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# AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR SELENIUM(IV)

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## NOTICES

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## TABLES

CONTENTS

# FOREWORD

Section 304(a)(1) of the Clean Water Act of 1977 (P.L. 95-217) requires the Administrator of the Environmental Protection Agency to publish water quality criteria that accurately reflect the latest scientific knowledge on the kind and extent of all identifiable effects on health and welfare that might be expected from the presence of pollutants in any body of water, including ground water. This document is a revision of proposed criteria based upon a consideration of comments received from other Federal agencies, State agencies, special interest groups, and individual scientists. Criteria contained in this document replace any previously published EPA aquatic life criteria for the same pollutant(s).

The term "water quality criteria" is used in two sections of the Clean Water Act, section 304(a)(1) and section 303(c)(2). The term has a different program impact in each section. In section 304, the term represents a non-regulatory, scientific assessment of ecological effects. Criteria presented in this document are such scientific assessments. If water quality criteria associated with specific stream uses are adopted by a State as water quality standards under section 303, they become enforceable maximum acceptable pollutant concentrations in ambient waters within that State. Water quality criteria adopted in State water quality standards could have the same numerical values as criteria developed under section 304. However, in many situations States might want to adjust water quality criteria developed under section 304 to reflect local environmental conditions and human exposure patterns before incorporation into water quality standards. It is not until their adoption as part of State water quality standards that criteria become regulatory.

Guidelines to assist States in the modification of criteria presented in this document, in the development of water quality standards, and in other water-related programs of this Agency, have been developed by EPA.

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## Introduction*

Selenium is distributed widely in nature, with an average crustal abundance of 9.0 µg/kg (Cooper et al. 1974; Raptis et al. 1983). The highest concentrations are found in sulfide deposits of copper, lead, mercury, silver, and zinc. Selenium also occurs as the selenide salt of several heavy metals and in such minerals as chalcopyrite, pendlandite, and pyrrhotite (Shamberger 1981). A major natural source of environmental selenium is the weathering of rocks and soils.

Selenium is abundant in fossil fuels, with concentrations in coal and fuel oil ranging from 470 to 8,100 µg/kg and from 2,400 to 7,500 µg/kg, respectively (Raptis et al. 1983). During combustion of coal, much of the selenium is converted to selenium dioxide and is emitted in the flue gases. However, when sulfur dioxide is present in the flue gas, selenium dioxide is reduced to elemental selenium (Frost and Ingvoldstad 1975). Much of the selenium emitted to the atmosphere during burning of fossil fuel is sorbed to fly ash, probably in the form of elemental selenium (Raptis et al. 1983). Although elemental selenium is insoluble and relatively nonbioavailable, it can be oxidized to selenium(IV) (Sarathchandra and Watkinson 1981) or reduced to selenides, including the highly volatile dimethyl selenide and dimethyl diselenide (Eisler 1985; Wilber 1980) by soil and aquatic microorganisms.

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* An understanding of the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses" (Stephan et al. 1985), hereafter referred to as the Guidelines, is necessary in order to understand the following text, tables, and calculations.

Selenium reaches freshwater and saltwater systems through wet and dry deposition from the air: leaching and runoff from land, particularly from regions with alkaline seleniferous soils; drainage from coal fly-ash and bottom-ash ponds: leaching from fly-ash deposits on land; discharges of industrial and domestic sewage; and remobilization from bottom sediments in aquatic systems. Concentrations of dissolved selenium in fresh ground and surface waters usually are between 0.01 and 400 μg/L (Fishbein 1984). In the North Atlantic Ocean, selenium concentrations range from 0.03 to 0.05 μg/L in the upper 500 m of the water column to 0.115 to 0.135 μg/L at a depth of 5000 m (Burton et al. 1980). In the North Pacific Ocean. the concentration of total selenium increases from 0.075 μg/L at 15 m to 0.190 μg/L at 3250 m (Cutter and Bruland 1984). Concentrations in coastal and estuarine waters are more variable. ranging from about 0.06 to 0.375 μg/L (Cutter 1978; Measures and Burton 1978: Wrench and Measures 1982).

Selenium occurs in aquatic ecosystems in four oxidation states. -2, 0. +4. and +6, which are interconverted readily in the environment through oxidation and reduction reactions (Callahan et al. 1979; Cutter 1982). Chemical equilibria are dependent on the pH and redox state of the medium. In addition, living organisms are able to synthesize a wide variety of organoselenium compounds. Because of these interactions. the biogeochemical cycle of selenium is very complex, and a combination of oxidation states and forms exists in most waters (Cutter and Bruland 1984: Measures and Burton 1978; Robberecht and Van Grieken 1982: Takayanagi and Wong 1984a.b; Uchida et al. 1980; Wrench and Measures 1982). Selenium(VI) constitutes 14 to 36% of the total selenium in the edible muscle tissue of several species of freshwater and saltwater fish (Cappon and Smith 1981). About

36% of the selenium present in freshwater plants is selenium(VI) (Eisler 1985).

Selenium is an essential trace nutrient for most, if not all, living organisms, and selenium deficiency has been found to affect humans (Frost and Ingvoldstad 1975; Raptis et al. 1983; Wilber 1983), sheep and cattle (Shamberger 1981), fish (Heisinger and Dawson 1983; Hilton et al. 1980; Poston et al. 1976), and an aquatic invertebrate (Keating and Dagbusan 1984). In addition, selenium apparently protects biota from the toxic effects of arsenic, cadmium, copper, inorganic and organic mercury, and the herbicide paraquat in both terrestrial and aquatic environments (Beijer and Jernelov 1978; Eisler 1985; Heisinger and Scott 1985; Heisinger et al. 1979; Levander 1977; Skerfving 1978; Wilber 1983; Winner 1984). Birge et al. (1979) and Huckabee and Griffith (1974), however, reported that selenium and mercury acted synergistically toward fish embryos. Heisinger (1981) found that selenium pretreatment protected 128-hr-old, but not 6-yr-old, embryos of Oryzias latipes, from cadmium and mercury, whereas prior exposure to selenium(IV) did not affect the sensitivity of white suckers to cadmium (Duncan and Klaverkamp 1983).

Because of the variety of forms of selenium(IV) and lack of definitive information about their relative toxicities, no available analytical measurement is known to be ideal for expressing aquatic life criteria for selenium(IV). Previous aquatic life criteria for selenium(IV) (U.S. EPA 1980) were expressed in terms of total recoverable selenium(IV), but the total recoverable measurement (U.S. EPA 1983a) is probably too rigorous in some situations. Acid-soluble selenium(IV) (operationally defined as the selenium(IV) that passes through a 0.45 μm membrane filter after the sample is acidified to pH = 1.5 to 2.0 with nitric acid) is probably the best measurement at the present for the following reasons:

1. This measurement is compatible with nearly all available data concerning toxicity of selenium(IV) to, and bioaccumulation of selenium(IV) by, aquatic organisms. No test results were rejected just because it was likely that they would have been substantially different if they had been reported in terms of acid-soluble selenium(IV). For example, results reported in terms of dissolved selenium(IV) would not have been used if the concentration of precipitated selenium(IV) had been substantial.
2. In samples of ambient water, measurement of acid-soluble selenium(IV) will probably measure all forms of selenium(IV) that are toxic to aquatic life or can be readily converted to toxic forms under natural conditions. In addition, this measurement probably will not measure several forms, such as selenium(IV) that is occluded in minerals, clays, and sand or is strongly sorbed to particulate matter, that are not toxic and are not likely to become toxic under natural conditions.
3. Although water quality criteria apply to ambient water, the measurement used to express criteria is likely to be used to measure selenium(IV) in aqueous effluents. Measurement of acid-soluble selenium(IV) probably will be applicable to effluents. If desired, dilution of effluent with receiving water before measurement of acid-soluble selenium(IV) might be used to determine whether the receiving water can decrease the concentration of acid-soluble selenium(IV) because of sorption.
4. The acid-soluble measurement is probably useful for most metals, thus minimizing the number of samples and procedures that are necessary.

5. The acid-soluble measurement does not require filtration at the time of collection, as does the dissolved measurement.

6. For the measurement of total acid-soluble selenium the only treatment required at the time of collection is preservation by acidification to pH = 1.5 to 2.0, similar to that required for the measurement of total recoverable selenium. Durations of 10 minutes to 24 hours between acidification and filtration probably will not affect the measurement of total acid-soluble selenium. However, acidification might not prevent conversion of selenium(IV) to selenium(VI) or vice versa. Therefore, measurement of acid-soluble selenium(IV) will probably require separation or measurement at the time of collection of the sample or special preservation to prevent conversion of one oxidation state of selenium to the other.

7. Durations of 10 minutes to 24 hours between acidification and filtration of most samples of ambient water probably will not affect the result substantially.

8. The carbonate system has a much higher buffer capacity from pH = 1.5 to 2.0 than it does from pH = 4 to 9 (Weber and Stumm 1963).

9. Differences in pH within the range of 1.5 to 2.0 probably will not affect the result substantially.

10. The acid-soluble measurement does not require a digestion step, as does the total recoverable measurement.

11. After acidification and filtration of the sample to isolate the acid-soluble selenium, the analysis can be performed using either furnace or hydride atomic absorption spectrophotometric or ICP-atomic emission spectrometric analysis for total acid-soluble selenium (U.S. EPA 1983a). It might be possible to separately measure acid-soluble selenium(IV)

and acid-soluble selenium(VI) using the methods described by Oppenheimer et al. (1984), Robberecht and Van Grieken (1982), and Uchida et al. (1980). Thus, expressing aquatic life criteria for selenium(IV) in terms of the acid-soluble measurement has both toxicological and practical advantages. On the other hand, because no measurement is known to be ideal for expressing aquatic life criteria for selenium(IV) or for measuring selenium(IV) in ambient water or aqueous effluents, measurement of both acid-soluble selenium(IV) and total recoverable selenium in ambient water or effluent or both might be useful. For example, there might be cause for concern if total recoverable selenium is much above an applicable limit for selenium(IV), even though acid-soluble selenium(IV) is below the limit.

Unless otherwise noted, all concentrations reported herein are expected to be essentially equivalent to acid-soluble selenium(IV) concentrations. All concentrations are expressed as selenium(IV), not as the chemical tested. The criteria presented herein supersede previous national aquatic life water quality criteria for selenium(IV) (U.S. EPA 1976,1980) because these new criteria were derived using improved procedures and additional information. Whenever adequately justified, a national criterion may be replaced by a site-specific criterion (U.S. EPA 1983b), which may include not only site-specific criterion concentrations (U.S. EPA 1983c), but also site-specific durations of averaging periods and site-specific frequencies of allowed excursions (U.S. EPA 1985). Comprehensive literature searches for information for this document were conducted through February, 1985; some newer information was also used.

Acute Toxicity to Aquatic Animals

The LC50 for selenium(IV) often decreases substantially with test duration. For example, Halter et al. (1980) reported LC50s for *Daphnia magna* as 710 µg/L at 2 days, 430 µg/L at 4 days, and 430 µg/L at 14 days. (Although Halter et al. (1980) did not specify the oxidation state used in their studies, Adams and Johnson (1981) state that the tests were conducted on sodium selenite.) Comparable values for the amphipod, *Hyalella azteca*, were 940 µg/L at 2 days, 340 µg/L at 4 days, and 70 µg/L at 14 days. Similarly, Adams (1976) reported that the average LC50 for rainbow trout was 4,350 µg/L at 4 days, 500 µg/L at 48 days, and 280 µg/L at 96 days. At 13°C the average LC50 for fathead minnows was 10,900 µg/L at 4 days and 1,100 at 48 days.

Adams (1976) found that the acute toxicity of selenium(IV) to the fathead minnow was directly related to water temperature with average 96-hr LC50s of 10,900 µg/L at 13°C, 6,700 µg/L at 20°C, and 2,800 µg/L at 25°C. Striped bass were more sensitive to selenium(IV) in soft than in hard water (Palawski et al. 1985). Lemly (1982) found that neither water temperature nor hardness had a significant effect on the final concentration in any tissue of centrarchids exposed to selenium(IV) for 120 days. At shorter durations, he found that both temperature and hardness influenced rates of uptake, which might cause the acute toxicity of selenium(IV) to vary with conditions of exposure.

Invertebrates are both the most sensitive and most resistant species (Table 1) with acute values ranging from 340 µg/L for *Hyalella azteca* (Halter et al. 1980) to 203,000 µg/L for the leech, *Nephelopsis obscura* (Brooke 1985). On the other hand, the acute values for fishes only range from 620 μg/L for the fathead minnow (Kimball, Manuscript) to 35,000 μg/L for the common carp (Sato et al. 1980).

Boyum (1984) reported a 48-hr LC50 of 6 μg/L for *Daphnia pulicaria*. Other species in the genus *Daphnia* were more resistant with LC50s from 450 μg/L (Boyum 1984) to 3,870 μg/L (Reading 1979; Reading and Buikema 1983), so the value of 6 μg/L is surprisingly low. Boyum (Personal communication, 14 February 1986) stated that the survival of *Daphnia pulicaria* in the lowest concentration tested was only 47 percent. Because of the high mortality at the lowest concentration, the value of 6 μg/L was not considered acceptable for use in calculating a criterion. However, the results of this and similar unreported tests by Boyum (personal communication, 14 February 1986) indicate that the LC50 for this species might be less than 100 μg/L.

Species Mean Acute Values (Table 1) were calculated as geometric means of the available acute values, and Genus Mean Acute Values (Table 3) were then calculated as geometric means of the available freshwater Species Mean Acute Values. Of the twenty-two genera for which freshwater acute values are available, the most sensitive genus, *Hyalella*, is 597 times more sensitive than the most resistant, *Nephelopsis*. The three most sensitive species are crustaceans, but the fourth most sensitive species is the fathead minnow. The range of sensitivities of the four most sensitive genera is a factor of 5. The freshwater Final Acute Value for selenium(IV) was calculated to be 370.9 μg/L using the procedure described in the Guidelines and the Genus Mean Acute Values in Table 3. The Final Acute Value is slightly higher than the acute value for the most sensitive genus.

Acute toxicity data that can be used to derive a saltwater criterion for selenium(IV) are available for eight species of invertebrates and eight species of fish that are resident in North America (Table 1). The range of acute values for saltwater invertebrates extends from 850 μg/L for adults of the copepod, Acartia tonsa, (Lussier 1986) to greater than 10,000 μg/L for embryos of the blue mussel, Mytilus edulis, (Martin et al. 1981) and embryos of the Pacific oyster, Crassostrea gigas, (Glickstein 1978; Martin et al. 1981). The range of acute values for fish is slightly broader than that for invertebrates, extending from 599 μg/L for larvae of the haddock, Melanogrammus aeglefinus to 17,350 μg/L for adults of the fourspine stickleback, Apeltes quadracus, (Cardin 1986). There was no consistent relationship between life stage of invertebrates or fish and their sensitivity to selenium(IV), and few data are available concerning the influence of temperature or salinity on the toxicity of selenium(IV) to saltwater animals. Acute tests with the copepod, Acartia tonsa, at 5 and 10°C gave similar results (Lussier 1986).

Of the 15 saltwater genera for which Genus Mean Acute Values are available (Table 3), the most sensitive genus, Melanogrammus, is nearly 29 times more sensitive than the most resistant, Apeltes. The sensitivities of the four most sensitive genera only differ by a factor of 2.1, and these four include three invertebrates and one fish, which is the most sensitive of the four. The saltwater Final Acute Value for selenium(IV) is 591.1 μg/L.

## Chronic Toxicity to Aquatic Animals

Chronic toxicity tests have been conducted on selenium(IV) with five freshwater species (Table 2), four of which are acutely sensitive species (Table 3). The rainbow trout is not only the most acutely resistant of these five species, but also is the most chronically sensitive, and thus has a much larger acute-chronic ratio than the other four species. Hodson et al. (1980) found that 47 μg/L caused a small reduction in percent hatch of rainbow trout, which is not considered unacceptable for the purposes of deriving water quality criteria. Goettl and Davies (1977) exposed rainbow trout to selenium(IV) for 27 months. They found that survival of fish exposed to 60 μg/L was similar to survival of control fish. Survival of fish exposed to 130 μg/L was about one-half that of the control and about 16 percent of these survivors were deformed as compared to no deformed control fish. However, in exposures starting with newly hatched fry, Hunn et al. (Manuscript) obtained a 60-day LC50 of 51 μg/L (Table 6). Division of this LC50 by 2 (Stephan et al. 1985) results in 25.5 μg/L, which should not cause an unacceptable level of mortality of rainbow trout.

The other four freshwater species with which chronic tests have been conducted on selenium(IV), including one fish species, are all more acutely sensitive, and more chronically resistant, than the rainbow trout. Kimball (Manuscript) conducted an early life-stage test on selenium(IV) with fathead minnows. Hatchability was not affected at any tested concentration. However, posthatch survival of fry exposed to 153 μg/L was only 68 percent of the control survival and was statistically significant ($P = 0.05$). The mean terminal length, but not weight, of fish exposed to 153 μg/L was different ($P = 0.05$) than that of control fish. Survival and growth of fish exposed to 83 μg/L were similar to those of control fish.

Kimball (Manuscript) also studied the effects of selenium(IV) on survival and reproduction of *Daphnia magna* in a 28-day renewal test. The

28-day LC50 was 240 μg/L (Table 6). Survival and reproduction of Daphnia magna exposed to 70 μg/L were similar to those of control animals. Survival at 120 μg/L was 100 percent, but reproduction, expressed as mean young per animal, was only 73 percent of that of control animals. This reduction was statistically significant ($P = 0.05$).

Owsley (1984) studied the chronic effects of selenium(IV) on Ceriodaphnia affinis. He found that concentrations from 18 to 360 μg/L did not affect survival or reproduction during the 20-day test.

Reading (1979) and Reading and Buikema (1983) reported the chronic effects of selenium(IV) on the survival, growth, and reproduction of Daphnia pulex in a 28-day renewal test. Statistical analyses were performed on 41 measures of growth and reproduction. At a concentration of 600 μg/L the number of live young in the first two broods was significantly ($P = 0.05$) reduced, and the percentage of dead young in brood 1 was significantly increased. Also, the adult length of brood 9 and total number of embryos in brood 6 was significantly greater than those of control animals. At the end of the test, survival, total number of embryos per animal, and mean brood size at 600 μg/L were equal to or greater than those of the control animals even though occasional differences were observed during the test. At a concentration of 800 μg/L there was a significant reduction in preadult mean length of molts 2 and 3, in mean number of live young in broods 1 and 2, and in the percentage of dead young in broods 1, 2, and 3. At the end of the test the mean total number of embryos and live young per adult at 800 μg/L was only about 60% that of control animals.

Data on the chronic toxicity of selenium(IV) are available for two saltwater species, the mysid, Mysidopsis bahia, and the sheepshead minnow, Cyprinodon variegatus (Table 2). The life-cycle test with Mysidopsis bahia, was started with 48-hr post-release juveniles and lasted for 28 days through production of offspring by the parental generation (Ward et al. 1981). Chronic exposure to mean measured concentrations of 320 µg/L or greater had a statistically significant effect on survival of the first generation mysids. No offspring were produced by mysids that survived exposure to 580 µg/L, and the number of offspring produced per female was significantly lower in 320 µg/L than in the control treatment. All offspring produced in all treatments survived until the end of the test. The highest exposure concentration not causing effects significantly different from the controls was 140 µg/L. The resulting chronic value for Mysidopsis bahia is 211.7 µg/L, and the acute-chronic ratio is 7.085.

An early life-stage test was performed with the sheepshead minnow, Cyprinodon variegatus (Ward et al. 1981). The test was started with newly-fertilized eggs and extended for two weeks after hatching to measure survival of the juveniles. Although exposure to selenium(IV) concentrations of 6,400 µg/L or greater did not have a statistically significant effect compared to the controls on hatching success of embryos, concentrations of 970 µg/L or greater significantly reduced survival of juveniles. The highest concentration that did not have a statistically significant effect on survival of newly hatched fish was 470 µg/L. The resulting chronic value for Cyprinodon variegatus is 675.2 µg/L and the acute-chronic ratio is 10.96 (Table 2).

Acute-chronic ratios are available for four of the five acutely most sensitive freshwater species, and these ratios range from <1.667 to 13.31 (Table 3). Although the lowest ratio is a "less than" value, the actual value is probably not too much lower. The two acute-chronic ratios that were determined with saltwater species also are within this range. The Final Acute-Chronic Ratio of 6.361 was calculated as the geometric mean of these six ratios. Division of the freshwater Final Acute Value by the Final Acute-Chronic Ratio results in a freshwater Final Chronic Value of 58.31 µg/L. However, this is higher than the 60-day LC50 of 51 µg/L calculated from the data reported by Hunn et al. (Manuscript) for rainbow trout. Thus the freshwater Final Chronic Value is lowered to 25.5 µg/L to protect this important species. The saltwater Final Chronic Value of 92.93 µg/L is quite a bit lower than the two saltwater chronic values, but neither of the species with which chronic tests have been conducted is acutely sensitive to selenium(IV).

Toxicity to Aquatic Plants

Data are available on the toxicity of selenium(IV) to seven species of freshwater algae (Table 4). Results ranged from an LC50 of 30,000 µg/L for the blue-green alga, *Anacystis nidulans* (Kumar and Prakash 1971) to 522 µg/L for incipient inhibition of the green alga, *Scenedesmus quadricauda* (Bringmann and Kuhn 1977a;1978a,b;1979;1980b). Hutchinson and Stokes (1975) reported retardation of growth of two green algae, *Chlorella vulgaris* and *Haematoccus cupensis*, by 50 µg/L and Foe and Knight (Manuscript) found that 75 µg/L decreased the dry weight of *Selenastrum capricornutum* (Table 6). Thus the sensitivities of freshwater algae to selenium(IV) cover about the same range as acute and chronic toxicities to aquatic animals. The 96-hr EC50 for the diatom, *Skeletonema costatum*, is 7,959 µg/L, based on reduction in chlorophyll a (Table 4). Growth of *Chlorella* sp., *Platymonas subcordiformis*, and *Fucus spiralis* increased at selenium(IV) concentrations from 10 to 10,000 µg/L (Table 6). These data suggest that saltwater plants will not be adversely affected by concentrations that do not affect saltwater animals.

## Bioaccumulation

Bioconcentration factors (BCFs) measured with freshwater species range from a high of 452 for the bluegill (Lemly 1982) to a low of 2 for the muscle of rainbow trout (Adams 1976). Adams (1976) studied both uptake and elimination of selenium-75 by fathead minnows at average concentrations of 12, 24 and 50 µg/L. He found that accumulation occurred in a curvilinear manner in the whole fish and in individual tissues at a rapid rate during the first eight days and at a slower rate for the next 88 days. Equilibrium was approached, but not reached, in 96 days. The highest concentrations were found in the viscera, possibly due to uptake of selenium adhering to food. Elimination of selenium also followed a curvilinear plot and became asymptotic with the time axis after 96 days. Elimination was most rapid from the viscera, with a half-life of 5.1 days, but the half-life exceeded 50 days for other tissues.

Adams (1976) also conducted uptake studies with rainbow trout exposed to selenium(IV) at concentrations ranging from 310 to 950 µg/L. Some of the trout died, and concentrations were somewhat higher in dead fish than in survivors. As with the fathead minnow, the viscera contained more selenium than did gill or muscle. Based on his tests with the two species, Adams (1976) concluded that there is an inverse relationship between BCF and the concentration of selenium(IV) in water.

Hodson et al. (1980) exposed rainbow trout to selenium(IV) from fertilization until 44 weeks posthatch. At 53 µg/L in the water the BCF ranged from 8 for whole body to 240 for liver. They concluded that selenium in tissue did not increase in proportion to selenium(IV) in water.

Barrows et al. (1980) exposed bluegills to selenious acid for 28 days. They reported a maximum BCF in the whole fish of 20 and a tissue half-life of between one and seven days. If bluegills bioconcentrate selenium the same as the rainbow trout tested by Adams (1976), the 28-day exposure was probably not long enough to reach steady-state.

Lemly (1982) exposed bluegills and largemouth bass to 10 µg/L for 120 days to determine the dynamics of uptake, retention, and elimination in waters of different hardness and temperature. For bluegills, the geometric mean whole-body BCF at 20 and 30°C was 452. For largemouth bass in similar tests, the BCF was 295. For both species, the spleen, liver, kidney, and heart had higher concentrations than the whole body. Neither water temperature nor hardness had a significant effect on concentrations in tissue after 90 days, although earlier values were influenced. After 30 days in clean water, selenium concentrations remained unchanged in spleen, liver, kidney, and white muscle, but the half-life in gills and erythrocytes was less than 15 days.

Ingestion of food organisms that had been exposed to selenium(IV) can be an important source of exposure of fish to selenium (Hodson and Hilton 1983; Sandholm et al. 1973; Turner and Swick 1983). Lemly (1985a) reported bioaccumulation factors (BAFs) of 485 to 2,019 for various taxa, although the organisms might have been exposed to a combination of selenium(IV) and selenium(VI). Addition of selenium(IV) to food reduced survival of rainbow trout (Goettl and Davies 1977).

Steady-state BCFs with two saltwater species ranged from 2.88 in chela muscle of adult shore crab, Carcinus maenas (Bjerregaard 1982) to 200 in whole adult euphausiids, Meganyctiphanes norvegica (Fowler and Benayoun 1976a). Selenium was accumulated to a higher concentration in gill than in hepatopancreas or muscle of the shore crab during exposure to 250 µg/L. The author suggested that much of the selenium associated with the gill might be sorbed to the gill surface. For the euphausiid, the BAF for selenium(IV) from food plus water was four times higher than the BCF (uptake from water alone).

No U.S. FDA action level or other maximum acceptable concentration in tissue is available for selenium, and, therefore, no Final Residue Value can be calculated.

Other Data

Bringmann and Kuhn (1959a,b;1976;1977a;1979;1980b;1981) and Patrick et al. (1975) reported the concentrations of selenium(IV) that caused incipient inhibition (defined variously, such as the concentration resulting in a 3% reduction in growth) for algae, bacteria, and protozoans (Table 6). Although incipient inhibition might be statistically significant, its ecological importance is unknown. Selenium(IV) at a concentration of 100 µg/L did not affect crustacean communities in enclosures in a lake contaminated by mercury (Salki et al. 1985).

Winner (1984) reported that selenium(IV) reduced the chronic toxicity of copper to *Daphnia pulex*. Klaverkamp et al. (1983) found that 1 and 10 µg/L reduced uptake of mercury by northern pike, *Esox lucius*, whereas 100 µg/L had no effect. Hodson et al. (1980) found delayed mortality during a 4-day period following cessation of exposure to selenium(IV). Severe reproductive and developmental abnormalities have been reported in aquatic birds nesting in selenium-contaminated irrigation drainwater ponds in the San Joaquin Valley in California (Ohlendorf et al. Manuscript).

Field studies on bodies of water that are either naturally or artificially high in selenium have indicated that selenium might be more toxic to various species of freshwater fish than observed in traditional chronic tests. Several of the studies have concerned Belews Lake in North Carolina (e.g., Cumbie and Van Horn 1978; Finley 1985; Lemly 1985a,b; Sorensen et al. 1984), but other bodies of water studied include Martin Lake in Texas (e.g., Sorensen and Bauer 1984a,b; Sorensen et al. 1982), Twin Buttes and 9-Mile in Wyoming (Kaiser et al. 1979), a drainage system in South Carolina (Cherry et al. 1976,1979), and the Kesterson Reservoir in California (Ohlendorf et al. Manuscript). Such studies, however, have provided circumstantial, rather than definitive, data on the effects of selenium on aquatic life for two major reasons:

1. The studies provide little, if any, data on the oxidation state of the selenium in the water. Because there are, as yet, no data to show that selenium(IV) and selenium(VI) are toxicologically or ecologically equivalent, it is difficult to interpret the results of field studies that do not use analytical methods (e.g., Oppenheimer et al. 1984; Robberecht and Van Grieken 1982; Uchida et al. 1980) that can separately measure selenium(IV) and selenium(VI).
2. Unless the addition of the test material is under the control of the investigator, rarely can a field study conclusively pinpoint the cause of the observed effects, because of the possibility that the observed effects were caused by a combination of agents or by an unmeasured agent. However, if circumstantial evidence from a number of dissimilar situations points in the same direction, the inference becomes stronger.

In spite of the limitations of the available results of field studies, they do raise important questions, such as:

a. What are the highest concentrations in water of selenium(IV), selenium(VI), and combinations of the two that do not unacceptably reduce reproduction, and survival of the resulting young, of sensitive warmwater fishes?

b. What are the relative toxicities of selenium(IV) and selenium(VI) in food and in water and are the two sources additive?

c. Are selenium(IV) and selenium(VI) toxicologically or ecologically equivalent in aquatic ecosystems?

Such questions are important and can be answered with properly designed field and laboratory studies.

Unused Data

Some data on the effects of selenium(IV) on aquatic organisms were not used because the studies were conducted with species that are not resident in North America (e.g., Asanullah and Palmer 1980; Fowler and Benayoun 1976b,c; Gotsis 1982; Niimi and LaHam 1975,1976; Wrench 1978). Results (e.g., Okasako and Siegel 1980) of tests conducted with brine shrimp, *Artemia* sp., were not used because these species are from a unique saltwater environment. Data were also not used if selenium(IV) was a component of a mixture, effluent, sludge, or a fly ash (e.g., Burton et al. 1983; Cherry et al. 1976,1979; Fava et al. 1985; Finley 1985; Jay and Muncy 1979; Ryther et al. 1979; Sorensen et al. 1982; Thomas et al. 1980b; Wong and Beaver 1981; Wong et al. 1982).

Adams and Johnson (1981), Beijer and Jernelov (1978), Biddinger and Gloss (1984), Chapman et al. (1968), Davies (1978), Dorney (1985), Eisler (1985), Hall and Burton (1982), Hodson and Hilton (1983), Jenkins (1980), National Academy of Sciences (1976), Phillips and Russo (1978), Raptis et al. (1983), Shamberger (1981), and Thompson et al. (1972) only contained data that had been published elsewhere. Data were not used if the organisms were exposed to selenium(IV) by gavage (e.g., Kleinow 1984; Kleinow and Brooks 1986a,b) or injection (e.g., Sheline and Schmidt-Nielson 1977). Braddon (1982) and Freeman and Sangalong (1977) only exposed enzymes or tissue extracts. Results were not used if the test procedures, test material, or results were not adequately described (e.g., Bovee 1978; Nassos 1980). Kaiser (1980) calculated the toxicity to Daphnia magna based on physio-chemical parameters. The daphnids were probably stressed by crowding in the tests reported by Schultz et al. (1980). Siebers and Ehlers (1979) exposed too few test organisms.

Reports of the concentrations of selenium in wild aquatic organisms (e.g., Fowler et al. 1975; Greig and Jones 1976; Heit and Klusek 1985; Kaiser et al. 1979; Lowe et al. 1985; Lucas et al. 1970; Lytle and Lytle 1982; Mehrle et al. 1982; Okazaki and Panietz 1981; Pakkala et al. 1972; Rudd and Turner 1983a,b; Rudd et al. 1980; Seelye 1982; Sorensen 1984a,b,c; Uthe and Bligh 1971) were not used to calculate bioaccumulation factors due to the absence or insufficient number of measurements of selenium(IV) in water.

## Summary

Acute values for 23 freshwater species in 22 genera range from 340 µg/L for the amphipod, Hyalella azteca, to 203,000 µg/L for the leech, Nephelopsis obscura. Although twelve of the twenty-three species are fishes, both the three most sensitive and the four most resistant species are invertebrates. Chronic values are available for two fishes and three invertebrates. The chronic values for the rainbow trout, fathead minnow, and Daphnia magna are between 88 and 113 µg/L, but those for two other cladocerans are above 300 µg/L. In a separate test, a 60-day LC50 of 51 µg/L was obtained with

rainbow trout. The acute-chronic ratios for the four acutely sensitive species are below 15.

Toxicity values for nine species of freshwater algae range from 50 to 30,000 µg/L. Uptake of selenium(IV) by fish takes about 100 days to reach steady-state and bioconcentration factors as high as 452 have been reported. Studies of bodies of water that contain high concentrations of selenium suggest that consumption of contaminated food contributes to decreased survival and reproduction of vartiety of warmwater fishes.

Acute toxicity values are available for 16 species of saltwater animals, including 8 invertebrates and 8 fishes, and range from 599 µg/L for larvae of the haddock, Melanogrammus aeglefinus, to 17,350 µg/L for adults of the fourspine stickleback, Apeltes quadracus. Fish and invertebrates have similar sensitivities, and the acute values for the seven most sensitive species only differ by a factor of 3.2. There was no consistent relationship between life stage of invertebrates or fish and their sensitivity to selenium(IV).

Chronic toxicity data are available for two saltwater animals, the mysid, Mysidopsis bahia, and the sheepshead minnow, Cyprinodon variegatus. The chronic values and the acute-chronic ratios are 211.7 µg/L and 7.274 for the mysid, and 675.2 µg/L and 10.96 for the sheepshead minnow. At a concentration of 7,959 µg/L, selenium(IV) caused a 50% reduction in chlorophyll a in a test with the saltwater diatom, Skeletonema costatum, but growth of three species of algae was stimulated by concentrations of 10 to 10,000 µg/L. The steady-state bioconcentration factors for two saltwater species range from 2.88 in chela muscle of adult shore crabs, Carcinus maenas, to 200 in whole adult euphausiids, Meganyctiphanes norvegica.

## National Criteria

The procedures described in the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses" indicate that, except possibly where a locally important species is very sensitive, freshwater aquatic organisms and their uses should not be affected unacceptably if the four-day average concentration of acid-soluble selenium(IV) does not exceed 26 µg/L more than once every three years on the average and if the one-hour average concentration does not exceed 190 µg/L more than once every three years on the average. If species such as the channel catfish and various sunfishes are as sensitive as some field data indicate they might be, the four-day average should be less than 10 µg/L.

The procedures described in the "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses" indicate that, except possibly where a locally important species is very sensitive, saltwater aquatic organisms and their uses should not be affected unacceptably if the four-day average concentration of acid-soluble selenium(IV) does not exceed 93 µg/L more than once every three years on the average and if the one-hour average concentration does not exceed 300 µg/L more than once every three years on the average. If selenium(IV) is more toxic to saltwater organisms in the field than in the laboratory, this criterion will not adequately protect saltwater organisms.

EPA believes that "acid-soluble" is probably the best measurement at present for expressing criteria for metals and the criteria for selenium(IV) were developed on this basis. However, at this time, no EPA approved method for such a measurement is available to implement criteria for metals through the regulatory programs of the Agency and the States. The Agency is considering development and approval of a method for a measurement such as "acid-soluble." Until one is approved, however, EPA recommends applying criteria for metals using the total recoverable method. This has two impacts: (1) certain species of some metals cannot be measured because the total recoverable method cannot distinguish between individual oxidation states, and (2) in some cases these criteria might be overly protective when based on the total recoverable method.

The allowed average excursion frequency of three years is the Agency's best scientific judgment of the average amount of time it will take an unstressed aquatic ecosystem to recover from a pollution event in which exposure to selenium(IV) exceeds the criterion. Stressed systems, for example one in which several outfalls occur in a limited area, would be expected to require more time for recovery. The resiliencies of ecosystems and their abilities to recover differ greatly, however, and site-specific criteria may be established if adequate justification is provided.

Use of criteria for developing water quality-based permit limits and for designing waste treatment facilities requires selection of an appropriate wasteload allocation model. Dynamic models are preferred for the application of these criteria. Limited data or other considerations might make their use impractical, in which case one must rely on a steady-state model. The Agency recommends interim use of 1Q5 and 1Q10 for the Criterion Maximum Concentration (CMC) design flow and 7Q5 and 7Q10 for the Criterion Continuous Concentration (CCC) design flow in steady-state models for unstressed and stressed systems, respectively. These matters are discussed in more detail in the Technical Support Document for Water Quality-Based Toxics Control (U.S. EPA 1985).

Table 1. Acute Toxicity of Selenium(IV) to Aquatic Animals

| Species | Method* | Chemical | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|
| | | FRESHWATER SPECIES | | | |
| Hydra (adult), *Hydra* sp. | S, M | Sodium selenite | 1,700 | 1,700 | Brooke 1985 |
| Leech (adult), *Nephelopsis obscura* | S, M | Sodium selenite | 203,000 | 203,000 | Brooke 1985 |
| Snail (adult), *Aplexa hypnorum* | S, M | Sodium selenite | 53,000 | - | Brooke 1985 |
| Snail (adult), *Aplexa hypnorum* | S, M | Sodium selenite | 23,000 | 34,910 | Brooke 1985 |
| Snail, *Physa* sp. | S, U | Sodium selenite | 24,100 | 24,100 | Reading 1979 |
| Cladoceran, *Ceriodaphnia affinis* | S, U | Sodium selenite | 600 | 600 | Owsley 1984 |
| Cladoceran, *Daphnia magna* | S, U | Sodium selenite | 2,500 | - | Bringmann and Kuhn 1959a |
| Cladoceran, *Daphnia magna* | S, U | Selenious acid*** | 430 | - | LeBlanc 1980 |
| Cladoceran, *Daphnia magna* | S, M | Sodium selenite | 1,100 | - | Dunbar et al. 1983 |
| Cladoceran, *Daphnia magna* | S, M | Sodium selenite | 430 | - | Boyum 1984 |
| Cladoceran, *Daphnia magna* | S, M | Selenious acid | 1,220 | - | Kimball, Manuscript |
| Cladoceran, *Daphnia magna* | S, M | Selenious acid | 1,220 | 961.9 | Kimball, Manuscript |
| Cladoceran, *Daphnia pulex* | S, M | Sodium selenite | 3,870 | 3,870 | Reading 1979; Reading and Buikema 1983 |

Table 1. (Continued)

| Species | Method[*] | Chemical | LC50 or EC50 (µg/L)[**] | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|
| Ostracod, *Cyclocypris* | S, U | Sodium selenite | 130,000 | 130,000 | Owsley 1984 |
| Amphipod (adult), *Gammarus pseudolimnaeus* | S, M | Sodium selenite | 4,300 | 4,300 | Brooke 1985 |
| Amphipod, *Hyalella azteca* | F, M | Sodium selenite | 340 | 340 | Halter et al. 1980 |
| Midge, *Tanytarsus dissimilis* | F, M | Selenium dioxide | 42,500 | 42,500 | Call et al. 1983 |
| Rainbow trout, *Salmo gairdneri* | S, U | Sodium selenite | 4,500 | - | Adams 1976 |
| Rainbow trout, *Salmo gairdneri* | S, U | Sodium selenite | 4,200 | - | Adams 1976 |
| Rainbow trout, *Salmo gairdneri* | S, U | Sodium selenite | 2,700 | - | Adams 1976 |
| Rainbow trout, *Salmo gairdneri* | S, U | Sodium selenite | 2,750 | - | Adams 1976 |
| Rainbow trout, *Salmo gairdneri* | -, - | Sodium selenite | 1,800 | - | Hunn et al. Manuscript |
| Rainbow trout, *Salmo gairdneri* | F, M | Sodium selenite | 12,500 | - | Goettl and Davies 1976 |
| Rainbow trout, *Salmo gairdneri* | F, M | Sodium selenite | 7,200 | - | Hodson et al. 1980 |
| Rainbow trout, *Salmo gairdneri* | F, M | Sodium selenite | 8,200 | - | Hodson et al. 1980 |
| Rainbow trout, *Salmo gairdneri* | F, M | Sodium selenite | 8,800 | 8,977 | Hodson et al. 1980 |
| Brook trout (adult), *Salvelinus fontinalis* | F, M | Selenium dioxide | 10,200 | 10,200 | Cardwell et al. 1976a,b |

Table 1. (Continued)

| Species | Method* | Chemical | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|
| Goldfish, *Carassius auratus* | F, M | Selenium dioxide | 26,100 | 26,100 | Cardwell et al. 1976a,b |
| Common carp, *Cyprinus carpio* | R, U | - | 35,000 | 35,000 | Sato et al. 1980 |
| Fathead minnow, *Pimephales promelas* | S, U | Sodium selenite | 10,500 | - | Adams 1976 |
| Fathead minnow, *Pimephales promelas* | S, U | Sodium selenite | 11,300 | - | Adams 1976 |
| Fathead minnow, *Pimephales promelas* | S, U | Sodium selenite | 6,000 | - | Adams 1976 |
| Fathead minnow, *Pimephales promelas* | S, U | Sodium selenite | 7,400 | - | Adams 1976 |
| Fathead minnow, *Pimephales promelas* | S, U | Sodium selenite | 3,400 | - | Adams 1976 |
| Fathead minnow, *Pimephales promelas* | S, U | Sodium selenite | 2,200 | - | Adams 1976 |
| Fathead minnow (30-day old), *Pimephales promelas* | S, M | Sodium selenite | 1,700 | - | Brooke 1985 |
| Fathead minnow (fry), *Pimephales promelas* | F, M | Selenium dioxide | 2,100 | - | Cardwell et al. 1976a,b |
| Fathead minnow (juvenile), *Pimephales promelas* | F, M | Selenium dioxide | 5,200 | - | Cardwell et al. 1976a,b |
| Fathead minnow, *Pimephales promelas* | F, M | Selenious acid | 620 | - | Kimball, Manuscript |
| Fathead minnow, *Pimephales promelas* | F, M | Selenious acid | 970 | 1,601 | Kimball, Manuscript |

Table 1. (Continued)

| Species | Method* | Chemical | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|
| White sucker, *Catostomus commersoni* | F, M | Sodium selenite | 29,000 | - | Klaverkamp et al. 1983 |
| White sucker, *Catostomus commersoni* | F, M | Sodium selenite | 31,400 | 30,180 | Duncan and Klaverkamp 1983 |
| Striped bass (63-day), *Morone saxatilis* | S, U | Sodium selenite | 1,325 | - | Palawski et al. 1985 |
| Striped bass (63-day), *Morone saxatilis* | S, U | Sodium selenite | 2,400 | 1,783 | Palawski et al. 1985 |
| Channel catfish (juvenile), *Ictalurus punctatus* | S, M | Sodium selenite | 16,000 | - | Brooke 1985 |
| Channel catfish, *Ictalurus punctatus* | F, M | Selenium dioxide | 13,600 | 13,600 | Cardwell et al. 1976a,b |
| Flagfish, *Jordanella floridae* | F, M | Selenium dioxide | 6,500 | 6,500 | Cardwell et al. 1976a,b |
| Mosquitofish, *Gambusia affinis* | S, U | Sodium selenite | 12,600 | 12,600 | Reading 1979 |
| Bluegill (juvenile), *Lepomis macrochirus* | S, M | Sodium selenite | 12,000 | - | Brooke 1985 |
| Bluegill, *Lepomis macrochirus* | F, M | Selenium dioxide | 28,500 | 28,500 | Cardwell et al. 1976a,b |
| Yellow perch, *Perca flavescens* | F, M | Sodium selenite | 11,700**** | 11,700 | Klaverkamp et al. 1983 |

Table 1. (Continued)

| Species | Method[a] | Chemical | Salinity (g/kg) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| | | | SALTWATER SPECIES | | | |
| Blue mussel (embryo), *Mytilus edulis* | S, U | Selenium oxide | 33.79 | >10,000 | >10,000 | Martin et al. 1981 |
| Pacific oyster (embryo), *Crassostrea gigas* | S, U | Selenium oxide | 33.79 | >10,000 | - | Glickstein 1978; Martin et al. 1981 |
| Pacific oyster (embryo), *Crassostrea gigas* | S, U | Sodium selenite | 33.79 | >10,000 | >10,000 | Glickstein 1978 |
| Copepod (adult), *Acartia clausi* | S, U | Selenious acid | 30 (5°C) | 1,738 | - | Lussier 1986 |
| Copepod (adult), *Acartia clausi* | S, U | Selenious acid | 30 (10°C) | 2,100 | 1,910 | Lussier 1986 |
| Copepod (adult), *Acartia tonsa* | S, U | Selenious acid | 30 | 850 | 850 | Lussier 1986 |
| Mysid (juvenile), *Mysidopsis bahia* | S, U | Selenious acid | - | 600 | - | U.S. EPA 1978 |
| Mysid (juvenile), *Mysidopsis bahia* | F, M | Selenious acid | 15-20 | 1,500 | 1,500 | Ward et al. 1981 |
| Brown shrimp (juvenile), *Penaeus aztecus* | S, U | Sodium selenite | 30 | 1,200 | 1,200 | Ward et al. 1981 |
| Dungeness crab (zoeae I larva), *Cancer magister* | S, U | Selenium oxide | 33.79 | 1,040 | 1,040 | Glickstein 1978 |
| Blue crab (juvenile), *Callinectes sapidus* | S, U | Sodium selenite | 30 | 4,600 | 4,600 | Ward et al. 1981 |
| Haddock (larva), *Melanogrammus aeglefinus* | S, U | Selenious acid | 30 | 599 | 599 | Cardin 1986 |
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | S, U | Selenious acid | - | 6,700 | - | Heitmuller 1981 |

Table 1. (Continued)

| Species | Method* | Chemical | Salinity (g/kg) | LC50 or EC50 (µg/L)** | Species Mean Acute Value (µg/L) | Reference |
|---|---|---|---|---|---|---|
| Sheepshead minnow (juvenile), *Cyprinodon variegatus* | F, M | Sodium selenite | 30 | 7,400 | 7,400 | Ward et al. 1981 |
| Atlantic silverside (juvenile), *Menidia menidia* | S, U | Selenious acid | 30 | 9,725 | 9,725 | Cardin 1986 |
| Fourspine stickleback (adult), *Apeltes quadracus* | S, U | Selenious acid | 30 | 17,350 | 17,350 | Cardin 1986 |
| Striped bass, *Morone saxatilis* | S, U | Sodium selenite | - | 1,550 | 1,550 | Palawski et al. 1985 |
| Pinfish (juvenile), *Lagodon rhomboides* | S, U | Sodium selenite | - | 4,400 | 4,400 | Ward et al. 1981 |
| Summer flounder (embryo), *Paralichthys dentatus* | S, U | Selenious acid | 30.2 | 3,497 | 3,497 | Cardin 1986 |
| Winter flounder (larva), *Pseudopleuronectes americanus* | S, U | Selenious acid | 30 | 14,240 | - | Cardin 1986 |
| Winter flounder (larva), *Pseudopleuronectes americanus* | S, U | Selenious acid | 28 | 15,070 | 14,650 | Cardin 1986 |

* S = static; R = renewal; F = flow-through; M = measured, U = unmeasured.

** Results are exposed as selenium, not as the chemical.

*** Reported by Barrows et al. (1980) in work performed in the same laboratory under the same contract.

**** Calculated from regression equation.

Table 2. Chronic Toxicity of Selenium(IV) to Aquatic Animals

| Species | Test* | Chemical | Limits (µg/L)** | Chronic Value (µg/L) | Reference |
|---|---|---|---|---|---|
| | | **FRESHWATER SPECIES** | | | |
| Cladoceran, *Ceriodaphnia affinis* | LC | Sodium selenite | >360*** | >360 | Owsley 1984 |
| Cladoceran, *Daphnia magna* | LC | Selenious acid | 70-120 | 91.65 | Kimball, Manuscript |
| Cladoceran, *Daphnia pulex* | LC | Sodium selenite | 600-800 | 692.8 | Reading 1979; Reading and Buikema 1983 |
| Rainbow trout, *Salmo gairdneri* | LC | Sodium selenite | 60-130 | 88.32 | Goettl and Davies 1977 |
| Rainbow trout, *Salmo gairdneri* | ELS | Sodium selenite | >47*** | >47 | Hodson et al. 1980 |
| Fathead minnow, *Pimephales promelas* | ELS | Selenious acid | 83-153 | 112.7 | Kimball, Manuscript |
| | | **SALTWATER SPECIES** | | | |
| Mysid, *Mysidopsis bahia* | LC | Selenious acid | 140-320 | 211.7 | Ward et al. 1981 |
| Sheepshead minnow, *Cyprinodon variegatus* | ELS | Sodium selenite | 470-970 | 675.2 | Ward et al. 1981 |

* LC = life-cycle or partial life-cycle; ELS = early life-stage.

** Results are based on measured concentrations of selenium.

*** None of the tested concentrations caused effects that were considered unacceptable.

Table 2 (continued)

**Acute-Chronic Ratio**

| Species | Acute Value (µg/L) | Chronic Value (µg/L) | Ratio |
|---|---|---|---|
| Cladoceran, *Ceriodaphnia affinis* | 600 | >360 | <1.667 |
| Cladoceran, *Daphnia magna* | 1,220 | 91.65 | 13.31 |
| Cladoceran, *Daphnia pulex* | 3,870 | 692.8 | 5.586 |
| Rainbow trout, *Salmo gairdneri* | 12,500 | 88.32 | 141.5 |
| Rainbow trout, *Salmo gairdneri* | 8,039* | >47 | <171.0 |
| Fathead minnow, *Pimephales promelas* | 775.5** | 112.7 | 6.881 |
| Mysid, *Mysidopsis bahia* | 1,500 | 211.7 | 7.085 |
| Sheepshead minnow, *Cyprinodon variegatus* | 7,400 | 675.2 | 10.96 |

* Geometric mean of three values in Table 1.

** Geometric mean of two values in Table 1.

Table 3. Ranked Genus Mean Acute Values with Species Mean Acute-Chronic Ratios

| Rank* | Genus Mean Acute Value (µg/L) | Species | Species Mean Acute Value (µg/L)** | Species Mean Acute-Chronic Ratio*** |
|---|---|---|---|---|
| | | FRESHWATER SPECIES | | |
| 22 | 203,000 | Leech, *Nephelopsis obscura* | 203,000 | - |
| 21 | 130,000 | Ostracod, *Cyclocypris* sp. | 130,000 | - |
| 20 | 42,500 | Midge, *Tanytarsus dissimilis* | 42,500 | - |
| 19 | 35,000 | Common carp, *Cyprinus carpio* | 35,000 | - |
| 18 | 34,910 | Snail, *Aplexa hypnorum* | 34,910 | - |
| 17 | 30,180 | White sucker, *Catostomus commersoni* | 30,180 | - |
| 16 | 28,500 | Bluegill, *Lepomis macrochirus* | 28,500 | - |
| 15 | 26,100 | Goldfish, *Carassius auratus* | 26,100 | - |
| 14 | 24,100 | Snail, *Physa* sp. | 24,100 | - |
| 13 | 13,600 | Channel catfish, *Ictalurus punctatus* | 13,600 | - |
| 12 | 12,600 | Mosquitofish, *Gambusia affinis* | 12,600 | - |
| 11 | 11,700 | Yellow perch, *Perca flavescens* | 11,700 | - |
| 10 | 10,200 | Brook trout, *Salvelinus fontinalis* | 10,200 | - |
| 9 | 8,977 | Rainbow trout, *Salmo gairdneri* | 8,977 | 141.5 |

Table 3. (Continued)

| Rank* | Genus Mean Acute Value (µg/L) | Species | Species Mean Acute Value (µg/L)** | Species Mean Acute-Chronic Ratio*** |
|---|---|---|---|---|
| 8 | 6,500 | Flagfish, *Jordanella floridae* | 6,500 | - |
| 7 | 4,300 | Amphipod, *Gammarus pseudolimnaeus* | 4,300 | - |
| 6 | 1,929 | Cladoceran, *Daphnia magna* | 961.0 | 13.31 |
| | | Cladoceran, *Daphnia pulex* | 3,870 | 5.586 |
| 5 | 1,783 | Striped bass, *Morone saxatilis* | 1,783 | - |
| 4 | 1,700 | Hydra, *Hydra* sp. | 1,700 | - |
| 3 | 1,601 | Fathead minnow, *Pimephales promelas* | 1,601 | 6.881 |
| 2 | 600 | Cladoceran, *Ceriodaphnia affinis* | 600 | <1.667 |
| 1 | 340 | Amphipod, *Hyalella azteca* | 340 | - |
| | | **SALTWATER SPECIES** | | |
| 15 | 17,350 | Fourspine stickleback, *Apeltes quadracus* | 17,350 | - |
| 14 | 14,650 | Winter flounder, *Pseudopleuronectes americanus* | 14,650 | - |
| 13 | >10,000 | Blue mussel, *Mytilus edulis* | >10,000 | - |
| 12 | >10,000 | Pacific oyster, *Crassostrea gigas* | >10,000 | - |

Table 3. (Continued)

| Rank* | Genus Mean Acute Value (µg/L) | Species | Species Mean Acute Value (µg/L)** | Species Mean Acute-Chronic Ratio*** |
|---|---|---|---|---|
| 11 | 9,725 | Atlantic silverside, *Menidia menidia* | 9,725 | - |
| 10 | 7,400 | Sheepshead minnow, *Cyprinodon variegatus* | 7,400 | 10.96 |
| 9 | 4,600 | Blue crab, *Callinectes sapidus* | 4,600 | - |
| 8 | 4,400 | Pinfish, *Lagodon rhomboides* | 4,400 | - |
| 7 | 3,497 | Summer flounder, *Paralichthys dentatus* | 3,497 | - |
| 6 | 1,550 | Striped bass, *Morone saxatilis* | 1,550 | - |
| 5 | 1,500 | Mysid, *Mysidopsis bahia* | 1,500 | 7.085 |
| 4 | 1,274 | Copepod, *Acartia clausi* | 1,910 | - |
| | | Copepod, *Acartic tonsa* | 850 | - |
| 3 | 1,200 | Brown shrimp, *Penaeus aztecus* | 1,200 | - |
| 2 | 1,040 | Dungeness crab, *Cancer magister* | 1,040 | - |
| 1 | 599 | Haddock, *Melanogrammus aeglefinus* | 599 | - |

Table 3. (Continued)

* Ranked from most resistant to most sensitive based on Genus Mean Acute Value. Inclusion of "greater than" values does not necessarily imply a true ranking, but does allow use of all genera for which data are available so that teh Final Acute Value is not unnecessarily lowered.

** From Table 1.

*** From Table 2

<u>Fresh water</u>

Final Acute Value = 370.9 μg/L

Criterion Maximum Concentration = (370.9 μg/L) / 2 = 185.4 μg/L

Final Acute-Chronic Ratio = 6.361 (see text)

Final Chronic Value = (370.9 μg/L) / 6.361 = 58.31 μg/L

Final Chronic Value = 25.5 μg/L (lowered to protect rainbow trout; see text)

<u>Salt water</u>

Final Acute Value = 591.1 μg/L

Criterion Maximum Concentration = (591.1 μg/L) / 2 = 295.5 μg/L

Final Acute-Chronic Ratio = 6.361 (see text)

Final Chronic Value = (591.1 μg/L) / 6.361 = 92.93 μg/L

## Table 4. Toxicity of Selenium(IV) to Aquatic Plants

| Species | Chemical | Duration (Days) | Effect | Result (µg/L)* | Reference |
|---|---|---|---|---|---|
| | | **FRESHWATER SPECIES** | | | |
| Green alga, *Scenedesmus dimorphus* | Sodium selenite | 14 | Growth retardation | 24,000 | Moede et al. 1980 |
| Green alga, *Scenedesmus quadricauda* | Sodium selenite | 8 | Incipient inhibition | 522 | Bringmann and Kuhn 1977a; 1978a,b; 1979; 1980b |
| Green alga, *Scenedesmus quadricauda* | Sodium selenite | - | Threshold toxicity | 2,500 | Bringman and Kuhn 1959a |
| Blue-green alga, *Microcystis aeruginisa* | Sodium selenite | 8 | Incipient inhibition | 9,400 (9,300) | Bringmann and Kuhn 1976; 1978a,b |
| Blue-green alga, *Anabaena cylindrica* | Sodium selenite | 14 | Growth retardation | 24,000 | Moede et al. 1980 |
| Blue-green alga, *Anabaena variabilis* | Sodium selenite | - | LC50 | 15,000** | Kumar and Prakash 1971 |
| Blue-green alga, *Anacystis nidulans* | Sodium selenite | - | LC50 | 30,000** | Kumar and Prakash 1971 |
| Green alga, *Selenastrum capricornutum* | Sodium selenite | 4 | EC50 | 2,900 | Richter 1982 |
| | | **SALTWATER SPECIES** | | | |
| Diatom *Skeletonema costatum* | Selenious acid*** | 4 | EC50 (reduction in chlorophyll *a*) | 7.93 | U.S. EPA 1978 |

* Results are expressed as selenium, not as the chemical.

** Estimated from graph.

*** Reported by Barrows et al. (1980) in work performed under the same contract.

## Table 5. Bioaccumulation of Selenium(IV) by Aquatic Organisms

| Species | Chemical | Concentration in Water (µg/L)* | Duration (days) | Tissue | BCF or BAF** | Reference |
|---|---|---|---|---|---|---|
| | | | **FRESHWATER SPECIES** | | | |
| Rainbow trout, *Salmo gairdneri* | Sodium selenite | - | 48 | Muscle | 2 | Adams 1976 |
| Rainbow trout, *Salmo gairdneri* | Sodium selenite | - | 48 | Whole body | 10*** | Adams 1976 |
| Rainbow trout, *Salmo gairdneri* | Sodium selenite | - | 351 | Whole body (estimate) | 8 | Hodson et al. 1980 |
| Fathead minnow, *Pimephales promelas* | Sodium selenite | - | 96 | Muscle | 11.6 | Adams 1976 |
| Fathead minnow, *Pimephales promelas* | Sodium selenite | - | 96 | Whole body | 17.6 | Adams 1976 |
| Bluegill, *Lepomis macrochirus* | Selenious acid | - | 28 | Whole body | 20 | Barrows et al. 1980 |
| Bluegill, *Lepomis macrochirus* | Sodium selenite | - | 120 | Whole body | 452 | Lemly 1982 |
| Largemouth bass, *Micropterus salmoides* | Sodium selenite | - | 120 | Whole body | 295 | Lemly 1982 |
| | | | **SALTWATER SPECIES** | | | |
| Euphausiid (adult), *Meganyctiphanes norvegica* | Sodium selenite | - | 28 | Whole animal | 200 | Fowler and Benayoun 1976a |
| Euphausiid (adult), *Meganyctiphanes norvegica* | Sodium selenite | - | 28 | Whole animal | 800† | Fowler and Benayoun 1976a |
| Shore crab (adult), *Carcinus maenas* | Sodium selenite | 250 | 29 | Gill | 14.40†† | Bjerregaard 1982 |
| Shore crab (adult), *Carcinus maenas* | Sodium selenite | 250 | 29 | Hepatopancreas | 4,080††,††† | Bjerregaard 1982 |
| Shore crab (adult), *Carcinus maenas* | Sodium selenite | 250 | 29 | Muscle | 2,880††,††† | Bjerregaard 1982 |

Table 5 (continued)

* Measured concentration of selenium.

** Bioconcentration factors (BCFs) and bioaccumulation factors (BAFs) are based on measured concentrations of selenium in water and in tissue.

*** Estimated from graph.

† Includes uptake from food.

†† Factor was converted from dry weight to wet weight basis.

††† Concentration of selenium was the same in exposed and control animals.

Table 6. Other Data on Effects of Selenium(IV) on Aquatic Organisms

| Species | Chemical | Duration | Effect | Result (µg/L)* | Reference |
|---|---|---|---|---|---|
| | | FRESHWATER SPECIES | | | |
| Green alga, *Scenedesmus quadricauda* | Sodium selenite | 96 hr | Incipient inhibition (river water) | 2,500 | Bringmann and Kuhn 1959a,b |
| Green alga, *Selenastrum capricornutum* | Sodium selenite | 72 hr | Decreased dry weight and chlorophyll *a* | 75 | Foe and Knight, Manuscript |
| Green alga, *Selenastrum capricornutum* | Sodium selenite | 72 hr | BCF = 120-212 | 10-100 | Foe and Knight, Manuscript |
| Green alga, *Selenastrum capricornutum* | Sodium selenite | 72 hr | BCF = 11,164 | 150 | Foe and Knight, Manuscript |
| Green alga, *Chlorella vulgaris* | - | - | Growth retardation | 50 | Hutchinson and Stokes 1975 |
| Green alga, *Haematoccus cupensis* | - | - | Growth retardation | 50 | Hutchinson and Stokes 1975 |
| Algae (diatoms), Mixed population | Sodium selenite | 18 days | Growth inhibition | 11,000 | Patrick et al. 1975 |
| Bacterium, *Escherichia coli* | Sodium selenite | - | Incipient inhibition | 90,000 | Bringmann and Kuhn 1959a |
| Bacterium, *Pseudomonas putida* | Sodium selenite | 16 hr | Incipient inhibition | 11,400 (11,200) | Bringmann and Kuhn 1976; 1977a; 1979; 1980b |
| Protozoan, *Entosiphon sulcatum* | Sodium selenite | 72 hr | Incipient inhibition | 1.8 (1.9) | Bringmann 1978; Bringmann and Kuhn 1979; 1980b; 1981 |
| Protozoan, *Microregma heterostoma* | Sodium selenite | 28 hr | Incipient inhibition | 183,000 | Bringmann and Kuhn 1959b |
| Protozoan, *Chilomonas paramecium* | Sodium selenite | 48 hr | Incipient inhibition | 62 | Bringman et al. 1980; Bringmann and Kuhn 1981 |

Table 6. (Continued)

| Species | Chemical | Duration | Effect | Result (µg/L)[a] | Reference |
|---|---|---|---|---|---|
| Protozoan, *Uronema parduczi* | Sodium selenite | 20 hr | Incipient inhibition | 118 | Bringmann and Kuhn 1980a; 1981 |
| Cladoceran, *Daphnia magna* | Sodium selenite | 48 hr | EC50 (river water) | 2,500 | Bringmann and Kuhn 1959a,b |
| Cladoceran, *Daphnia magna* | Sodium selenite | 24 hr | LC50 | 16,000 | Bringmann and Kuhn 1977a |
| Cladoceran, *Daphnia magna* | Sodium selenite | 24 hr | EC50 (swimming) | 9.9 | Bringmann and Kuhn 1977b |
| Cladoceran, *Daphnia magna* | Sodium selenite | 48 hr | LC50 (fed) | 710 | Halter et al. 1980 |
| Cladoceran, *Daphnia magna* | Sodium selenite | 96 hr | LC50 (fed) | 430 | Halter et al. 1980 |
| Cladoceran, *Daphnia magna* | Sodium selenite | 14 days | LC50 (fed) | 430 | Halter et al. 1980 |
| Cladoceran, *Daphnia magna* | Selenious acid | 48 hr | LC50 (fed) | 1,200 | Kimball, Manuscript |
| Cladoceran, *Daphnia magna* | Selenious acid | 48 hr | LC50 (fed) | 1,200 | Kimball, Manuscript |
| Cladoceran, *Daphnia magna* | Selenious acid | 28 days | LC50 (fed) | 240 | Kimball, Manuscript |
| Amphipod, *Hyalella azteca* | Sodium selenite | 14 days | LC50 (fed) | 70 | Halter et al. 1980 |
| Coho salmon (fry), *Oncorhynchus kisutch* | Sodium selenite | 43 days | LC50 | 160 | Adams 1976 |
| Rainbow trout (fry), *Salmo gairdneri* | Sodium selenite | 21 days | LC50 | 460 | Adams 1976 |
| Rainbow trout (fry), *Salmo gairdneri* | Sodium selenite | 21 days | Reduction in growth | 250 | Adams 1976 |

Table 6. (Continued)

| Species | Chemical | Duration | Effect | Result (µg/L)[*] | Reference |
|---|---|---|---|---|---|
| Rainbow trout, *Salmo gairdneri* | Sodium selenite | 48 days | LC50 | 500 | Adams 1976 |
| Rainbow trout, *Salmo gairdneri* | Sodium selenite | 96 days | LC50 | 280 | Adams 1976 |
| Rainbow trout, *Salmo gairdneri* | Sodium selenite | 9 days | LC50 | 5,400<br>5,410 | Hodson et al. 1980 |
| Rainbow trout, *Salmo gairdneri* | Sodium selenite | 9 days | LC50 | 6,900<br>6,920 | Hodson et al. 1980 |
| Rainbow trout, *Salmo gairdneri* | Sodium selenite | 9 days | LC50 | 7,000<br>7,020 | Hodson et al. 1980 |
| Rainbow trout, *Salmo gairdneri* | Sodium selenite | 41 days | Reduction of hatch of eyed embryos | 47 | Hodson et al. 1980 |
| Rainbow trout, *Salmo gairdneri* | Sodium selenite | 50 wk | Blood iron decreased | 53 | Hodson et al. 1980 |
| Rainbow trout, *Salmo gairdneri* | Sodium selenite | 60 days | LC50 | 51[**] | Hunn et al. Manuscript |
| Northern pike, *Esox lucius* | Sodium selenite | 76 hrs | LC50 | 11,100 | Klaverkamp et al. 1983 |
| Goldfish, *Carassius auratus* | Selenium dioxide | 14 days | LC50 | 6,300 | Cardwell et al. 1976a,b |
| Goldfish, *Carassius auratus* | Sodium selenite | 10 days | Mortality | 5,000 | Ellis et al. 1937 |
| Goldfish, *Carassius auratus* | Sodium selenite | 46 days | Gradual anorexia and mortality | 2,000 | Ellis et al. 1937 |
| Goldfish, *Carassius auratus* | Selenium dioxide | 7 days | LC50 | 12,000 | Weir and Hine 1970 |
| Goldfish, *Carassius auratus* | Selenium dioxide | 48 hr | Conditional avoidance | 250 | Weir and Hine 1970 |

Table 6. (Continued)

| Species | Chemical | Duration | Effect | Result (µg/L)* | Reference |
|---|---|---|---|---|---|
| Fathead minnow, *Pimephales promelas* | Sodium selenite | 48 days | LC50 | 1,100 | Adams 1976 |
| Fathead minnow, *Pimephales promelas* | Selenium dioxide | 9 days | LC50 | 2,100 | Cardwell et al. 1976a,b |
| Fathead minnow, *Pimephales promelas* | Sodium selenite | 96 hr | LC50 (fed) | 1,000 | Halter et al. 1980 |
| Fathead minnow, *Pimephales promelas* | Sodium selenite | 14 days | LC50 (fed) | 600 | Halter et al. 1980 |
| Fathead minnow, *Pimephales promelas* | Selenious acid | 8 days | LC50 (fed) | 400<br>430 | Kimball, Manuscript |
| Creek chub, *Semotilus atromaculatus* | Selenium dioxide | 48 hr | Mortality | ≥12,000 | Kim et al. 1977 |
| Bluegill, *Lepomis macrochirus* | Sodium selenite | 48 days | LC50 | 400 | Adams 1976 |
| Bluegill, *Lepomis macrochirus* | Selenium dioxide | 14 days | LC50 | 12,500 | Cardwell et al. 1976a,b |
| African clawed frog, *Xenopus laevis* | Sodium selenite | 7 days | LC50 | 1,520 | Browne and Dumont 1979 |
| Yellow perch, *Perca flavescens* | Sodium selenite | 10 days | LC50 | 4,800 | Klaverkamp et al. 1983 |
| | | SALTWATER SPECIES | | | |
| Anaerobic bacterium, *Methanococcus vannielii* | Sodium selenite | 110 hr | Stimulated growth | 79.01 | Jones and Stadtman 1977 |
| Green alga, *Chlorella* sp. | Sodium selenite | 14 days | 5-12% increase in growth | 10-10,000 | Wheeler et al. 1982 |
| Green alga, *Platymonas subcordiformis* | Sodium selenite | 14 days | 23% increase | 100-10,000 | Wheeler et al. 1982 |

Table 6. (Continued)

| Species | Chemical | Duration | Effect | Result (µg/L)* | Reference |
|---|---|---|---|---|---|
| Diatom, *Thalassiosira aestivalis* | Selenium oxide | 72 hr | No effect on cell morphology | 78.96 | Thomas et al. 1980a |
| Brown alga, *Fucus spiralis* | Sodium selenite | 60 days | 1355% increase in growth of thalli | 2.605 | Fries 1982 |

* Results are expressed as selenium, not as the chemical.

** Calculated from the authors' data using the probit method.

## REFERENCES


Adams, W.J. 1976. The toxicity and residue dynamics of selenium in fish and aquatic invertebrates. Ph.D. thesis. Michigan State University, East Lansing, MI. Available from: University Microfilms, Ann Arbor, MI. Order No. 76-27056.

Adams, W.J. and H.E. Johnson. 1981. Selenium: A hazard assessment and a water quality criterion calculation. In: Aquatic toxicology and hazard assessment: Fourth symposium. Branson, D.R. and K.L. Dickson (Eds.). ASTM STP 737. American Society for Testing and Materials, Philadelphia, PA. pp. 124-137.

Ahsanullah, M. and D.H. Palmer. 1980. Acute toxicity of selenium to three species of marine invertebrates, with notes on a continuous-flow test system. Aust. J. Mar. Freshwater Res. 31:795-802.

Barrows, M.E., S.R. Petrocelli, K.J. Macek and J.J. Carroll. 1980. Bioconcentration and elimination of selected water pollutants by bluegill sunfish (Lepomis macrochirus). In: Dynamics, exposure and hazard assessment of toxic chemicals. Hague, R. (Ed.). Ann Arbor Science Publishers, Ann Arbor, MI. pp. 379-392.

Beijer, K. and A. Jernelov. 1978. Ecological aspects of mercury-selenium interactions in the marine environment. Environ. Health Perspect. 25:43-45.

Biddinger, G.R. and S.P. Gloss. 1984. The importance of trophic transfer in the bioaccumulation of chemical contaminants in aquatic ecosystems. Residue Rev. 91:103-144.

Birge, W.J., J.A. Black, A.G. Westerman and J.E. Hudson. 1979. The effects of mercury on reproduction of fish and amphibians. In: The biogeochemistry of mercury in the environment. Nriagu, J.O. (Ed.). Elsevier, New York, NY. pp. 629-655.

Bjerregaard, P. 1982. Accumulation of cadmium and selenium and their mutual interaction in the shore crab _Carcinus maenas_ L. Aquat. Toxicol. 2:113-125.

Bovee, E.C. 1978. Effects of heavy metals especially selenium, vanadium and zirconium on movement, growth and survival of certain aquatic life. PB-292563/4SL. National Technical Information Service, Springfield, VA.

Boyum, K.W. 1984. The toxic effects of selenium on the zooplankton, _Daphnia magna_ and _D. pulicaria_ in water and the food source (_Chlamydomonas reinhardtii_). Ph.D. thesis. University of Wisconsin-Milwaukee, Milwaukee, WI. Available from: University Microfilms, Ann Arbor, MI. Order No. 85-09248.

Braddon, S.A. 1982. Investigations into the mechanism of action of Se on Hg toxicity using a sea bass model. Fed. Proc. 41: No. 5585 (abstract).

Bringmann, G. 1978. Determination of the biological toxicity of waterbound substances towards protozoa. I. Bacteriovorous flagellates (model organism: _Entosiphon sulcatum_ Stein). Z. Wasser Abwasser Forsch. 11:210-215.

Bringmann, G. and R. Kuhn. 1959a. The toxic effects of waste water on aquatic bacteria, algae, and small crustaceans. Gesund.-Ing. 80:115-120.

Bringmann, G. and R. Kuhn. 1959b. Water toxicology studies with protozoans as test organisms. Gesund.-Ing. 80:239-242.

Bringmann, G. and R. Kuhn. 1976. Comparative results of the harmful effects of water pollutants on bacteria (Pseudomonas putida) and blue algae (Microcystis aeruginosa). Gas-Wasserfach, Wasser-Abwasser 117:410-413.

Bringmann, G. and R. Kuhn. 1977a. Limiting values for the damaging action of water pollutants to bacteria (Pseudomonas putida) and green algae (Scenedesmus quadricauda) in the cell multiplication inhibition test. Z. Wasser Abwasser Forsch. 10:87-98.

Bringmann, G. and R. Kuhn. 1977b. Results of the damaging effect of water pollutants on Daphnia magna. Z. Wasser Abwasser Forsch. 10:161-166.

Bringmann, G. and R. Kuhn. 1978a. Limiting values for the noxious effects of water pollutant material to blue algae (Microcystis aeruginosa) and green algae (Scenedesmus quadricauda) in cell propagation inhibition tests. Vom Wasser 50:45-60.

Bringmann, G. and R. Kuhn. 1978b. Testing of substances for their toxicity threshold: Model organisms Microcystis (Diplocystis) aeruginosa and Scenedesmus quadricauda. Mitt. Int. Ver. Theor. Angew. Limnol. 21:275-284.

Bringmann, G. and R. Kuhn. 1979. Comparison of toxic limiting concentrations of water contamination toward bacteria, algae and protozoa in the cell-growth inhibition test. Haustech. Bauphys. Umwelttech. 100:249-252.

Bringmann, G. and R. Kuhn. 1980a. Determination of the harmful biological effect of water pollutants on protozoa. II. Bacteriovorous ciliates. Z. Wasser Abwasser Forsch. 13:26-31.

Bringmann, G. and R. Kuhn. 1980b. Comparison of the toxicity thresholds of water pollutants to bacteria, algae, and protozoa in the cell multiplication inhibition test. Water Res. 14:231-241.

Bringmann, G. and R. Kuhn. 1981. Comparison of the effects of harmful substances on flagellates as well as ciliates and on halozoic bacteriophagous and saprozoic protozoa. Gas-Wasserfach, Wasser-Abwasser 122:308-313.

Bringmann, G., R. Kuhn and A. Winter. 1980. Determination of biological damage from water pollutants to protozoa. III. Saprozoic flagellates. Z. Wasser Abwasser Forsch. 13:170-173.

Brooke, L. 1985. University of Wisconsin-Superior, Superior, WI. (Memorandum to R.R. Garton, U.S. EPA, Duluth, MN. October 3).

Browne, C.L. and J.N. Dumont. 1979. Toxicity of selenium to developing Xenopus laevis embryos. J. Toxicol. Environ. Health 5:699-710.

Burton, J.D., W.A. Maher, C.I. Measures and P.J. Statham. 1980. Aspects of the distribution and chemical form of selenium and arsenic in ocean waters and marine organisms. Thalassia Jugosl. 16:155-164.

Burton, D.T., L.W. Hall, Jr., R.J. Klauda and S.L. Margrey. 1983. Effects of treated bleached kraft mill effluent on eggs and prolarvae of striped bass (Morone saxatilis). Water Resour. Bull. 19:869-879.

Butler, G.W. and P.J. Peterson. 1967. Uptake and metabolism of inorganic Se-75 by Spirodela oligorrhiza. Aust. J. Biol. Sci. 20:77-86.

Call, D.J., L.T. Brooke, N. Ahmad and J.E. Richter. 1983. Toxicity and metabolism studies with EPA (Environmental Protection Agency) priority pollutants and related chemicals in freshwater organisms. EPA-600/3-83-095. National Technical Information Service, Springfield, VA.

Callahan, M.A., M.W. Slimak, N.W. Gabel, I.P. May, C.F. Fowler, J.R. Freed, P. Jennings, R.L. Durfee, F.C. Whitmore, B. Maestri, W.R. Mabey, B.R. Holt and C. Gould. 1979. Water-related environmental fate of 129 priority pollutants. Vol I. EPA-440/4-79-029a. National Technical Information Service, Springfield, VA. pp. 16-1 to 16-13.

Cappon, C.J. and J.C. Smith. 1981. Mercury and selenium content and chemical form in fish muscle. Arch. Environ. Contam. Toxicol. 10:305-319.

Cardin, J.A. 1986. U.S. EPA, Narragansett, RI. (Memorandum to D.J. Hansen, U.S. EPA, Narragansett, RI.)

Cardwell, R.D., D.G. Foreman, T.R. Payne and D.J. Wilbur. 1976a. Acute toxicity of selenium dioxide to freshwater fishes. Arch. Environ. Contam. Toxicol. 4:129-144.

Cardwell, R.D., D.G. Foreman, T.R. Payne and D.J. Wilbur. 1976b. Acute toxicity of selected toxicants to six species of fish. PB-252488 or EPA-600/3-76-008. National Technical Information Service, Springfield, VA.

Chapman, W.H., H.L. Fisher and M.W. Pratt. 1968. Concentration factors of chemical elements in edible aquatic organisms. UCRL-50564. National Technical Information Service, Springfield, VA.

Cherry, D.S., R.K. Guthrie, J.H. Rodgers, Jr., J. Cairns, Jr. and K.L. Dickson. 1976. Responses of mosquitofish (Gambusia affinis) to ash effluent and thermal stress. Trans. Am. Fish. Soc. 105:686-694.

Cherry, D.S., R.K. Guthrie, F.F. Sherberger and S.R. Larrick. 1979. The influence of coal ash and thermal discharges upon the distribution and bioaccumulation of aquatic invertebrates. Hydrobiologia 62:257-267.

Cooper, W.C., K.G. Bennett and F.C. Croxton. 1974. The history, occurrence, and properties of selenium. In: Selenium. Zingaro, R.A. and W.C. Cooper (Eds.). Van Nostrand Reinhold Company, New York, NY. pp. 1-30.

Cumbie, P.M. and S.L. Van Horn. 1978. Selenium accumulation associated with fish mortality and reproductive failure. Proc. Annu. Conf. Southeast. Assoc. Fish Wildl. Agencies 32:612-624.

Cutter, G.A. 1978. Species determination of selenium in natural waters. Anal. Chim. Acta 98:59-66.

Cutter, G.A. 1982. Selenium in reducing waters. Science 217:829-831.

Cutter, G.A. and K.W. Bruland. 1984. The marine biogeochemistry of selenium: A re-evaluation. Limnol. Oceanogr. 29:1179-1192.

Davies, A.G. 1978. Pollution studies with marine plankton. Part II. Heavy metals. Adv. Mar. Biol. 15:381-508.

Dorney, J.R. 1985. The freshwater chemistry and toxicity of selenium with an emphasis on its effect in North Carolina. North Carolina Department of Natural Resources and Community Development, Division of Environmental Management, Water Quality Section, Raleigh, NC.

Duncan, D.A. and J.F. Klaverkamp. 1983. Tolerance and resistance to cadmium in white suckers (Catastomus commersoni) previously exposed to cadmium, mercury, zinc, or selenium. Can. J. Fish. Aquat. Sci. 40:128-138.

Dunbar, A.M., J.M. Lazorchak and W.T. Waller. 1983. Acute and chronic toxicity of sodium selenate to Daphnia magna Straus. Environ. Toxicol. Chem. 2:239-244.

Eisler, R. 1985. Selenium hazards to fish, wildlife, and invertebrates: A synoptic review. Contaminant Hazard Reviews. Report No. 5. Biological Report 85(1.5). U.S. Fish and Wildlife Service, Laurel, MD.

Ellis, M.M., et al. 1937. Selenium poisoning in fishes. Proc. Soc. Exp. Biol. Med. 36:519.

Fava, J.A., J.J. Gift, A.F. Maciorowski, W.L. McCulloch and H.J. Reisinger II. 1985. Comparative toxicity of whole and liquid phase sewage sludges to marine organisms. In: Aquatic toxicology and hazard assessment: Seventh symposium. Cardwell, R.D., R. Purdy and R.C. Bahner (Eds.). ASTM STP 854. American Society for Testing and Materials, Philadelphia, PA. pp. 229-252.

Finley, K.A. 1985. Observations of bluegills fed selenium-contaminated Hexagenia nymphs collected from Belews Lake, North Carolina. Bull. Environ. Contam. Toxicol. 35:816-825.

Fishbein, L. 1984. Overview of analysis of carcinogenic and/or mutagenic metals in biological and environmental samples. I. Arsenic, beryllium, cadmium, chromium, and selenium. Int. J. Environ. Anal. Chem. 17:113-170.

Foe, C. and A.W. Knight. Manuscript. Selenium bioaccumulation, regulation, and toxicity in the green alga, Selenastrum capricornutum, and dietary toxicity of the contaminated alga to Daphnia magna.

Fowler, S.W. and G. Benayoun. 1976a. Selenium kinetics in marine zooplankton. Mar. Sci. Commun. 2:43-67.

Fowler, S.W. and G. Benayoun. 1976b. Influence of environmental factors on selenium flux in two marine invertebrates. Mar. biol. (Berlin) 37:59-68.

Fowler, S.W. and G. Benayoun. 1976c. Accumulation and distribution of selenium in mussels and shrimp tissues. Bull. Environ. Contam. Toxicol. 16:339-346.

Fowler, B.A., R.C. Fay, R.L. Walter, R.D. Willis and W.F. Gutknecht. 1975. Levels of toxic metals in marine organisms collected from southern California coastal waters. Environ. Health Perspect. 12:71-76.

Freeman, H.C. and G.B. Sangalang. 1977. A study of the effects of methyl mercury, cadmium, arsenic, selenium, and PCB (Aroclor 1254) on adrenal and testicular steroidogeneses in vitro, by gray seal Halichoerus gyrpus. Arch. Environ. Contam. Toxicol. 5:369-383.

Fries, L. 1982. Selenium stimulates growth of marine macroalgae in axenic culture. J. Phycol. 18:328-331.

Frost, D.V. and D. Ingvoldstad. 1975. Ecological aspects of selenium and tellurium in human and animal health. Chem. Scr. 8A:96-107.

Glickstein, N. 1978. Acute toxicity of mercury and selenium to Crassostrea gigas embryos and Cancer magister larvae. Mar. Biol. (Berlin) 49:113-117.

Goettl, J.P., Jr., and P.H. Davies. 1976. Water pollution studies. Job Progress Report, Federal Aid Project F-33-R-11, Colorado Division of Wildlife, Fort Collins, CO. pp. 31-34.

Goettl, J.P., Jr., and P.H. Davies. 1977. Water pollution studies. Job Progress Report, Federal Aid Project F-33-R-12, Colorado Division of Wildlife, Fort Collins, CO.

Gotsis, O. 1982. Combined effects of selenium/mercury and selenium/copper on the cell population of the alga Dunaliella minuta. Mar. Biol. (Berlin) 71:217-222.

Greig, R.A. and J.J. Jones. 1976. Nondestructive neutron activation analysis of marine organisms collected from ocean dump sites of the middle eastern United States. Arch. Environ. Contam. Toxicol. 4:420-434.

Hall, L.W., Jr. and D.T. Burton. 1982. Effects of power plant coal pile and coal waste runoff and leachate on aquatic biota: An overview with research recommendations. Crit. Rev. Toxicol. 10:287-301.

Halter, M.T., W.J. Adams and H.E. Johnson. 1980. Selenium toxicity to Daphnia magna, Hyallela azteca, and the fathead minnow in hard water. Bull. Environ. Contam. Toxicol. 24:102-107.

Heisinger, J.F. 1981. Antagonism of selenium and cadmium pretreatments to subsequent embryotoxic doses of mercury and cadmium in fish embryos. PB82-256645. National Technical Information Service, Springfield, VA.

Heisinger, J.F. and S.M. Dawson. 1983. Effect of selenium deficiency on liver and blood glutathione peroxidase activity in the black bullhead. J. Exp. Zool. 225:325-327.

Heisinger, J.F. and L. Scott. 1985. Selenium prevents mercuric chloride induced acute osmoregulatory failure without glutathione peroxidase involvement in the black bullhead (Ictalurus melas). Comp. Biochem. Physiol. 80C:295-297.

Heisinger, J.F., C.D. Hansen and J.H. Kim. 1979. Effect of selenium dioxide on the accumulation and acute toxicity of mercuric chloride in goldfish. Arch. Environ. Contam. Toxicol. 8:279-283.

Heit, M. and C.S. Klusek. 1985. Trace element concentrations in the dorsal muscle of white suckers and brown bullheads from two acidic Adirondack lakes. Water Air Soil Pollut. 25:87-96.

Heitmuller, P.T., T.A. Hollister and P.R. Parrish. 1981. Acute toxicity of 54 industrial chemicals to sheepshead minnows (Cyprinodon variegatus). Bull. Environ. Contam. Toxicol. 27:596-604.

Hilton, J.W., P.V. Hodson and S.J. Slinger. 1981. The requirement and toxicity of selenium in rainbow trout (Salmo gairdneri). J. Nutr. 110:2527-2535.

Hodson, P.V. and J.W. Hilton. 1983. The nutritional requirements and toxicity to fish of dietary and waterborne selenium. Ecol. Bull. 35:335-340.

Hodson, P.V., D.J. Spry and B.R. Blunt. 1980. Effects on rainbow trout (Salmo gairdneri) of a chronic exposure to waterborne selenium. Can. J. Fish. Aquat. Sci. 37:233-240.

Huckabee, J.W. and N.A. Griffith. 1974. Toxicity of mercury and selenium to the eggs of carp (Cyprinus carpio). Trans. Am. Fish. Soc. 103:822-825.

Hunn, J.B., S.J. Hamilton and D.R. Buckler. Manuscript. Toxicity of sodium selenite to rainbow trout fry. Columbia National Fisheries Research Laboratory, Columbia, MO.

Hutchinson, T.C. and P.M. Stokes. 1975. Heavy metal toxicity and algal bioassays. In: Water quality parameters. Barabas, S. (Ed.). ASTM STP 573. American Society for Testing and Materials, Philadelphia, PA. pp. 320-343.

Jay, F.B. and R.J. Muncy. 1979. Toxicity to channel catfish of wastewater from an Iowa coal benefication plant. Iowa State J. Res. 54:45-50.

Jenkins, D.W. 1980. Biological monitoring of toxic trace metals. Vol. 2. Toxic trace metals in plants and animals of the world. Part III. EPA-600/3-80-092. National Technical Information Service, Springfield, VA. pp. 1090-1129.

Jones, J.B. and T.C. Stadtman. 1977. Methanococcus vanielii: Culture and effects of selenium and tungsten on growth. J. Bacteriol. 1977:1404-1406.

Kaiser, I.I., P.A. Young and J.D. Johnson. 1979. Chronic exposure of trout to waters with naturally high selenium levels: Effects on transfer RNA methylation. J. Fish. Res. Board Can. 36:689-694.

Kaiser, K.L. 1980. Correlation and prediction of metal toxicity to aquatic biota. Can. J. Fish. Aquat. Sci. 37:211-218.

Keating, K.I. and B.C. Dagbusan. 1984. Effect of selenium deficiency on cuticle integrity in the Cladocera (Crustacea). Proc. Natl. Acad. Sci. U.S.A. 81:3433-3437.

Kim, J.H., E. Birks and J.F. Heisinger. 1977. Protective action of selenium against mercury in northern creek chubs. Bull. Environ. Contam. Toxicol. 17:132-136.

Kimball, G. Manuscript. The effects of lesser known metals and one organic to fathead minnows (Pimephales promelas) and Daphnia magna. (Available from C.E. Stephan, U.S. EPA, Duluth, MN.)

Klaverkamp, J.F., D.A. Hodgins and A. Lutz. 1983. Selenite toxicity and mercury-selenium interactions in juvenile fish. Arch. Environ. Contam. Toxicol. 12:405-413.

Kleinow, K.M. 1984. The uptake, disposition, and elimination of selenate, selenite and selenomethionine in the fathead minnow (Pimephales promelas). Ph.D. thesis. University of Wisconsin-Milwaukee, Milwaukee, WI. Available from: University Microfilms, Ann Arbor, MI. Order No. 85-09260.

Kleinow, K.M. and A.S. Brooks. 1986a. Selenium compounds in the fathead minnow (Pimephales promelas)-I. Uptake, distribution and elimination of orally administered selenate, selenite and l-selenomethionine. Comp. Biochem. Physiol. 83C:61-69.

Kleinow, K.M. and A.S. Brooks. 1986b. Selenium compounds in the fathead minnow (Pimephales promelas)-II. Quantitative approach to gastrointestinal absorption, routes of elimination and influence of dietary pretreatment. Comp. Biochem. Physiol. 83C:71-76.

Kumar, H.D. and G. Prakash. 1971. Toxicity of selenium to the blue-green algae, Anacystis nidulans and Anabena variabilis. Ann. Bot. (Lond.) 35: 697-705.

LeBlanc, G.A. 1980. Acute toxicity of priority pollutants to water flea (Daphnia magna). Bull. Environ. Contam. Toxicol. 24:684-691.

Lemly, A.D. 1982. Response of juvenile centrarchids to sublethal concentrations of waterborne selenium. I. Uptake, tissue distribution, and retention. Aquat. Toxicol. 2:235-252.

Lemly, A.D. 1985a. Toxicology of selenium in a freshwater reservoir: Implications for environmental hazard evaluation and safety. Ecotoxicol. Environ. Safety 10:314-338.

Lemly, A.D. 1985b. Ecological basis for regulating aquatic emissions from the power industry: The case with selenium. Regul. Toxicol. Pharmacol. 5:465-486.

Levander, O.A. 1977. Metabolic interrelationships between arsenic and selenium. Environ. Health. Perspect. 19:159-164.

Lowe, T.P., T.W. May, W.G. Brumbaugh and D.A. Kane. 1985. National contaminant biomonitoring program: Concentrations of seven elements in freshwater fish, 1978-1981. Arch. Environ. Contam. Toxicol. 14:363-388.

Lucas, H.F., Jr., D.N. Edgington and P.J. Colby. 1970. Concentrations of trace elements in Great Lakes fishes. J. Fish. Res. Board Can. 27:677-684.

Lussier, S.M. 1986. U.S. EPA, Narragansett, RI. (Memorandum to D.J. Hansen, U.S. EPA, Narragansett, RI.)

Lytle, T.F. and J.S. Lytle. 1982. Heavy metals in oysters and clams of St. Louis Bay, Mississippi. Bull. Environ. Contam. Toxicol. 29:50-57.

Martin, M., K.E. Osborn, P. Billig and N. Glickstein. 1981. Toxicities of ten metals to Crassostrea gigas and Mytilus edulis embryos and Cancer magister larvae. Mar. Pollut. Bull. 12:305-308.

Measures, C.I. and J.D. Burton. 1978. Behaviour and speciation of dissolved selenium in estuarine waters. Nature 273:293-295.

Mehrle, P.M., T.A. Haines, S. Hamilton, J.L. Ludke, F.L. Mayer and M.A. Rebick. 1982. Relationship between body contaminants and bone development in East-Coast striped bass. Trans. Am. Fish. Soc. 111:231-241.

Moede, A., R.W. Greene and D.F. Spencer. 1980. Effects of selenium on the growth and phosphorus uptake of Scenedesmus dimorphus and Anaebena cylindrica. Environ. Exp. Bot. 20:207-212.

Nassos, P.A., J.R. Coats, R.L. Metcalf, D.D. Brown and L.G. Hansen. 1980. Model ecosystem, toxicity, and uptake evaluation of selenium-75-selenite. Bull. Environ. Contam. Toxicol. 24:752-758.

National Academy of Sciences. 1976. Selenium. Committee on Medical and Biologic Effects of Environmental Pollutants. National Academy of Sciences, Washington, DC.

Niimi, A.J. and Q.N. LaHam. 1975. Selenium toxicity on the early life stages of zebrafish (Brachydanio rerio). J. Fish. Res. Board Can. 32:803-806.

Niimi, A.J. and Q.N. LaHam. 1976. Relative toxicity of organic and inorganic compounds of selenium to newly hatched zebrafish (Brachydanio rerio). Can. J. Zool. 54:501-509.

Ohlendorf, H.M., D.J. Hoffman, M.K. Saiki and T.W. Aldrich. Manuscript. Embryonic mortality and abnormalities of aquatic birds: Apparent impacts of selenium from irrigation drain water.

Okasako, J. and S. Siegel. 1980. Mercury antagonists: Effects of sodium chloride and sulfur group (VIa) compounds on encystment of the brine shrimp *Artemia*. Water Air Soil Pollut. 14:235-240.

Okazaki, R.K. and M.H. Panietz. 1981. Depuration of twelve trace metals in tissues of the oysters *Crassostrea gigas* and *C. virginica*. Mar. Biol. (Berlin) 63:113-120.

Oppenheimer, J.A., A.D. Eaton and P.H. Kreft. 1984. Speciation of selenium in groundwater. EPA-600/2-84-190 or PB85-125979. National Technical Information Service, Springfield, VA.

Owsley, J.A. 1984. Acute and chronic effects of selenite-selenium on *Ceriodaphnia affinis*. M.S. thesis, Vanderbilt University, Nashville, TN.

Pakkala, I.S., W.H. Gutenmann, D.J. Lisk, G.E. Burdick and E.J. Harris. 1972. A survey of the selenium content of fish from 49 New York state waters. Pestic. Monitor J. 6:107-114.

Palawski, D., J.B. Hunn and F.J. Dwyer. 1985. Sensitivity of young striped bass to organic and inorganic contaminants in fresh and saline waters. Trans. Am. Fish. Soc. 114:748-753.

Patrick, R., T. Bott and R. Larson. 1975. The role of trace elements in management of nuisance growths. EPA-660/2-75-008. National Technical Information Service, Springfield, VA.

Phillips, G.R. and R.C. Russo. 1978. Metal bioaccumulation in fishes and aquatic invertebrates: A literature review. EPA-600/3-78-103. National Technical Information Service, Springfield, VA.

Poston, H.A., G.G. Combs, Jr. and L. Leibovitz. 1976. Vitamin E and selenium interrelations in the diet of Atlantic salmon (Salmo salar). Gross histological and biochemical deficiency signs. J. Nutr. 106:892-904.

Raptis, S.E., G. Kaiser and G. Tolg. 1983. A survey of selenium in the environment and a critical review of its determination at trace levels. Fresenius Z. Anal. Chem. 316:105-123.

Reading, J.T. 1979. Acute and chronic effects of selenium on Daphnia pulex. M.S. thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Reading, J.T. and A.L. Buikema, Jr. 1983. Chronic effects of selenite-selenium on Daphnia pulex. Arch. Environ. Contam. Toxicol. 12:399-404.

Richter, J.E. 1982. Results of algal toxicity tests with priority pollutants. U.S. EPA, Duluth, MN. (Memorandum to C.E. Stephan, U.S. EPA, Duluth, MN. June 30.)

Robberecht, H. and R. Van Grieken. 1982. Selenium in environmental waters: Determination, speciation, and concentration levels. Talanta 29:823-844.

Rudd, J.W.M. and M.A. Turner. 1983a. The English-Wabigoon River system: II. Suppression of mercury and selenium bioaccumulation by suspended and bottom sediments. Can. J. Fish. Aquat. Sci. 40:2218-2227.

Rudd, J.W.M. and M.A. Turner. 1983b. The English-Wabigoon River system: V. Mercury and selenium bioaccumulation as a function of aquatic primary productivity. Can. J. Fish. Aquat. Sci. 40:2251-2259.

Rudd, J.W.M., M.A. Turner, B.E. Townsend, A. Swick and A. Furutani. 1980. Dynamics of selenium in mercury-contaminated experimental fresh water ecosystems. Can. J. Fish. Aquat. Sci. 37:848-857.

Ryther, J., T.M. Losordo, A.K. Furr, T.F. Parkinson, W.H. Gutenman, I.S. Pakkala and D.J. Lisk. 1979. Concentration of elements in marine organisms cultured in seawater flowing through coal-fly ash. Bull. Environ. Contam. Toxicol. 23:207-210.

Sandholm, M., H.E. Oksanen and L. Pesonen. 1973. Uptake of selenium by aquatic organisms. Limnol. Oceanogr. 18:496-499.

Salki, A., M. Turner, K. Patalas, J. Rudd and D. Findlay. 1985. The influence of fish-zooplankton-phytoplankton interactions on the results of selenium toxicity experiments within large enclosures. Can. J. Fish. Aquat. Sci. 42:1132-1143.

Sarathchandra, S.U. and J.H. Watkinson. 1981. Oxidation of elemental selenium to selenite by Bacillus megaterium. Science 211:600-601.

Sato, T., Y. Ose and T. Sakai. 1980. Toxicological effect of selenium on fish. Environ. Pollut. (Series A) 21:217-224.

Schultz, T.W., S.R. Freeman and J.N. Dumont. 1980. Uptake, depuration, and distribution of selenium in Daphnia and its effects on survival and ultrastructure. Arch. Environ. Contam. Toxicol. 9:23-40.

Seelye, J.G., R.J. Hesselberg and M.J. Mac. 1982. Accumulation by fish of contaminants released from dredged sediments. Environ. Sci. Technol. 16: 459-464.

Shamberger, R.J. 1981. Selenium in the environment. Sci. Total Environ. 17:59-74.

Shamberger, R.J., S.A. Tytko and C.E. Willis. 1976. Antioxidants and cancer. Part VI. Selenium and age-adjusted human cancer mortality. Arch. Environ. Health. 1976:231-235.

Sheline, J. and B. Schmidt-Nielsen. 1977. Methylmercury-selenium: Interaction in the killifish, Fundulus heteroclitus. In: Physiological responses of marine biota to pollutants. Vernberg, F.J., A. Calabrese, F.P. Thurberg, and W.B. Vernberg (Eds.). Academic Press, New York, NY. pp. 119-130.

Siebers, D. and U. Ehlers. 1979. Heavy metal action in transintegumentary absorption of glycine in two annelid species. Mar. Biol. (Berlin) 50:175-179.

Skerfving, S. 1978. Interaction between selenium and methylmercury. Environ. Health Perspect. 25:57-65.

Sorensen, E.M.B. and T.L. Bauer. 1984a. Planimetric analysis of redear suufish Lepomis microlophus hepatopancreas following selenium exposure. Environ. Toxicol. Chem. 3:159-166.

Sorensen, E.M.B. and T.L. Bauer. 1984b. Correlation between selenium accumulation in sunfish and changes in condition factor and organ weight. Environ. Pollut. (Series A) 34:357-366.

Sorensen, E.M.B., T.L. Bauer, J.S. Bell and C.W. Harlan. 1982. Selenium accumulation and cytotoxicity in teleosts following chronic, environmental exposure. Bull. Environ. Contam. Toxicol. 29:688-696.

Sorensen, E.M.B., P.M. Cumbie, T.L. Bauer, J.S. Bell and C.W. Harlan. 1984. Histopathological, hematological, condition-factor, and organ weight changes associated with selenium accumulation in fish from Belews Lake, North Carolina. Arch. Environ. Contam. Toxicol. 13:153-162.

Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman and W.A. Brungs. 1985. Guidelines for deriving numerical national water quality criteria for the protection of aquatic organisms and their uses. PB85-227049. National Technical Information Service, Springfield, VA.

Takayanagi, K. and G.T.F. Wong. 1984a. Organic and colloidal selenium in southern Chesapeake Bay and adjacent waters. Marine Chem. 14:141-148.

Takayanagi, K. and G.T.F. Wong. 1984b. Total selenium and selenium(IV) in the James River estuary and southern Chesapeake Bay. Estuarine Coastal Shelf Sci. 18:113-119.

Thomas, W.H., J.T. Hollibaugh and D.L.R. Siebert. 1980a. Effects of heavy metals on the morphology of some marine phytoplankton. Phycologia 19:202-209.

Thomas, W.H., J.T. Hollibaugh, D.L.R. Siebert and G.T. Wallace, Jr. 1980b. Toxicity of a mixture of ten metals to phytoplankton. Mar. Ecol. Prog. Ser. 2:213-220.

Thompson, S.E., C.A. Burton, D.J. Quinn and Y.C. Ng. 1972. Concentration factors of chemical elements in edible aquatic organisms. UCRL-50564. Rev. 1. National Technical Information Service, Springfield, VA.

Turner, M.A. and A.L. Swick. 1983. The English-Wabigoon River system: IV. Interaction between mercury and selenium accumulated from waterborne and dietary sources by northern pike (*Esox lucius*). Can. J. Fish. Aquat. Sci. 40:2241-2250.

U.S. EPA. 1976. Quality criteria for water. EPA-440/9-76-023. National Technical Information Service, Springfield, VA.

U.S. EPA. 1978. In-depth studies on health and environmental impacts of selected water pollutants. (Table of data available from C.E. Stephan, U.S. EPA, Duluth, MN.)

U.S. EPA. 1980. Ambient water quality criteria for selenium. EPA-440/5-80-070. National Technical Information Service, Springfield, VA.

U.S. EPA. 1983a. Methods for chemical analysis of water and wastes. EPA-600/4-79-020 (Revised March 1983). National Technical Information Service, Springfield, VA.

U.S. EPA. 1983b. Water quality standards regulation. Fed. Regist. 48:51400-51413. November 8.

U.S. EPA. 1983c. Water quality standards handbook. Office of Water Regulations and Standards, Washington, DC.

U.S. EPA. 1985. Technical support document for water-quality based toxics control. Office of Water, Washington, DC.

Uchida, H., Y. Shimoishi and K. Toei. 1980. Gas chromatographic determination of selenium (-II,0), -(IV), and -(VI) in natural waters. Environ. Sci. Technol. 14:541-544.

Uthe, J.F. and E.G. Bligh. 1971. Preliminary survey of heavy metal contamination of Canadian freshwater fish. J. Fish. Res. Board Can. 28:786-788.

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Ward, G.S., T.A. Hollister, P.T. Heitmuller and P.R. Parrish. 1981. Acute and chronic toxicity of selenium to estuarine organisms. Northeast Gulf Sci. 4:73-78.

Weber, W.J., Jr. and W. Stumm. 1963. Mechanism of hydrogen ion buffering in natural waters. J. Am. Water Works Assoc. 55:1553-1578.

Weir, P.A. and C.H. Hine. 1970. Effects of various metals on behavior of conditioned goldfish. Arch. Environ. Health 20:45-51.

Wheeler, A.E., R.A. Zingaro, K. Irgolic and N.R. Bottino. 1982. The effect of selenate, selenite, and sulfate on the growth of six unicellular marine algae. J. Exp. Mar. Biol. Ecol. 57:181-194.

Wilber, C.G. 1980. Toxicology of selenium: A review. Clin. Toxicol. 17:171-230.

Wilber, C.G. 1983. Selenium: A potential environmental poison and a necessary food constituent. Charles C. Thomas Publ., Springfield, IL.

Winner, R.W. 1984. Selenium effects on antennal integrity and chronic copper toxicity in Daphnia pulex (deGeer). Bull. Environ. Contam. Toxicol. 33:605-611.

Wong, P.T.S., Y.K Chau and D. Patel. 1982. Physiological and biochemical responses of several freshwater algae to a mixture of metals. Chemosphere 11:367-376.

Wrench, J.J. 1978. Selenium metabolism in the marine phytoplankters Tetraselmis tetrathele and Dunaliella minuta. Mar. Biol. (Berlin) 49:231-236.

Wrench, J.J. and C.I. Measures. 1982. Temporal variations in dissolved selenium in a coastal ecosystem. Nature 299:431-433.