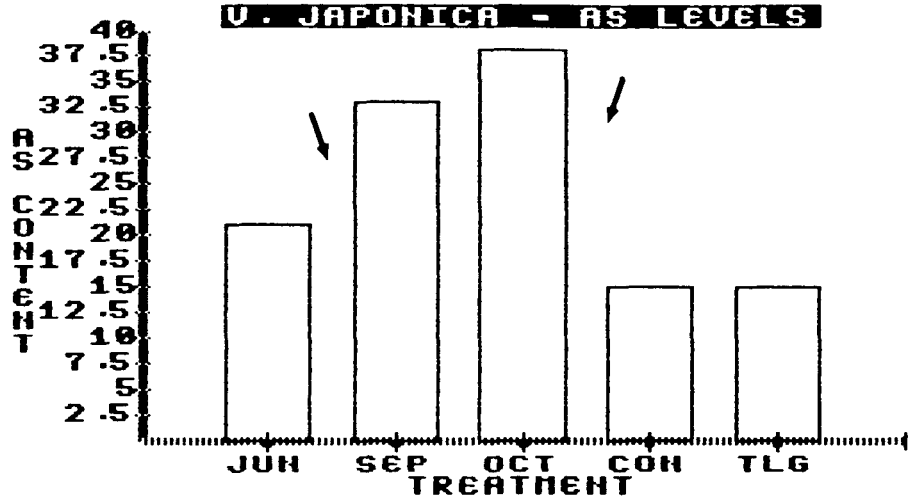


FIG. 42 Mean level of Cadmium in Venerupis japonica for June, September, October, Controls, and Tailings (ug/g)

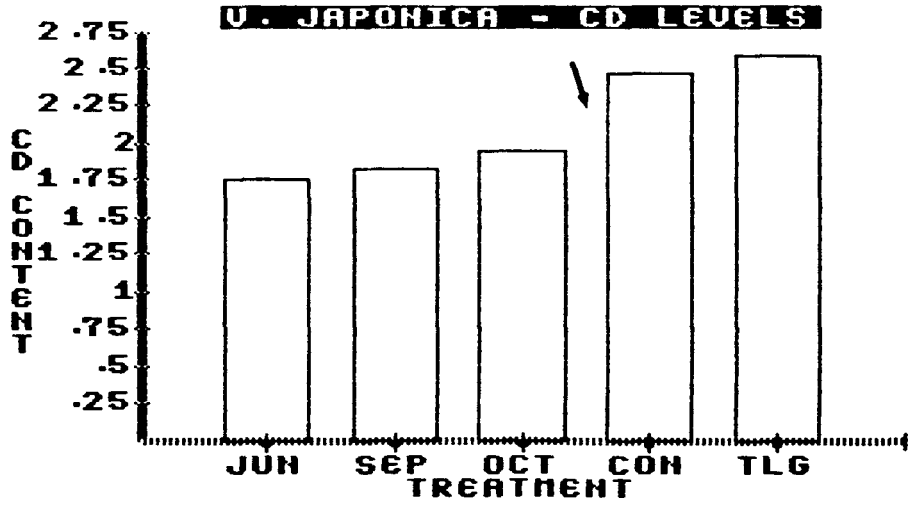


FIG. 43 Mean level of Chromium in Venerupis japonica for June, September, October, Controls, and Tailings (ug/g)

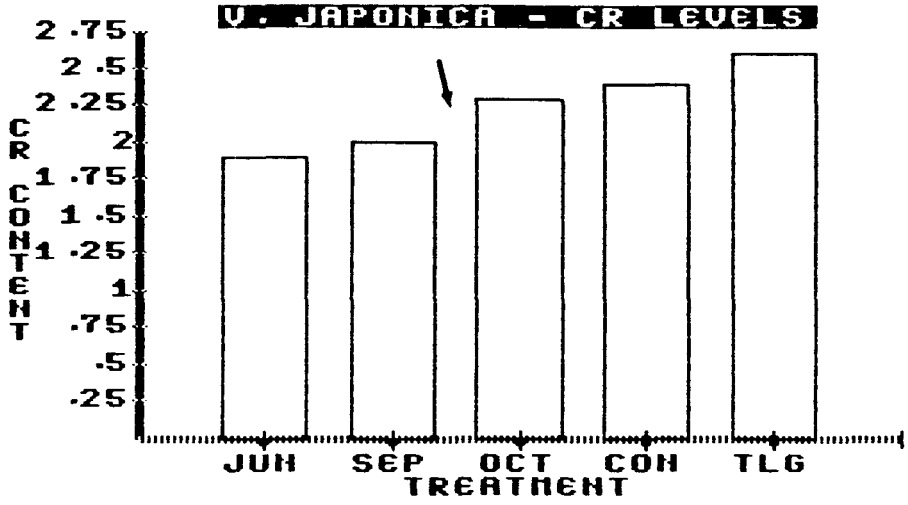


FIG. 44 Mean level of Copper in Venerupis japonica for June, September, October, Controls, and Tailings (ug/g)

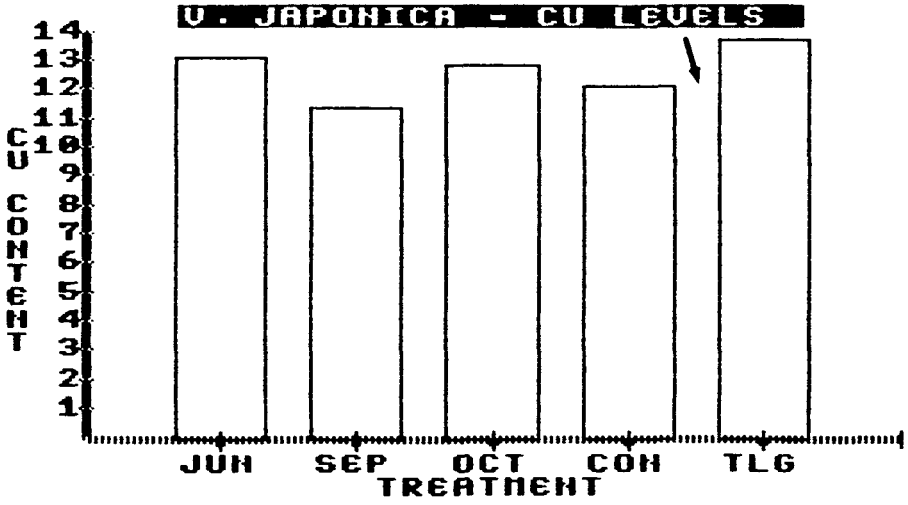


FIG. 45 Mean level of Molybdenum in Venerupis japonica for June, September, October, Controls, and Tailings (ug/g)

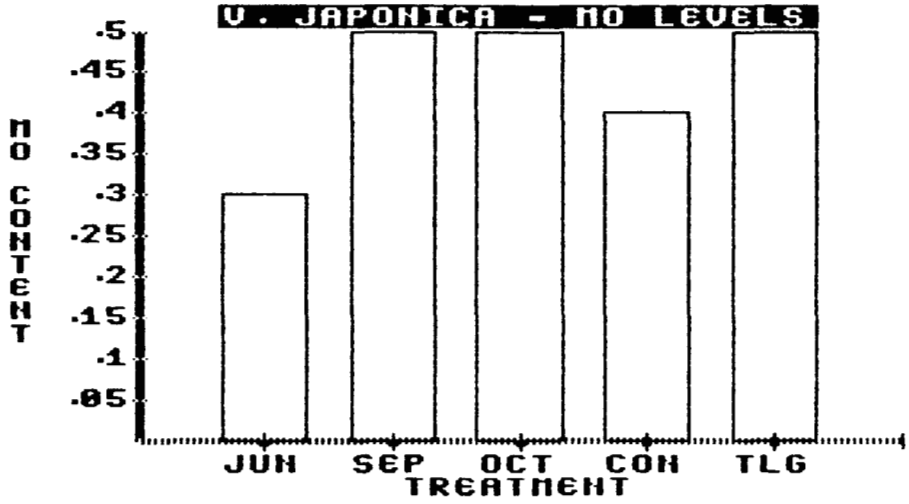


FIG. 46 Mean level of Nickel in Venerupis japonica for June, September, October, Controls, and Tailings (ug/g)

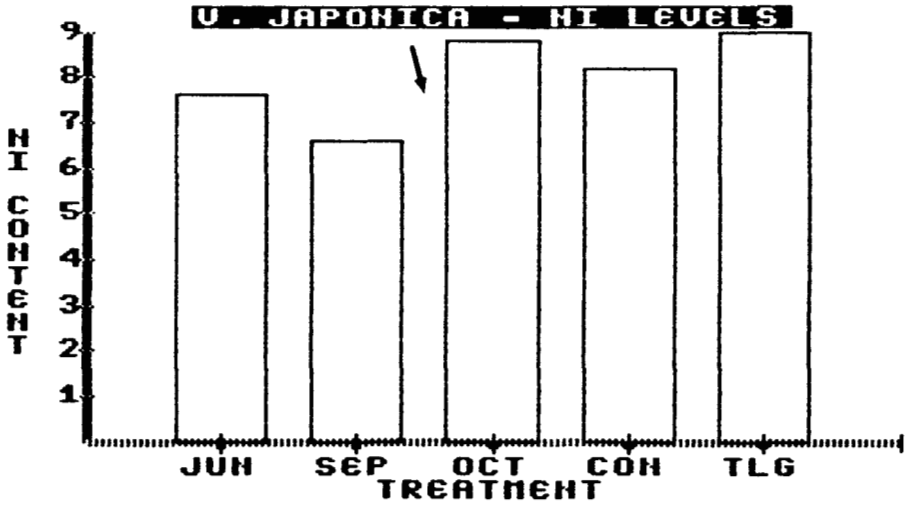


FIG. 47 Mean level of Lead in Venerupis japonica for June, September, October, Controls, and Tailings (ug/g)

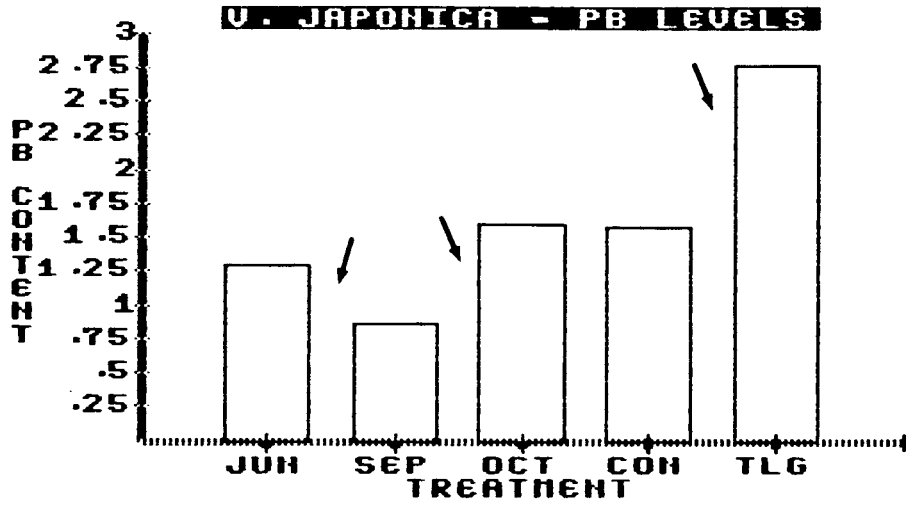


FIG. 48 Mean level of Vanadium in Venerupis japonica for June, September, October, Controls, and Tailings (ug/g)

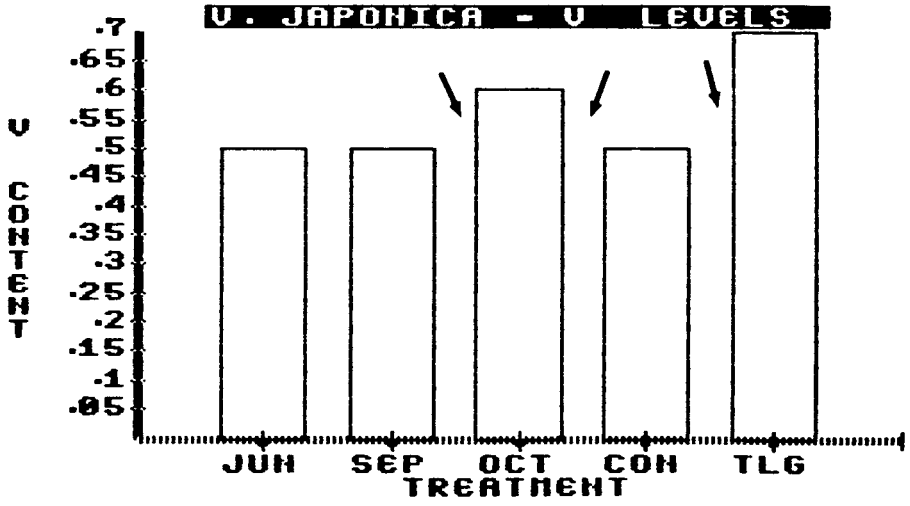


FIG. 49 Mean level of Zinc in Venerupis japonica for June, September, October, Controls, and Tailings (ug/g)

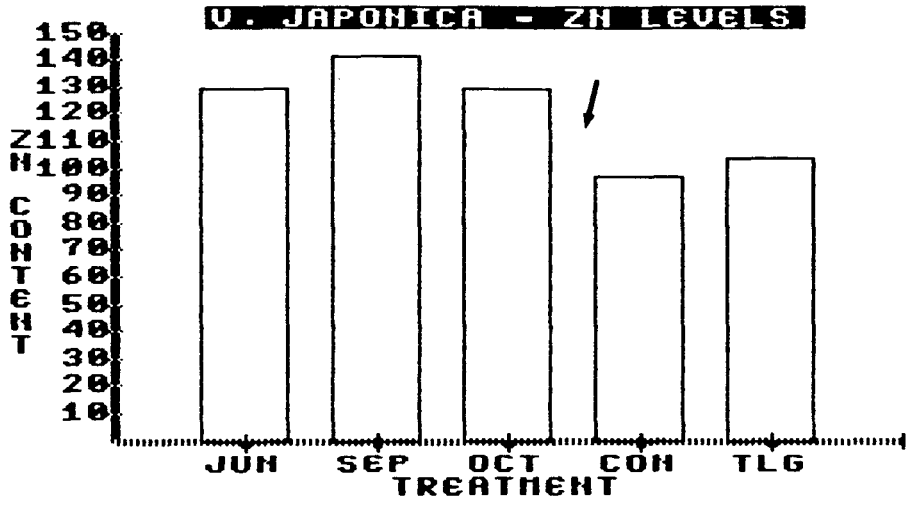


FIG. 50 Mean level of Iron in Venerupis japonica for June, September, October, Controls, and Tailings (ug/g)

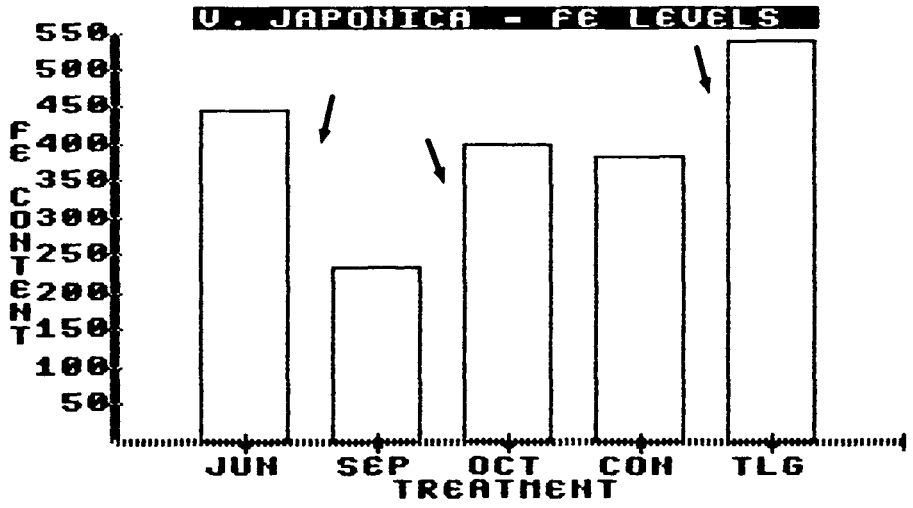


Table 16. Metal content of the Amax tailings and Control sediments. (ug/g)

Metal	Contr. Start	Amax Start	Contr. End	Amax End	Mean Contr.	Mean Amax	Amax Tailings (% of Control)
As	8	10	8	10	8.0	10.0	125 %
Cd	0.3	11.9	0.3	12.1	0.3	12.0	4000 %
Cr	81.4	11.1	72.4	10.6	76.9	10.9	14 %
Cu	268	53.6	378	67.6	323.0	60.6	19 %
Mo	3.2	69.9	1.8	56.2	2.5	63.1	2520 %
Ni	67	17	51	20	59.0	18.5	31 %
Pb	66	292	78	262	74.0	277.0	380 %
V	76	31	82	28	79.0	29.5	37 %
Zn	163	451	191	453	177.0	452.0	255 %
Fe	33300	22200	33400	22900	33350	22550	68 %

FIG. 51 Metal content of Tailings sediment

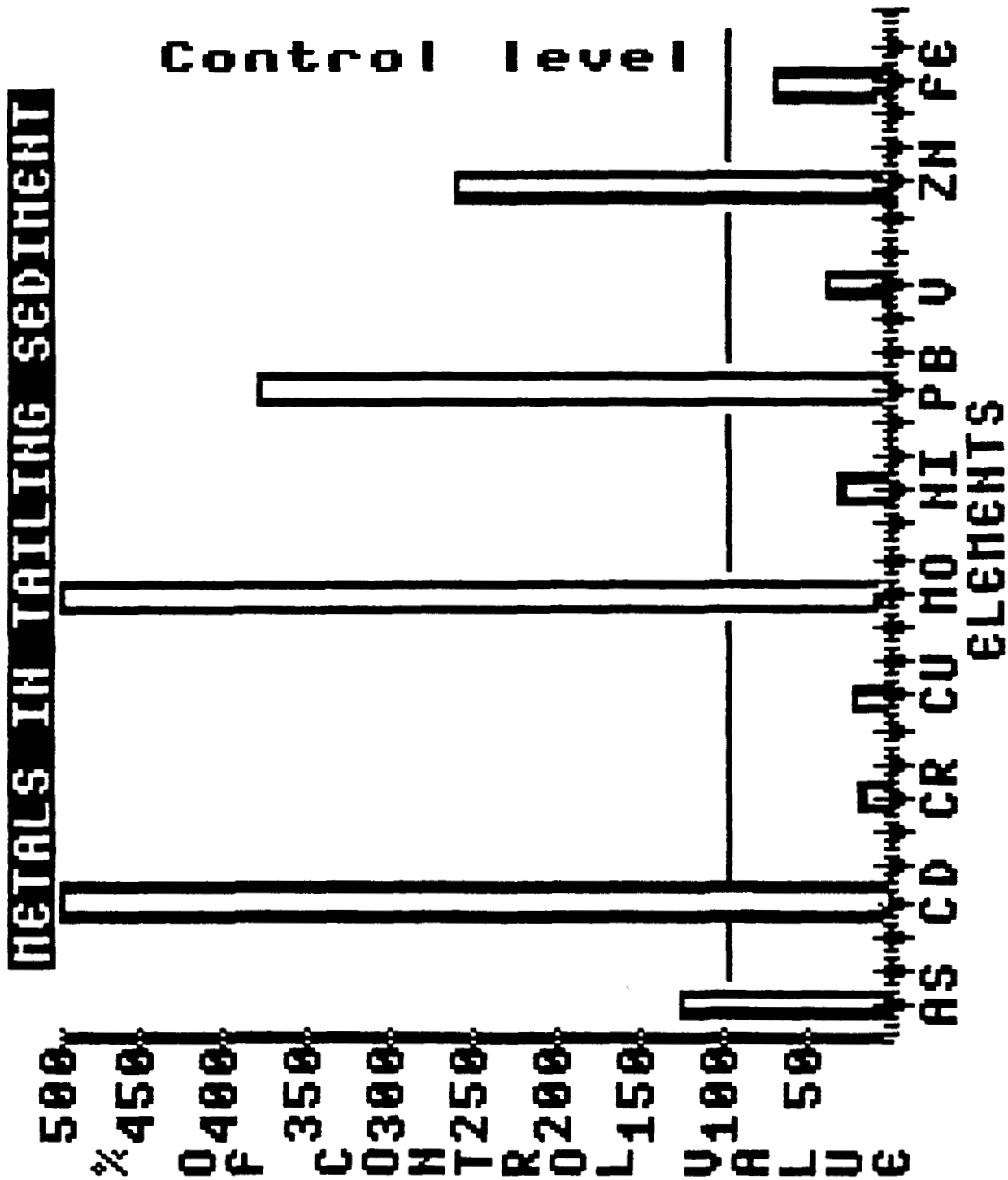


Table 17. Metal content of the Amax water and Control water (ug/l)

Metal	Contr. start	Amax start	Contr. end	Amax end	Mean Contr.	Mean Amax
As						
Cd	0.1	0.1	0.1	0.2	0.1	0.15
Cr						
Cu	0.5	0.3	1.5	1.5	1.0	0.9
Mo						
Ni	< 2	< 2	< 2	< 2	2	2
Pb	0.4	0.1	1.0	0.7	0.7	0.4
V						
Zn	1.8	1.2	2.5	< 0.2	2.2	0.7
Fe						

4.0 DISCUSSION

An extremely large variety of factors influence the bioaccumulation of metals by marine organisms. Even in a reasonably well-controlled experiment such as this one, the interaction of unknown factors can make the data more difficult to interpret. It is useful, therefore, to examine some of the more likely sources of variability prior to a detailed examination of the actual results of the study.

4.1 Sources of Variability

4.1.1 Factors influencing release from sediments

McGreer and Reid (1980), citing Lu and Chen (1977), list diffusion, desorption, dissolution, redox reaction, complex formation, biological effects, and physical disturbance as being important factors in the mobilization of trace metals from marine sediments. They also suggest that the form of the metal, the type of organic material, and salinity are important. McGreer et al. (1980) found that release of metals from mine tailings increased with increasing salinity and, in some cases, with increased dissolved oxygen. However, they concluded that metal-binding associations within the tailings were dominant in controlling release of metals.

It appears, then, that sediments may vary widely in the degree to which they bind or release metals into the water. This was clearly indicated in the comparison of mine tailings by McGreer et al. (1980).

4.1.2 Ecological and physiological characteristics

The type of habitat selected by a species and its feeding behaviour should have great effects on the degree to which it accumulates heavy metals. As noted earlier, some sediments may bind the heavy metals rather tightly and the overlying water column may not contain high levels of that metal. In such a situation, deposit-feeding organisms would be expected to accumulate more of the metal than a suspended filter-feeder. Macoma balthica, used in this study, is described as a deposit-feeder (McGreer et al., 1980). Macoma nasuta also may tend to concentrate metals from sediments since it is known to exist in heavily polluted areas and is described by Quayle (1960) as a detritus feeder.

Size of the organism is known to influence rate of bioaccumulation. Cunningham (1979) indicated that young animals generally accumulate more per gram of body weight than older animals, but there were many exceptions. This was attributed to the influence of metabolic rate. Respiratory rates in Mya arenaria and Macoma balthica decreased with increased body size (Cunningham, 1979). The organisms used in this study were selected within a narrow range of sizes for each species in order to minimize any effect that size might have. Correlation tests were performed on some of the data but no significant correlations were found between size and bioaccumulation.

Cunningham (1979) discusses the effects of sexual maturation and reproduction on bioaccumulation. Female oysters concentrated manganese to a greater extent than did the males. Also, spawning oysters showed a reduced mercury concentration in spite of continued exposure to high ambient levels of mercury. Boalch et al. (1981) cite a study by Boyden (1974) for evidence that sexual state influences concentration of trace metals in Mytilus. Boalch et al. (1981) also suggest that the health of the animals be monitored to ensure that body condition does not distort results.

4.1.3 Seasonal effects

Boalch et al. (1981) cite Boyden (1977) and Phillips (1976) as suggestive of seasonal variation in Mytilus. In their own work, Boalch et al. (1981) found a significant correlation between condition index and metal concentrations, except for copper. While seasonal trends seem to exist in their data, no overall seasonal pattern could be defined. Although efforts were made to hold the animals under relatively constant conditions, there is no way to eliminate responses to photoperiod or endogenous rhythms. Thus, seasonal trends may exist in the data from this study, but it is not possible to identify and correct for it. It is, however, useful to examine the data for Venerupis japonica for seasonal effects, since this species was maintained in the laboratory for a longer period than the other species. The data in Fig. 41 show an increase in arsenic level from June to October. This bioaccumulation could be a "seasonal" effect or it could be a response to arsenic in the control seawater. Since no data was collected on the arsenic content of the collection site or the seawater used in the experiment, it is not possible to draw any conclusions on this point. It is interesting that the arsenic level decreases significantly from October to the end of the experiment in February. Again, this is suggestive of a "seasonal" effect but cannot be positively identified as such. The sediment in the Control tank could have bound arsenic and produced the reduction observed in the tissues. Data for other elements (Figs. 42-50) suggest the possibility of seasonal effects. However, without data on sexual state, physical condition, and water chemistry, it is not possible to ascertain the cause of the observed changes.

4.2 Experimental Design

In any experiment, however well planned and executed, there are aspects of the design and data collection that limit the interpretation of the data, and these should be acknowledged.

4.2.1 Condition of the animals

No measure was made of "condition factor" such as weight/length relationships which might have permitted explanation of some of the data on the basis of seasonal or sexual changes in the animals.

4.2.2 Sampling intensity

Samples of water and sediment were taken only at the beginning and end of the experiment, and these were all single samples. The lack of replicates does not permit any estimate of variability. The small changes observed between initial and final samples might reflect real changes, but without replicate samples, this cannot be concluded safely. Thus, the writer has elected to assume that the differences are due to sampling variability and has used an average of the initial and final values as the indicator of the true experimental condition. It would be useful to have some measure of the within-sample variability for both water and sediment. Also, measurements of water, sediments, and tissues at some mid-point would have permitted use of regression techniques in the data analysis.

4.2.3 Water flow

Water flow was maintained at a slow rate or "trickle" through the tanks, but this rate was not measured. Thus, it is not possible to estimate the time required to change the tank volume. This exchange time could be important in establishing time for metals in the sediment to reach an equilibrium state with the water.

4.2.4 Control sediment

No neutral sediment was actually added to the control tanks, but sediment that collected in the tanks was allowed remain. The values for some metals were unusually high in the control sediment. Copper was particularly high, with values from 268 to 368 ug/g. By comparison, the highest copper values sampled by Chapman and Barlow (1984) in their survey of B.C. coastal areas was only 199 ug/g (from Vancouver Harbour). It is difficult to explain the accumulation of such a high concentration from the water supply alone. Chromium was also higher in the control sediment (72 to 81 ug/g) than in the highest values reported (64.2 ug/g) by Chapman and Barlow (1984) from Port Alberni.

It is possible that the high copper and chromium concentrations in the control sediment may have altered the results through some interaction with the uptake of other metals. It would have been preferable to have maintained the control animals on a clean sediment with known low levels of metals. In view of the unusually high values, it would be prudent to entertain the possibility that the control situation had been contaminated in some unknown manner.

4.3 Bioaccumulation

The data reveal a number of significant differences between Controls and Tailings groups. In several cases there are also significant differences between the initial and final control values. This is disturbing because the experimental design does not permit a more definitive conclusion about seasonal effects. If it were possible to ascribe initial-final differences in the control group to seasonal effects, it would give stronger grounds for concluding that the differences between controls and tailings groups were, in fact, due to experimental conditions. In a number of cases the tailings values are essentially the same as the initial values, with the control values being significantly different from both initial and tailings values. This type of result could be due to some effect of the control condition, such as the Control sediment, or it could be a real seasonal effect. It is desirable, in such situations, to have additional data that can indicate the mechanism by which the experimental difference occurred, or at least to help substantiate the probability that the differences are due to the experimental conditions. The most likely source of substantiation in this study would be the establishment of positive correlations between the bioaccumulation and the ambient levels of the metal. However, most of these organisms are filter-feeders and may obtain most of the metal, not from the sediments directly, but from the water column. Data on water chemistry were not collected for all metals under test. Also, since only four samples were collected and analyzed, it is difficult to determine with certainty the degree of correlation between water chemistry and sediment chemistry. The correlations based on the four sets of samples are in Table 18. The correlations varied from 0.135 for Iron to -0.858 for Zinc. Both zinc and lead were negatively correlated.

These correlation coefficients (r values) do not indicate the quantitative change of one value with respect to another, but measure the intensity of association between the variables (Zar, 1984). Regression of water on sediment indicated that none of the slopes were different from 0 at the 5% significance level. As discussed previously, a large number of factors influence the release of metals from sediments. Discussions with another researcher and a brief check of some of his unpublished data indicates that a strong correlation between sediment chemistry and water chemistry is not likely (Thompson, 1984; pers. comm.). Accordingly, it is possible to demonstrate that significant differences exist in bioaccumulation of some metals, but it is not possible to ascribe those differences definitely to the experimental conditions under test.

Data for Control and Tailings for each species and each metal were examined by linear regression. The legitimacy of such an analysis is somewhat questionable since the data provide only two points on the x-coordinate, and it is not possible to ascertain that the linear relationship is the correct one. The technique was employed to obtain an estimate of the degree of correlation between the tissue levels and sediment levels. The coefficients of determination (R-squared) obtained are in Table 19. This coefficient provides an estimate of the strength of the linear relationship.

The bioaccumulation of metals can be indicated quantitatively by the ratio of tissue metal concentrations of Tailings animals to Controls (T/C ratio). The data are summarized in this manner in Table 20.

4.3.1 Arsenic

The data for all species (except M. balthica) are presented in Fig. 52. Bioaccumulation as a result of the experimental conditions is probable in both Mya arenaria and Macoma nasuta. Venerupis had no change, and levels of arsenic decreased in Cirratulus. Tissue metal ratios (Tailings/Controls) were not large (M. nasuta = 1.7 and Mya = 2.7). Konasewich et al. (1982) indicate that arsenic is probably bioaccumulated through the water column rather than through the food chain. Arsenic was present in the tailings at a level of only 125% of the level in the control sediments, so high rates of accumulation were not anticipated. Arsenic levels in the water were not measured in this study. Konasewich et al. (1982) point out that long-term studies are required to study arsenic uptake, with continued accumulation reported past 280 days. The length of this study (approximately 100 days) may not have been long enough to measure the uptake adequately.

4.3.2 Cadmium

The combined data for all species is shown in Fig. 53. The tailings contained 40 times the amount of cadmium present in the control sediments.

Bioaccumulation due to the experimental conditions may have occurred in M. balthica and is indicated for M. nasuta with a Tailings/Control ratio of 4.3. Similar ratios for Mytilus and Yoldia exposed to Amax sediments ranged from 1.3 to 3.7 (McLeay et al., 1984). Konasewich et al. (1982) cite Luoma and Jenne (1975) in describing the uptake of cadmium by M. balthica from sediments. Cadmium was accumulated if it was not bound to organic material.

4.3.3 Chromium

The combined data for chromium are shown in Fig. 54. There is an indication of modest bioaccumulation by Mya with a Tailings/Control ratio of 1.42. Other species tested showed no change or a decrease in Chromium. Since levels of chromium in the tailings were low (14% of the control sediment level), bioaccumulation was not expected.

4.3.4 Copper

The combined data are shown in Fig. 55. None of the test species showed any bioaccumulation of copper, but Cirratulus showed significantly lower levels on the tailings sediment. These findings are consistent with the low levels of copper present in the tailings (19% of control levels).

4.3.5 Molybdenum

Combined data are shown in Fig. 56. All species except Venerupis had significantly higher tissue concentrations of molybdenum after exposure to Amax tailings. The molybdenum concentration in the tailings was 25 times the concentration in the control sediments. Tissue metal ratios ranged from 1.3 for Venerupis to 7.5 for Mya. McLeay et al. (1984) obtained tissue ratios from 1.8 to 5.5 for Mytilus and Yoldia.

4.3.6 Nickel

Combined data are shown in Fig. 57. In all test species levels were similar in the Tailings and Control conditions. The tailings sediment was low in nickel, having only 31% of the control value. There do appear to be differences between the species with regard to the "normal" level of nickel, but these differences were not tested for significance.

4.3.7 Lead

The combined data are shown in Fig. 58. The levels of lead in the tailings were approximately 4 times the level in the Control sediments. All test species except Cirratulus had significantly elevated levels of lead in the tissues. M. balthica also had increased lead levels. The tissue ratios ranged from 1.3 for Cirratulus to 14.3 for Mya. Tissue ratios of 19.2 to 24.2 were reported by McLeay et al. for Yoldia and Mytilus.

4.3.8 Vanadium

Combined data are shown in Fig. 59. Vanadium was present in the tailings at a level of 37% of the Control sediment content. Only Mya showed any tendency to concentrate vanadium, and this may be a seasonal effect rather than a response to experimental conditions.

4.3.9 Zinc

Combined data for zinc are shown in Fig. 60. Zinc levels in the tailings were 2.5 times the Control level. Both Mya and M. nasuta had elevated tissue levels of zinc. Tissue ratios were 1.3 and 1.6, indicating a moderate accumulation. This corresponds well with values for Yoldia (1.8 to 2.6) and Mytilus (1.0 to 1.5) (McLeay et al., 1984).

4.3.10 Iron

The combined data are shown in Fig. 61. Iron levels in the tailings were only 68% of the control levels. However, all species except Cirratulus had increased levels of iron after exposure to the tailings. Cirratulus levels declined. There is the possiblity that these figures reflect species differences in response to iron, or some interaction with another metal.

Table 18 Correlation coefficients for water chemistry vs sediment chemistry.

Metal	Mean Sediment (ug/g)	Mean Water (ug/l)	R	Slope of regression
As				
Cd	6.15	0.125	.587	.004
Cr				
Cu	191.8	0.950	.295	.001
Mo				
Ni				
Pb	174.5	0.550	-.483	-.002
V				
Zn	314.5	1.450	-.858	-.005
Fe	27950	2.975	.135	0

Table 19 Coefficients of determination from linear regressions of tissue metal on sediment metal

	R-squared values			
Metal	Venerupis	Cirratulus	Macoma	Mya
As	0	0.244 *	0.218 *	0.636 *
Cd	0.006	0.009	0.222 *	0.004
Cr	0.082	0.092	0.022	0.231 *
Cu	0.102 *	0.468 *	0.074	0.041
Mo	0.161 *	0.178 *	0.321 *	0.326 *
Ni	0.027	0.038	0	0.126
Pb	0.316 *	0.034	0.386 *	0.308 *
V	0.221 *	0.412 *	0.038	0.242 *
Zn	0.033	0.023	0.262 *	0.203 *
Fe	0.254 *	0.248 *	0.214 *	0.264 *

Note: * indicates that slope was significantly different from 0 at the .05 level.

Coefficient of determination indicates the proportion of total variability accounted for by regression.

Correlation Coefficients (Tissue / Sediment)

Metal	Venerupis	Cirratulus	Macoma	Mya
As	-0.007	-0.494 *	0.467 *	0.797 *
Cd	0.080	0.095	0.471 *	0.067
Cr	-0.286	0.304	0.147	-0.480 *
Cu	-0.319 *	0.684 *	-0.271	0.202
Mo	0.401 *	0.442 *	0.567 *	0.571 *
Ni	-0.165	0.196	0.013	-0.355
Pb	0.562 *	0.185	0.622 *	0.555 *
V	-0.470 *	0.642 *	-0.194	-0.491 *
Zn	0.181	-0.152	0.512 *	0.451 *
Fe	-0.504 *	0.498 *	-0.463 *	-0.514 *

Table 20 Means of tissue metal concentrations (ug/g) and tissue metal ratios (Tailings/Control) for all species and metals tested.
(* indicates Tailings concentration higher than Control)

Condition	As *	Cd *	Cr	Cu	Mo *	Ni	Pb *	V	Zn *	Fe
C.s.										
Controls	11.6	.73	.69	64.4	1.12	5.82	8.31	3.67	113	2548
Tailings	7.4	.82	3.33	28.2	2.69	4.84	11.10	1.14	105	1387
T/C	0.63	1.12	0.71	0.43	2.40	0.83	1.34	0.27	0.94	0.54
M.n.										
Controls	23.3	.49	1.82	17.8	3.01	2.17	4.89	1.03	129	397
Tailings	39.5	2.10	1.58	22.4	6.44	2.13	46.13	1.48	206	1340
T/C	1.69	4.29	0.87	1.26	2.14	0.98	9.43	1.44	1.60	3.38
Mya										
Controls	6.9	1.11	1.24	17.8	0.98	1.40	1.49	0.56	93	317
Tailings	18.8	1.16	1.76	15.3	7.34	2.09	21.27	1.40	121	1237
T/C	2.7	1.05	1.42	0.86	7.49	1.49	14.3	2.5	1.3	3.94
V.j.										
Controls	15.3	2.47	2.36	12.1	0.40	8.23	1.58	0.54	97	383
Tailings	15.3	2.58	2.62	13.7	0.52	8.95	2.77	0.70	103	538
T/C	1.0	1.04	1.11	1.13	1.3	1.09	1.75	1.30	1.06	1.40

FIG. 52 Mean levels of tissue Arsenic for all species for Initial, Controls, and Tailings (ug/g)

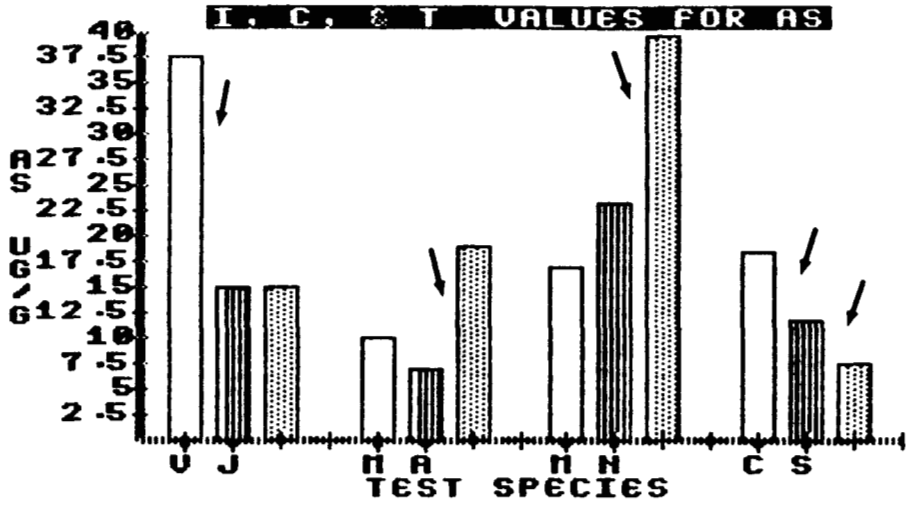


FIG. 53 Mean levels of tissue Cadmium for all species for Initial, Controls, and Tailings (ug/g)

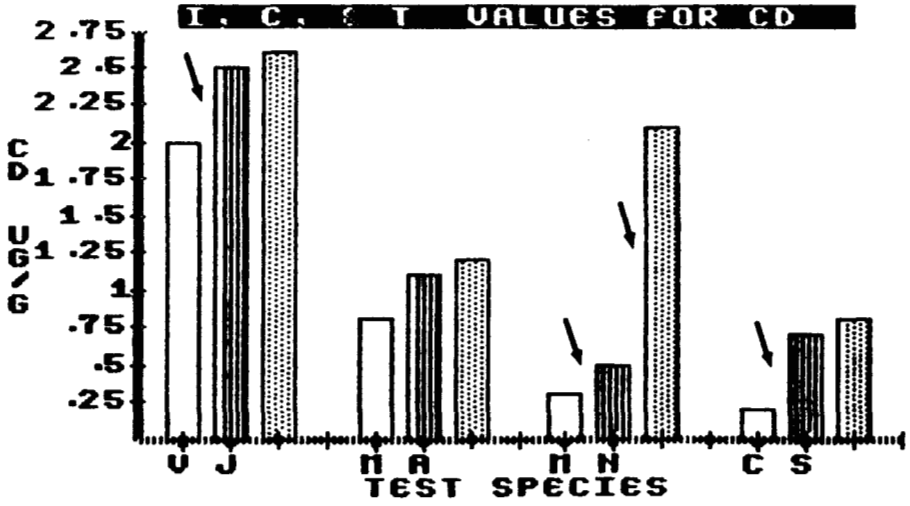


FIG. 54 Mean levels of tissue Chromium for all species for Initial, Controls, and Tailings (ug/g)

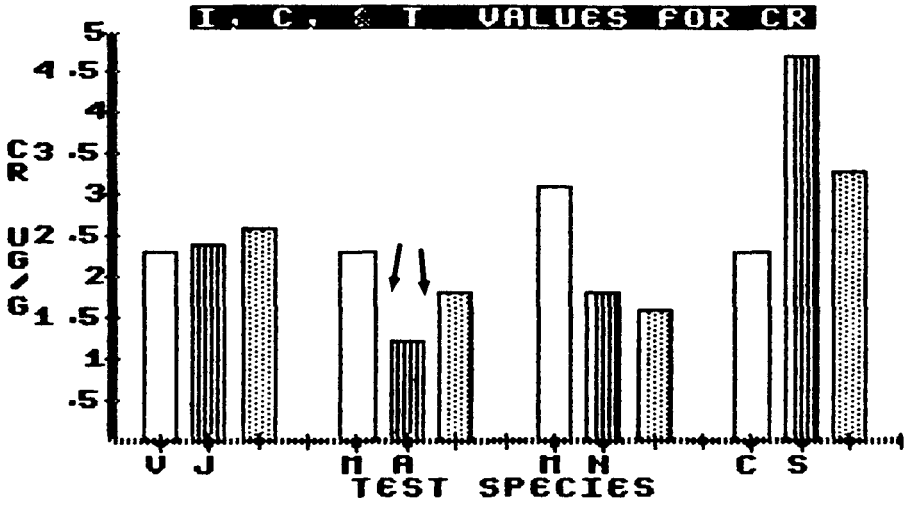


FIG. 55 Mean levels of tissue Copper for all species for Initial, Controls, and Tailings (ug/g)

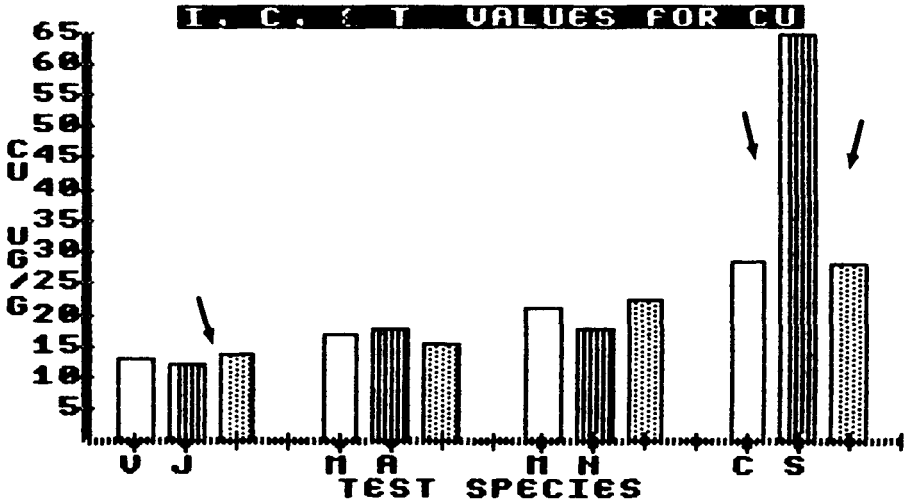


FIG. 56 Mean levels of tissue Molybdenum for all species for Initial, Controls, and Tailings (ug/g)

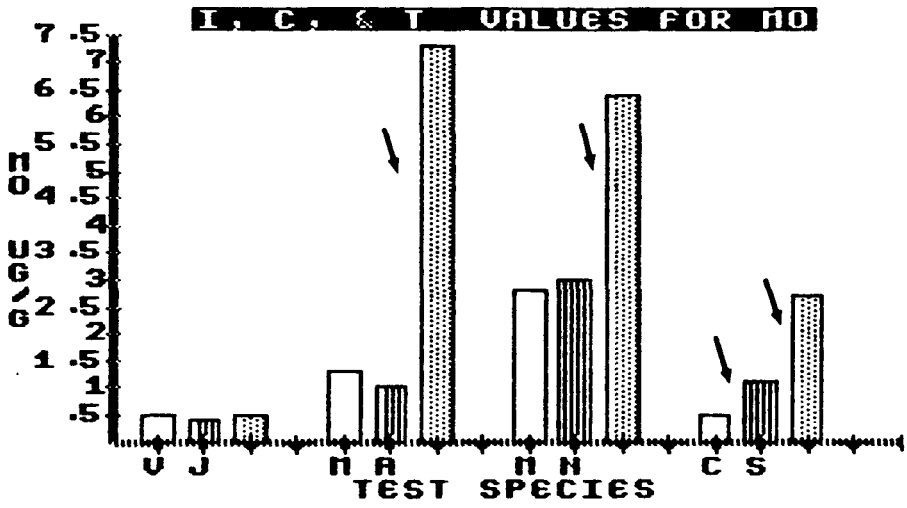


FIG. 57 Mean levels of tissue Nickel for all species for Initial, Controls, and Tailings (ug/g)

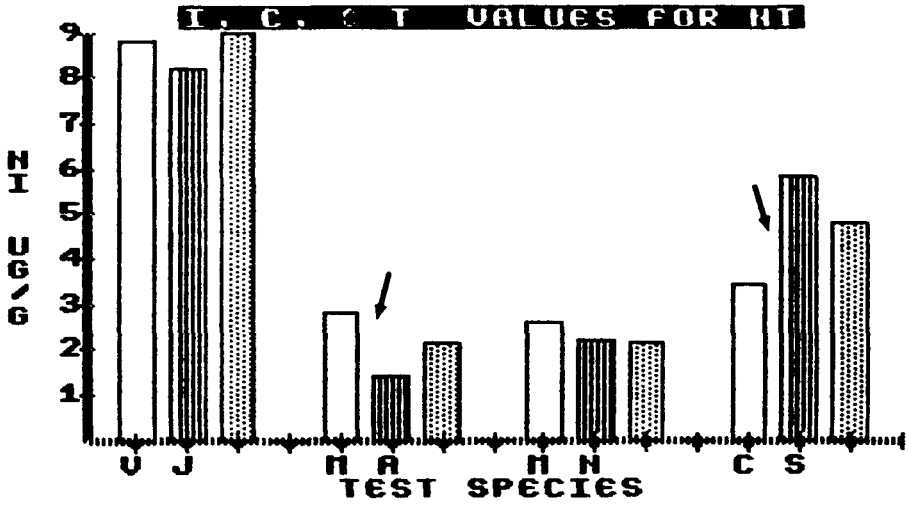


FIG. 58 Mean levels of tissue Lead for all species for Initial, Controls, and Tailings (ug/g)

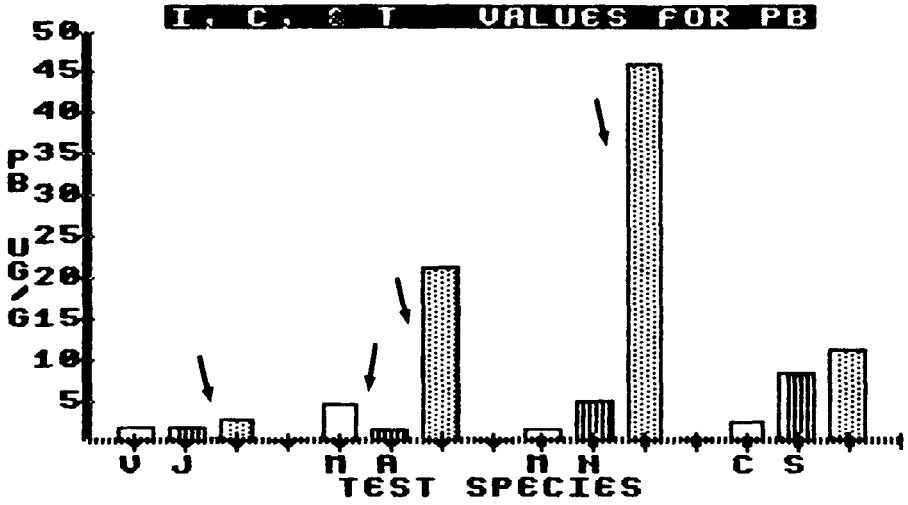


FIG. 59 Mean levels of tissue Vanadium for all species for Initial, Controls, and Tailings (ug/g)

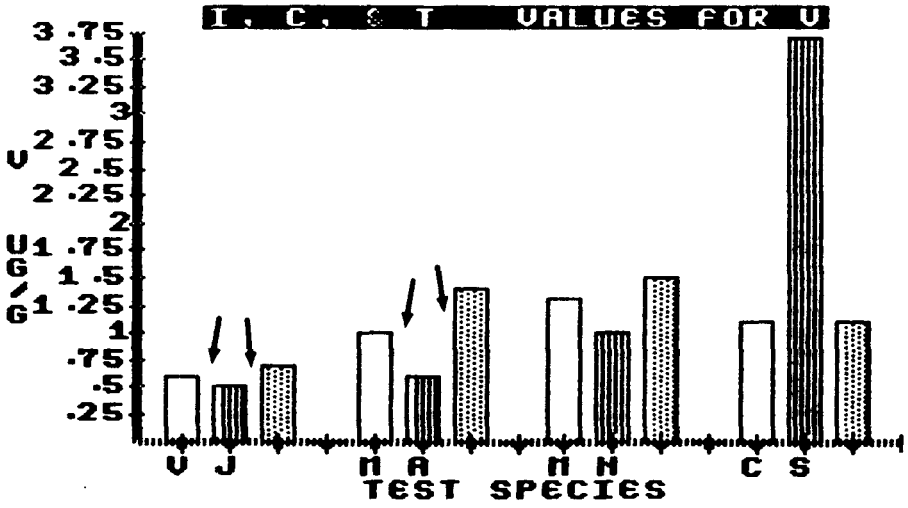


FIG. 60 Mean levels of tissue Zinc for all species for Initial, Controls, and Tailings (ug/g)

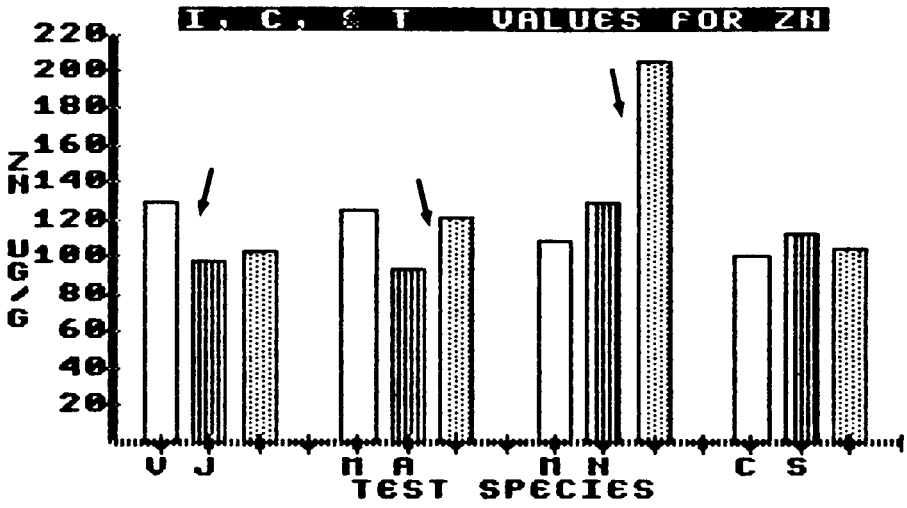
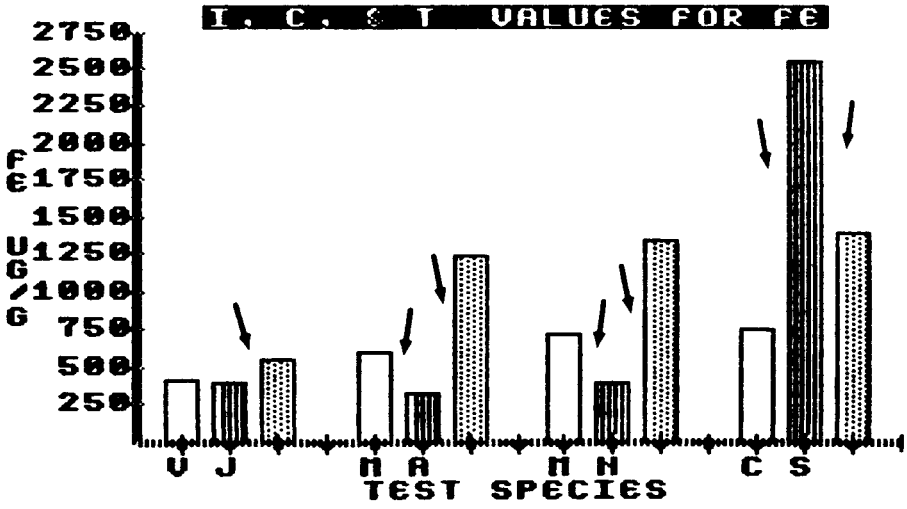


FIG. 61 Mean levels of tissue Iron for all species for Initial, Controls, and Tailings (ug/g)



5.0 SUMMARY

The test species showed great variability in their response to the test metals. Correlation coefficients for tissue metal with sediment levels varied in direction and magnitude for the test species. Cadmium, molybdenum, and lead had positive correlations for all species, but cadmium was not strongly correlated, except perhaps for Macoma. Molybdenum had the most consistent correlation, indicating that all test species had some tendency to accumulate molybdenum from the tailings. Lead showed similar values to molybdenum except for Cirratulus, which had a much weaker correlation. Iron was negatively correlated, again except for Cirratulus, indicating that the clams all tended to accumulate iron from the tailings despite its lower concentration in the tailings. The strongest correlation observed was for Mya and arsenic (0.797).

The degree of bioaccumulation over the 100-day study period was not very dramatic, with tissue levels often well below those of other studies.

Many anomolies do exist and these are ascribed tentatively to seasonal effects, species response differences, or interactions between metals (competition for uptake; inhibition of uptake; potentiation of uptake).

In view of the low correlations observed and the relatively large variability encountered, it is imperative that the data be interpreted carefully and used with some caution.

Future studies of this type should include more extensive data on water chemistry. Also, it would be advisable to include species such as Macoma balthica and Mytilus edulis which have been studied extensively by other investigators. Some regular measure of physical condition and reproductive state would be useful in interpreting the data. It is highly recommended that several samples be taken periodically between the beginning and end of the experiment. With such a design, the more powerful techniques of multiple regression could be employed during data analysis. The paper by McGreer et al. contains some additional guidance for study design.

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