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Ambient Water Quality Criteria for

Lead - 1984

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Document provides a summary of important aquatic toxicological data pertaining to lead. Criterion Maximum and Criterion Continuous Concentrations (CMC and CCC) are calculated. Any necessary adjustments are discussed. An extensive bibliography is provided.

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AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR

LEAD

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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 criteria for water quality accurately reflecting the latest scientific knowledge on the kind and extent of all identifiable effects on health and welfare which may 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. The criteria contained in this document replace any previously published EPA aquatic life criteria.

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. The criteria presented in this publication are such scientific assessments. Such water quality criteria associated with specific stream uses when adopted as State water quality standards under section 303 become enforceable maximum acceptable levels of a pollutant in ambient waters. The water quality criteria adopted in the State water quality standards could have the same numerical limits as the criteria developed under section 304. However, in many situations States may 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 the State water quality standards that the criteria become regulatory.

Guidelines to assist the 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.

Edwin L. Johnson
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particulate matter, that are not toxic and are not likely to become toxic under natural conditions. Although this measurement (and many others) will measure soluble, complexed forms of lead, such as the EDTA complex of lead, that probably have low toxicities to aquatic life, concentrations of these forms probably are negligible in most ambient water.

3. Although water quality criteria apply to ambient water, the measurement used to express criteria is likely to be used to measure lead in aqueous effluents. Measurement of acid-soluble lead should be applicable to effluents because it will measure precipitates, such as carbonate and hydroxide precipitates of lead, that might exist in an effluent and dissolve when the effluent is diluted with receiving water. If desired, dilution of effluent with receiving water before measurement of acid-soluble lead might be used to determine whether the receiving water can decrease the concentration of acid-soluble lead because of sorption.
4. The acid-soluble measurement should be 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. 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 total recoverable measurement.
7. Durations of 10 minutes to 24 hours between acidification and filtration 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 lead, the analysis can be performed using either atomic absorption spectroscopy or ICP-atomic emission spectroscopy (U.S. EPA, 1983a), as with the total recoverable measurement.

Thus, expressing aquatic life criteria for lead 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 lead or for measuring lead in ambient water or aqueous effluents, measurement of both acid-soluble lead and total recoverable lead in ambient water or effluent or both might be useful. For example, there might be cause for concern if total recoverable lead is much above an applicable limit, even though acid-soluble lead is below the limit.

Unless otherwise noted, all concentrations reported herein are expected to be essentially equivalent to acid-soluble lead concentrations. All concentrations are expressed as lead, not as the chemical tested. The criteria presented herein supersede previous aquatic life water quality criteria for lead (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 exceedences (U.S. EPA, 1985). The latest literature search for information for this document was conducted in May, 1984; some newer information was also used.

a charge of two. The slope for rainbow trout was 2.475 and therefore was not used. A test of equality of slopes showed that P=0.16, indicating that it is not unreasonable to assume that the slopes for the three species are the same.

The pooled slope of 1.273 was used with the data in Table 1 to calculate Species Mean Acute Values at a hardness of 50 mg/L (Table 1). Genus Mean Acute Values (Table 3) were then calculated as geometric means of the available freshwater Species Mean Acute Values. Even though values are available for only four invertebrate species, of the ten genera for which acute values are available, the most sensitive genus, Gammarus, was 1,650 times more sensitive than the most resistant, Tanytarsus. The freshwater Final Acute Value of 67.54 µg/L was calculated at a hardness of 50 mg/L from the Genus Mean Acute Values in Table 3 using the procedure described in the Guidelines. Thus, the freshwater Criterion Maximum Concentration (in µg/L) = $e^{(1.273[\ln(\text{hardness})]-1.460)}$.

Tests of the acute toxicity of lead to saltwater organisms have been conducted with nine species of invertebrates and four species of fish (Table 1). In flow-through toxicity tests with two fish species, less than 50 percent of the test organisms were killed at 3,140 µg/L, which is the solubility of lead in sea water under the test conditions, but the acute value for the mummichog is 315 µg/L. The range of sensitivities of bivalve molluscs is also great, probably reflecting differences in life stage. The adult soft-shell clam had an LC50 of 27,000 µg/L, whereas the acute values with larvae of four species ranged from 476 to 2,450 µg/L. Of the eleven saltwater genera for which acute values are available, the most sensitive genus, Fundulus, was 85 times more sensitive than the most resistant, Mya (Table 3). The sensitivities of the six most sensitive genera differed by only a factor of 2.5, even though these six lowest Genus Mean Acute Values are from tests lead oxide (Table 6) is much less acutely toxic than lead nitrate (Table 1) to the mosquitofish in water containing a high concentration of suspended clay particles.

Different species exhibit different sensitivities to lead, and many other factors might affect the results of tests of the toxicity of lead to aquatic organisms. Criteria can quantitatively take into account such a factor, however, only if enough data are available to show that the factor similarly affects the results of tests with a variety of species. Hardness is often thought of as having a major effect on the toxicity of lead, although the observed effect is probably due to one or more of a number of usually interrelated ions, such as hydroxide, carbonate, calcium, and magnesium. Hardness is used here as a surrogate for the ions which affect the results of toxicity tests on lead. An analysis of covariance (Dixon and Brown, 1979; Neter and Wasserman, 1974) was performed using the natural logarithm of the acute value as the dependent variable, species as the treatment or grouping variable, and the natural logarithm of hardness as the covariate or independent variable. This analysis of covariance model was fit to the data in Table 1 for the four species for which acute values are available over a range of hardness such that the highest hardness is at least three times the lowest and the highest is also at least 100 mg/L higher than the lowest. An F-test showed that, under the assumption of equality of slopes, the probability of obtaining four slopes as dissimilar as these is P=0.03. This was interpreted as indicating that it is unreasonable to assume that the slopes for these four species are the same. The slopes for Daphnia magna, fathead minnow, and bluegill (see end of Table 1) were close to the slope of 1.0 that is expected on the basis that lead, calcium, magnesium, and carbonate all have selected chronic limits based on a very low incidence of black-colored tails and spinal deformities (4.7 and 0.7 percent, respectively). For the purposes of deriving water quality criteria, such low percentages of such effects were not considered unacceptable. The concentration of 27 µg/L was selected as the upper limit because it caused spinal curvature in 32.2 percent of the fish, whereas 13.2 µg/L only caused curvature in 3.6 percent of the fish. The occurrence of black tails was not considered to be an unacceptable effect.

Spinal deformities were also caused by lead in a life-cycle test with brook trout (Holcombe, et al. 1976) and in an early life-stage test with rainbow trout (Sauter, et al. 1976). Results of tests by Sauter, et al. (1976) with the northern pike, walleye, lake trout, channel catfish, white sucker, and bluegill were not included in Tables 2 or 6 because of excessive mortality in the controls. Even though the hardnesses were similar, the chronic value obtained for rainbow trout by Sauter, et al. (1976) is higher than the chronic value derived from Davies, et al. (1976), possibly because Sauter, et al. exposed the fish for 2 months, whereas Davies, et al. exposed the fish for 19 months.

Davies, et al. (1976) described the long-term effects on rainbow trout fry and fingerlings exposed to various concentrations of lead for 19 months in hard and soft water (Table 6). Although these tests were neither life-cycle (no natural reproduction) nor early life-stage (no embryos exposed), they do provide information concerning the relationship between water hardness and the chronic toxicity of lead to fish. In the test in hard water, only 0 and 10 percent of the trout developed spinal deformities at measured lead concentrations of 190 and 380 µg/L, respectively. In soft water 44 and 97 conducted with a variety of species and life stages. The saltwater Final Acute Value was calculated to be 287.4 μg/L.

Chronic Toxicity to Aquatic Animals

Chapman, et al. (Manuscript) studied the chronic toxicity of lead to *Daphnia mägna* at three different hardnesses (Table 2). The daphnids were nearly 11 times more sensitive to lead in soft water than in hard water. The value in soft water was about one-fourth that obtained by Biesinger and Christensen (1972) with the same species in a different soft water in a test in which the concentrations of lead were not measured (Table 6). The chronic values of Chapman, et al. were regressed against hardness; the slope was 2.328, but the 95% confidence limits were -8.274 and 12.931.

A life-cycle test on lead in hard water was conducted by Borgmann, et al. (1978) with a snail. These authors used biomass as their endpoint and reported that lead concentrations as low as 19 μg/L significantly decreased survival, but not growth or reproduction. It is not clear, however, how these investigators arrived at such a low effect concentration. This publication did, however, contain suitable information for determining a chronic value. Chronic limits were taken directly from the cumulative percent survival figure which showed no observed effect on survival at 12 μg/L and almost complete mortality at 54 μg/L. The chronic value (geometric mean of the lower and upper limits) for snails was therefore established at 25.46 μg/L (Table 2).

Davies, et al. (1976) published results of an early life-stage test with rainbow trout in soft water (Table 2). Even though this test was started with embryos and continued for 19 months after hatch, it could not be considered a life-cycle test because no reproduction occurred. Davies, et al. (1976)

A variety of effects on saltwater organisms have been observed. Gray and Ventilla (1973) observed a reduction in growth rate in a ciliate protozoan after 12-hr exposures to lead concentrations of 150 and 300 µg/L. Woolery and Lewin (1976) observed a reduction in photosynthesis and respiration in the diatom, Pheodactylum tricornutum, at concentrations of lead ranging from 100 to 10,000 µg/L. However, Hannan and Patouillet (1972) obtained no inhibition of growth of the same species at a concentration of 1,000 µg/L after 72 hours. Rivkin (1979), using growth rate to determine toxicity to the diatom, Skeletonema costatum, reported a 12-day EC50 of 5.1 µg/L. Hessler (1974) observed delayed cell division in the phytoplankton, Platymonas subcordiformus, during exposure to 2,500 µg/L for 72 hours. At 60,000 µg/L, however, Hessler (1974) reported not only growth retardation but also death. Benijts-Claus and Benijts (1975) observed delayed larval development in the mud crab, Rhithropanopeus harrisii, during exposure to 50 µg/L. Weis and Weis (1977) observed depressed axis formation in developing embryos of Fundulus heteroclitus at lead concentrations of 100 µg/L. Reish and Carr (1978) found that 1,000 µg/L suppressed reproduction of two polychaete species, Ctenodrilus serratus and Ophryotrocha diadema, in a 21-day test.

Unused Data

Some data on the effects of lead on aquatic organisms were not used because the studies were conducted with species that are not resident in North America. Jennett, et al. (1981) did not identify their test animals beyond common names such as "algae, crayfish, and minnows". Nehring, et al. (1979) did not identify their organisms to species, so it is not known if

Marcelli (1979), Pawlaczyk-Szpilowa and Slowik (1981), Rao and Saxena (1980), and Rolfe, et al. (1977) exposed algae, invertebrates, and fish to lead but failed to adequately describe their test methods. Carpenter (1926, 1930), Carter and Cameron (1973), Ellgaard and Rudner (1982), Ellis (1940), Grande and Andersen (1983), Jones (1938, 1939), Nyman (1981), Ozoh (1979), Rathore, et al. (1979), Shaw and Grushkin (1957), Shaw and Lowrance (1956), Vijaymadhavan and Iwai (1975), Wang (1959), and Weir and Hine (1970) conducted tests in distilled, deionized, chlorinated, or "tap" water.

Biegert and Valkovic (1980) expressed their acute data in hours to death and concentrations were a factor of ten apart. The concentrations of lead overlapped in the tests by Sparks, et al. (1983). Tests on the toxicity of lead to algae were not used if the medium contained too much of a complexing agent such as EDTA (Davis, 1978).

Results of laboratory bioconcentration tests were not used if the test was not flow-through (Montgomery, et al. 1978; Watling, 1983), if the test did not last long enough (Wong, et al. 1981), if no soft tissues were analyzed (Sturesson, 1978), if the concentration in water was not known (Ray, et al. 1981) or was not measured often enough (Freeman, 1978, 1980), or if control mortalities were high (Valiela, et al. 1974). Studies such as those by Ancellin, et al. (1973), Aubert, et al. (1974), and Nash, et al. (1981), which used radioactive isotopes of lead, were not used because of the possibility of isotope discrimination. Newman and McIntosh (1983b) conducted a depuration study, but not an uptake study.

A large number of reports on lead toxicity and residues in wild aquatic organisms could not be used for the calculation of bioaccumulation factors or toxicity due to an insufficient number of measurements of the concentration report: Ferard, et al. (1982), Foster (1982a,b), Gentile, et al. (1982), Marion and Denizeau (1983), Passino and Cotant (1979), Say and Whitton (1983), Vighi (1981), Wehr and Whitton (1983a,b), and Whitton, et al. (1982). Dorfman and Whitworth (1969) exposed brook trout to lead only on week days and the concentrations were not measured during tests lasting up to 38 days. These authors and Carpenter (1927), Rushton (1922), and Tarzwell and Henderson (1960) conducted tests with only one or two fish at a time. Rainbow trout tested by Hodson, et al. (1978b) were not acclimated to abrupt changes in pH before stressing them with lead. Experiments reported by Hodson, et al. (1982) were designed to measure lead uptake in opercular bone and formation of black tails correlated to different growth rates of rainbow trout; however, these fish were only exposed to one sublethal concentration of lead. No data are available on the concentrations of lead in water during the studies reported by Hodson, et al. (1983a). Sicko-Goad (1982), Sicko-Goad and Lazinsky (1981, 1982), and Sicko-Goad and Stoermer (1979) exposed algae to only one sublethal concentration of lead. The 96-hr values reported by Buikema, et al. (1974a,b) were subject to error because of possible reproductive interactions (Buikema, et al. 1977). Clarke and Clarke (1974) reported that their test water was contaminated with lead leached from plastic exposure tanks. Exposure times were not reported by Brown (1976) and Haider (1964). Kariya, et al. (1969) and Turnbull (1954) failed to report the number of fish tested. High control mortalities occurred in all except one test reported by Sauter, et al. (1976). Control mortality exceeded 10 percent in two tests by Mount and Norberg (1984).

English, et al. (1963) published results based on volume dilutions instead of nominal or measured concentrations. Brown (1968), Garavini and on data for four species. Bioconcentration factors are available for four invertebrate and two fish species and range from 42 to 1,700.

Acute values are available for 13 saltwater animal species and range from 315 µg/L for the mummichog to 27,000 µg/L for the soft-shell clam. A chronic toxicity test was conducted with a mysid; unacceptable effects were observed at 37 µg/L but not at 17 µg/L and the acute-chronic ratio for this species is 124.8. A species of macroalgae was affected at 20 µg/L. Available bioconcentration factors range from 17.5 to 2,570.

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 (in µg/L) of lead does not exceed the numerical value given by $e^{(1.273[\ln(\text{hardness})]-4.705)}$ more than once every three years on the average and if the one-hour average concentration (in µg/L) does not exceed the numerical value given by $e^{(1.273[\ln(\text{hardness})]-1.460)}$ more than once every three years on the average. For example, at hardnesses of 50, 100, and 200 mg/L as $CaCO_3$ the four-day average concentrations of lead are 1.3, 3.2, and 7.7 µg/L, respectively, and the one-hour average concentrations are 34, 82, and 200 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 lead does not of lead in the water: Anderson (1977), Badsha and Goldspink (1982), Brezina and Arnold (1977), Brezina, et al. (1974), Brown and Chow (1977), Eide and Myklestad (1980), Enk and Mathis (1977), Evans and Lasenby (1983), Gale, et al. (1973a,b, 1982), Gordon, et al. (1980), Holm (1980), Kharkar, et al. (1976), Knowlton, et al. (1983), Leland and McNurney (1974), Lucus and Edgington (1970), Martin and Mudre (1982), Martin, et al. (1984), Mathis and Cummings (1973), Mathis and Kevern (1975), May and McKinney (1981), Mehrle, et al. (1982), Newman and McIntosh (1983a), Pagenkopf and Newman (1974), Pakkala, et al. (1972), Pennington, et al. (1982), Popham and D'Auria (1981), Price and Knight (1978), Randall, et al. (1981), Ray (1978), Sidwell, et al. (1978), Simpson (1979), Smith, et al. (1981), Tong, et al. (1974), Trollope and Evans (1976), Tsui and McCart (1981), Uthe and Bligh (1971), Vinikour, et al. (1980), Wachs (1982), Walsh, et al. (1977), Welsh and Denny (1980), Wixson and Bolter (1972), and Wren, et al. (1983).

<u>Summary</u>

The acute toxicity of lead to several species of freshwater animals has been shown to decrease as the hardness of water increases. At a hardness of 50 mg/L the acute sensitivities of ten species range from 142.5 μg/L for an amphipod to 235,900 μg/L for a midge. Data on the chronic effects of lead on freshwater animals are available for two fish and two invertebrate species. The chronic toxicity of lead also decreases as hardness increases and the lowest and highest available chronic values (12.26 and 128.1 μg/L) are both for a cladoceran, but in soft and hard water, respectively. Acute-chronic ratios are available for three species and range from 18 to 62. Freshwater algae are affected by concentrations of lead above 500 μg/L, based exceed 5.6 µg/L more than once every three years on the average and if the one-hour average concentration does not exceed 140 µg/L more than once every three years on the average.

EPA believes that a measurement such as "acid-soluble" would provide a more scientifically correct basis upon which to establish criteria for metals. The criteria were developed on this basis. However, at this time, no EPA approved methods for such a measurement are available to implement the criteria through the regulatory programs of the Agency and the States. The Agency is considering development and approval of methods for a measurement such as "acid-soluble". Until available, however, EPA recommends applying the criteria using the total recoverable method. This has two impacts: (1) certain species of some metals cannot be analyzed directly because the total recoverable method does not distinguish between individual oxidation states, and (2) these criteria may be overly protective when based on the total recoverable method.

The recommended exceedence frequency of three years is the Agency's best scientific judgment of the average amount of time it will take an unstressed system to recover from a pollution event in which exposure to lead 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 resilience of ecosystems and their ability to recover differ greatly, however, and site-specific criteria may be established if adequate justification is provided.

The use of criteria in designing waste treatment facilities requires the selection of an appropriate wasteload allocation model. Dynamic models are preferred for the application of these criteria. Limited data or other

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)***	Reference
Rainbow trout, *Salmo gairdneri*	S, U	Lead nitrate	290	542,000	-	Goettl, et al. 1972; Davies & Everhart, 1973; Davies, et al. 1976
Rainbow trout, *Salmo gairdneri*	S, U	Lead nitrate	353	471,000	-	Goettl, et al. 1972; Davies & Everhart, 1973; Davies, et al. 1976
Rainbow trout, *Salmo gairdneri*	FT, U	Lead nitrate	28	1,170	2,448†	Goettl, et al. 1972; Davies & Everhart, 1973; Davies, et al. 1976
Brook trout (18 mos), *Salvelinus fontinalis*	FT, M	Lead nitrate	44	4,100	4,820	Holcombe, et al. 1976
Goldfish, *Carassius auratus*	S, U	Lead chloride	20	31,500	101,100	Pickering & Henderson, 1966
Fathead minnow, *Pimephales promelas*	S, U	Lead chloride	20	5,580	-	Pickering & Henderson, 1966
Fathead minnow, *Pimephales promelas*	S, U	Lead chloride	20	7,330	-	Pickering & Henderson, 1966
Fathead minnow, *Pimephales promelas*	S, U	Lead chloride	360	482,000	25,440	Pickering & Henderson, 1966
Mosquitofish (adult), *Gambusia affinis*	S, U	Lead nitrate	-	240,000††	-	Wallen, et al. 1957
Guppy (6 mos), *Poecilia reticulata*	S, U	Lead chloride	20	20,600	66,140	Pickering & Henderson, 1966
Bluegill, *Lepomis macrochirus*	S, U	Lead chloride	20	23,800	-	Pickering & Henderson, 1966
Bluegill, *Lepomis macrochirus*	S, U	Lead chloride	360	442,000	52,310	Pickering & Henderson, 1966

Table 1. Acute Toxicity of Lead to Aquatic Animals

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)***	Reference
			FRESHWATER SPECIES			
Snail, *Aplexa hypnorum*	FT, M	Lead nitrate	61	1,340	1,040	Call, et al. 1981
Cladoceran, *Daphnia magna*	S, U	Lead chloride	-	931	-	Anderson, 1948
Cladoceran, *Daphnia magna*	S, U	Lead nitrate	-	5,000****	-	Bringmann & Kuhn, 1959a,b
Cladoceran, *Daphnia magna*	R, M	Lead nitrate	54	612	-	Chapman, et al. Manuscript
Cladoceran, *Daphnia magna*	R, M	Lead nitrate	110	952	-	Chapman, et al. Manuscript
Cladoceran, *Daphnia magna*	R, M	Lead nitrate	152	1,910	447.8	Chapman, et al. Manuscript
Cladoceran, *Daphnia pulex*	S, U	Lead nitrate	45	5,100*****	-	Mount & Norberg, 1984
Cladoceran, *Simocephalus vetulus*	S, U	Lead nitrate	45	4,500*****	-	Mount & Norberg, 1984
Amphipod, *Gammarus pseudolimnaeus*	FT, M	Lead nitrate	46	124	-	Spehar, et al. 1978
Amphipod, *Gammarus pseudolimnaeus*	FT, M	Lead nitrate	48	140	142.6	Call, et al. 1983
Crayfish, *Orconectes limosus*	S, M	Lead chloride	-	3,300	-	Boutet & Chaisemartin, 1973
Midge, *Tanytarsus dissimilis*	FT, M	Lead nitrate	48	224,000	235,900	Call, et al. 1983
Rainbow trout (2 mos), *Salmo gairdneri*	FT, M	Lead nitrate	-	8,000	-	Hale, 1977

Table 1. (Continued)

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

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

*** Freshwater Species Mean Acute Values are calculated at a hardness of 50 mg/L using the pooled slope.

**** In river water.

***** Not used in calculations because the values in Mount and Norberg (1984) are much higher than values for other species in the same genus and family.

† Calculated from acute value of 1,170 µg/L using pooled slope (see text).

†† High turbidity.

Results of Covariance Analysis of Freshwater Acute Toxicity versus Hardness

Species	n	Slope	95% Confidence Limits	Degrees of Freedom
Daphnia magna	3	1.021	-3.592, 5.634	1
Rainbow trout	3	2.475	-0.357, 5.308	1
Fathead minnow	3	1.495	0.458, 2.533	1
Bluegill	2	1.011	(cannot be calculated)	0
All of above	11	1.608*	1.014, 2.202	6
All of above except rainbow trout	8	1.273**	0.909, 1.637	4

* P=0.03 for equality of slopes.

** P=0.16 for equality of slopes.

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)***	Reference
			SALTWATER SPECIES			
Blue mussel (larva), *Mytilus edulis*	S, U	Lead nitrate	-	476	476	Martin, et al. 1981
Pacific oyster (larva), *Crassostrea gigas*	S, U	Lead nitrate	-	758	758	Martin, et al. 1981
Eastern oyster (larva), *Crassostrea virginica*	S, U	Lead nitrate	-	2,450	2,450	Calabrese, et al. 1973
Quahog clam (larva), *Mercenaria mercenaria*	S, U	Lead nitrate	-	780	780	Calabrese & Nelson, 1974
Soft-shell clam (adult), *Mya arenaria*	S, U	Lead nitrate	-	27,000	27,000	Eisler, 1977
Copepod, *Acartia clausi*	S, U	Lead nitrate	-	668	668	Gentile, 1982
Mysid, *Mysidopsis bahia*	FT, M	Lead nitrate	-	3,130	3,130	Lussier, et al. Manuscript
Amphipod, *Ampelisca abdita*	R, U	Lead nitrate	-	547	547	Scott, et al. Manuscript
Dungeness crab, *Cancer magister*	S, U	Lead nitrate	-	575	575	Martin, et al. 1981
Sheepshead minnow, *Cyprinodon variegatus*	FT, M	Lead nitrate	-	>3,140	>3,140	Cardin, 1981
Mummichog, *Fundulus heteroclitus*	S, U	Lead nitrate	-	315	315	Dorfman, 1977
Inland silverside, *Menidia beryllina*	FT, M	Lead nitrate	-	>3,140	>3,140	Cardin, 1981
Atlantic silverside, *Menidia menidia*	S, U	Lead nitrate	-	>10,000	>10,000	Berry, 1981

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Table 2. (Continued)

Acute-Chronic Ratio

Species	Hardness (mg/L as $CaCO_3$)	Acute Value (µg/L)	Chronic Value (µg/L)	Ratio
Cladoceran, *Daphnia magna*	52-54	612	12.26	49.92
Cladoceran, *Daphnia magna*	102-110	952	118.8	8.013
Cladoceran, *Daphnia magna*	151-152	1,910	128.1	14.91
Rainbow trout, *Salmo gairdneri*	28	1,170	18.88	61.97
Brook trout, *Salvelinus fontinalis*	44	4,100	83.08	49.35
Mysid, *Mysidopsis bahia*	-	3,130	25.08	124.8

Table 2. Chronic Toxicity of Lead to Aquatic Animals

Species	Test*	Chemical	Hardness (mg/L as $CaCO_3$)	Limits (µg/L)**	Chronic Value (µg/L)**	Reference
			FRESHWATER SPECIES			
Snail, *Lymnaea palustris*	LC	Lead nitrate	139	12-54	25.46	Borgmann, et al. 1978
Cladoceran, *Daphnia magna*	LC	Lead nitrate	52	9-16.7	12.26	Chapman, et al. Manuscript
Cladoceran, *Daphnia magna*	LC	Lead nitrate	102	78-181	118.8	Chapman, et al. Manuscript
Cladoceran, *Daphnia magna*	LC	Lead nitrate	151	85-193	128.1	Chapman, et al. Manuscript
Rainbow trout, *Salmo gairdneri*	ELS	Lead nitrate	28	13.2-27	18.88	Goettl, et al. 1972; Davies & Everhart, 1973; Davies, et al. 1976
Rainbow trout, *Salmo gairdneri*	ELS	Lead nitrate	35	71-146	101.8	Sauter, et al. 1976
Brook trout, *Salvelinus fontinalis*	LC	Lead nitrate	44	58-119	83.08	Holcombe, et al. 1976
			SALTWATER SPECIES			
Mysid, *Mysidopsis bahia*	LC	Lead nitrate	-	17-37	25.08	Lussier, et al. Manuscript

* LC = life cycle or partial life cycle, ELS = early life stage.

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

Results of Regression Analysis of Freshwater Chronic Toxicity versus Hardness

Species	n	Slope	95% Confidence Limits	Degrees of Freedom
Daphnia magna	3	2.328	-8.274, 12.951	1

Table 3. (Continued)

Rank*	Genus Mean Acute Value (µg/L)**	Species	Species Mean Acute Value (µg/L)**	Species Mean Acute-Chronic Ratio
10	>5,604	Inland silverside, *Menidia beryllina*	>3,140	-
		Atlantic silverside, *Menidia menidia*	>10,000	-
9	>3,140	Sheepshead minnow, *Cyprinodon variegatus*	>3,140	-
8	3,130	Mysid, *Mysidopsis bahia*	3,130	124.8
7	1,363	Pacific oyster, *Crassostrea gigas*	758	-
		Eastern oyster, *Crassostrea virginica*	2,450	-
6	780	Quahog clam, *Mercenaria mercenaria*	780	-
5	668	Copepod, *Acartia clausi*	668	-
4	575	Dungeness crab, *Cancer magister*	575	-
3	547	Amphipod, *Ampelisca abdita*	547	-
2	476	Blue mussel, *Mytilus edulis*	476	-
1	315	Mummichog, *Fundulus heteroclitus*	315	-

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		
10	235,900	Midge, *Tanytarsus dissimilis*	235,900	-
9	101,100	Goldfish, *Carassius auratus*	101,100	-
8	66,140	Guppy, *Poecilia reticulata*	66,140	-
7	52,310	Bluegill, *Lepomis macrochirus*	52,310	-
6	25,440	Fathead minnow, *Pimephales promelas*	25,440	-
5	4,820	Brook trout, *Salvelinus fontinalis*	4,820	49.35
4	2,448	Rainbow trout, *Salmo gairdneri*	2,448	61.97
3	1,040	Snail, *Aplexa hypnorum*	1,040	-
2	447.8	Cladoceran, *Daphnia magna*	447.8	18.13***
1	142.6	Amphipod, *Gammarus pseudolimnaeus*	142.6	-
		SALTWATER SPECIES		
11	27,000	Soft-shell clam, *Mya arenaria*	27,000	-

Table 4. Toxicity of Lead to Aquatic Plants

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Effect	Result (µg/L)*	Reference
			FRESHWATER SPECIES		
Alga, *Ankistrodesmus* sp.	Lead chloride	-	24% growth inhibition	1,000	Monahan, 1976
Alga. *Ankistrodesmus falcatus*	Lead chloride	-	40% reduction in growth	2,500	Devi Prasad & Devi Prasad, 1982
Alga, *Chlorella* sp.	Lead chloride	-	53% growth inhibition	500	Monahan, 1976
Alga, *Chlorella saccharophila*	Lead chloride	-	EC50	63,800	Rachlin, et al. 1982
Alga, *Chlorococcum* sp.	Lead chloride	-	29% reduction in growth	2,500	Devi Prasad & Devi Prasad, 1982
Alga, *Scenedesmus* sp.	Lead chloride	-	35% growth inhibition	500	Monahan, 1976
Alga, *Scenedesmus obliquus*	Lead chloride	-	28% reduction in growth	2,500	Devi Prasad & Devi Prasad, 1982
Alga, *Selenastrum* sp.	Lead chloride	-	52% growth inhibition	500	Monahan, 1976
Diatom, *Navicula incerta*	Lead chloride	-	EC50	10,960	Rachlin, et al. 1983
Eurasian watermilfoil, *Myriophyllum spicatum*	-	-	32-day EC50 (root growth)	363,000	Stanley, 1974
			SALTWATER SPECIES		
Alga, *Champia parvula*	Lead nitrate	-	Stopped sexual reproduction	20.3	Steele & Thursby, 1983
Alga, *Champia parvula*	Lead nitrate	-	Reduced female growth	20.3	Steele & Thursby, 1983

Table 3. (Continued)

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* Ranked from most resistant to most sensitive based on Genus Mean Acute Value.

** Freshwater Genus Mean Acute Values and Species Mean Acute Values are at a hardness of 50 mg/L.

***Geometric mean of three values in Table 2.

<u>Fresh water</u>

Final Acute Value = 67.54 µg/L (at a hardness of 50 mg/L)

Criterion Maximum Concentration = (67.54 µg/L) / 2 = 33.77 µg/L (at a hardness of 50 mg/L)

Pooled Slope = 1.273 (see Table 1)

ln(Criterion Maximum Intercept) = ln(33.77) - [slope x ln(50)]

= 3.520 - (1.273 x 3.912) = -1.460

Criterion Maximum Concentration = $e^{(1.273[\ln(\text{hardness})]-1.460)}$

Final Acute-Chronic Ratio = 51.29 (see text)

Final Chronic Value = (67.54 µg/L) / 51.29 = 1.317 µg/L (at a hardness of 50 mg/L)

ln(Final Chronic Intercept) = ln(1.317) - [slope x ln(50)]

= 0.2754 - (1.273 x 3.912) = -4.705

Final Chronic Value = $e^{(1.273[\ln(\text{hardness})]-4.705)}$

<u>Salt water</u>

Final Acute Value = 287.4 µg/L

Criterion Maximum Concentration = (287.4 µg/L) / 2 = 143.7 µg/L

Final Acute-Chronic Ratio = 51.29 (see text)

Final Chronic Value = (287.4 µg/L) / 51.29 = 5.603 µg/L

Table 5. Bioaccumulation of Lead by Aquatic Organisms

Species	Tissue	Chemical	Duration (days)	Bioconcentration Factor*	Reference
		FRESHWATER SPECIES			
Snail, *Lymnaea palustris*	Whole body	Lead nitrate	120	1,700**	Borgmann, et al. 1978
Snail, *Physa integra*	Whole body	Lead nitrate	28	738**	Spehar, et al. 1978
Stonefly, *Pteronarcys dorsata*	Whole body	Lead nitrate	28	1,120**	Spehar, et al. 1978
Caddisfly, *Brachycentrus* sp.	Whole body	Lead nitrate	28	499**	Spehar, et al. 1978
Brook trout (embryo-3 mos), *Salvelinus fontinalis*	Whole body	Lead nitrate	140	42**	Holcombe, et al. 1976
Bluegill, *Lepomis macrochirus*	Whole body	-	-***	45**	Atchison, et al. 1977
		SALTWATER SPECIES			
Diatom, *Ditylum brightwellii*	Cells	Lead chloride	14	725**	Canterford, et al. 1978
Blue mussel, *Mytilus edulis*	Soft parts	Lead nitrate	40	650**	Schulz-Baldes, 1974
Blue mussel, *Mytilus edulis*	Soft parts	Lead chloride	37	200**	Talbot, et al. 1976
Blue mussel, *Mytilus edulis*	Soft parts	Lead nitrate	130	2,570**	Schulz-Baldes, 1972
Blue mussel, *Mytilus edulis*	Soft parts	Lead nitrate	130	2,080**	Schulz-Baldes, 1972
Blue mussel, *Mytilus edulis*	Soft parts	Lead nitrate	130	796**	Schulz-Baldes, 1972
Eastern oyster, *Crassostrea virginica*	Soft parts	Lead nitrate	140	536	Zaroogian, et al. 1979

Table 4. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Effect	Result (µg/L)*	Reference
Alga, *Champia parvula*	Lead nitrate	-	Reduced tetrasporangia production	23.3	Steele & Thursby, 1983
Alga, *Champia parvula*	Lead nitrate	-	Reduced tetrasporophyte growth	23.3	Steele & Thursby, 1983
Alga, *Dunaliella salina*	Lead nitrate	-	65% growth reduction	900	Pace, et al. 1977
Diatom, *Ditylum brightwelli*	Lead chloride	-	EC50	40	Canterford & Canterford, 1980
Diatom, *Asterionella japonica*	Lead nitrate	-	EC50	207	Fisher & Jones, 1981

* Results are expressed as lead, not as the chemical. All results are based on unmeasured concentrations.

Table 6. Other Data on Effects of Lead on Aquatic Organisms

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Result (μg/L)*	Reference
			FRESHWATER SPECIES			
Green alga, *Scenedesmus quadricauda*	Lead nitrate	-	96 hrs	Incipient inhibition	2,500**	Bringmann & Kuhn, 1959a,b
Blue alga, *Microcystis aeruginosa*	Lead acetate	-	8 days	Incipient inhibition	450	Bringmann, 1975; Bringmann & Kuhn, 1976, 1978a,b
Green alga, *Scenedesmus quadricauda*	Lead acetate	-	8 days	Incipient inhibition	3,700	Bringmann & Kuhn, 1977a, 1978a,b, 1979, 1980b
Alga, *Anabaena* sp.	Lead nitrate	-	24 hrs	50% reduction of $^{14}CO_2$ fixation	15,000 26,000 15,000	Malanchuk & Gruendling, 1973
Alga, *Chlamydomonas* sp.	Lead nitrate	-	24 hrs	50% reduction of $^{14}CO_2$ fixation	17,000 17,000	Malanchuk & Gruendling, 1973
Angiosperm, *Potamogeton pectinatus*	Lead acetate	-	3 days	Reduced respiration	325,200	Jana & Choudhuri, 1982
Angiosperm, *Vallisneria spiralis*	Lead acetate	-	3 days	Reduced respiration	3,252,000	Jana & Choudhuri, 1982
Desmid, *Cosmarium* sp.	Lead nitrate	-	24 hrs	50% reduction of $^{14}CO_2$ fixation	5,000 5,000 5,000	Malanchuk & Gruendling, 1973
Diatom, *Navicula* sp.	Lead nitrate	-	24 hrs	50% reduction of $^{14}CO_2$ fixation	17,000 28,000 17,000	Malanchuk & Gruendling, 1973
Bacterium, *Escherichia coli*	Lead nitrate	-	-	Incipient inhibition	1,300	Bringmann & Kuhn, 1959a
Bacterium, *Pseudomonas putida*	Lead acetate	-	16 hrs	Incipient inhibition	1,800	Bringmann & Kuhn, 1976, 1977a, 1979, 1980b
Protozoan, *Entosiphon sulcatum*	Lead acetate	-	72 hrs	Incipient inhibition	20	Bringmann, 1978; Bringmann & Kuhn, 1979, 1980b, 1981

Table 5. (Continued)

Species	Tissue	Chemical	Duration (days)	Bioconcentration Factor*	Reference
Eastern oyster, *Crassostrea virginica*	Soft parts	Lead nitrate	49	68**	Pringle, et al. 1968
Eastern oyster, *Crassostrea virginica*	Soft parts	Lead nitrate	70	1,400	Shuster & Pringle, 1969
Quahog clam, *Mercenaria mercenaria*	Soft parts	Lead nitrate	56	17.5**	Pringle, et al. 1968

* Results are based on lead, not the chemical.

** Bioconcentration factor was converted from dry weight to wet weight basis.

***This field study was conducted with a natural population of bluegills living in a small lake which was extensively analyzed for lead, zinc, and cadmium.

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Result (µg/L)*	Reference
Mayfly, *Ephemerella grandis*	Lead nitrate	50	14 days	LC50	3,500	Nehring, 1976
Mayfly (nymph), *Ephemerella grandis*	Lead nitrate	50	14 days	BCF = 2,366	-	Nehring, 1976
Mayfly, *Ephemerella subvaria*	Lead sulfate	44	7 days	LC50	16,000	Warnick & Bell, 1969
Stonefly, *Pteronarcys californica*	Lead nitrate	50	14 days	BCF = 86	-	Nehring, 1976
Stonefly, *Pteronarcys dorsata*	Lead nitrate	46	28 days	No effect on survival	565	Spehar, et al. 1978
Caddisfly, *Hydropsyche betteni*	Lead sulfate	44	7 days	LC50	32,000	Warnick & Bell, 1969
Caddisfly, *Brachycentrus* sp.	Lead nitrate	46	28 days	No effect on survival	565	Spehar, et al. 1978
Midge, (embryo - 3rd instar), *Tanytarsus dissimilis*	Lead nitrate	47	10 days	LC50	258	Anderson, et al. 1980
Rainbow trout, *Salmo gairdneri*	Lead nitrate	135	28 days	Inhibition of ALA-D activity	13	Hodson, 1976
Rainbow trout (12 mos), *Salmo gairdneri*	-	135	14 days	Inhibition of ALA-D activity	10	Hodson, et al. 1977
Rainbow trout, *Salmo gairdneri*	Lead nitrate	135	21 days	LC50	2,400	Hodson, et al. 1978a
Rainbow trout, *Salmo gairdneri*	Lead nitrate	135	32 wks	Black-tails in 3 of 10 remaining fish	120	Hodson, et al. 1978a; Sippel, et al. 1983
Rainbow trout, *Salmo gairdneri*	Lead nitrate	135	32 wks	Affected RBC, iron content, and ALA-D in blood	13	Hodson, et al. 1978a

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Result (µg/L)*	Reference
Rainbow trout, *Salmo gairdneri*	-	135	29 wks	All fish had black tails and decrease in ALA-D in blood	87	Hodson, et al. 1979a, 1980
Rainbow trout, *Salmo gairdneri*	Lead nitrate	135	30 wks	64% inhibition of ALA-D activity and black tails in 88% of fish	65	Hodson, et al. 1979b
Rainbow trout, *Salmo gairdneri*	Lead nitrate	135	20 days	45% inhibition of ALA-D activity	25	Hodson, et al. 1983b
Rainbow trout (embryo, larva), *Salmo gairdneri*	Lead chloride	101	28 days	EC50 (death and deformity)	220	Birge, et al. 1980
Rainbow trout (embryo, larva), *Salmo gairdneri*	Lead chloride	101	28 days	EC1 (death and deformity)	10.3	Birge, et al. 1980, 1981
Rainbow trout (fingerling), *Salmo gairdneri*	Lead nitrate	353	19 mos	Lordoscoliosis	850	Goettl, et al. 1972; Davies, et al. 1976
Rainbow trout (sac fry), *Salmo gairdneri*	Lead nitrate	28	19 mos	Lordoscoliosis	31	Goettl, et al. 1972; Davies, et al. 1976
Brook trout, *Salvelinus fontinalis*	-	-	21 days	Stamina	14	Adams, 1975
Brook trout (12 mos), *Salvelinus fontinalis*	Lead nitrate	135	14 days	Inhibition of ALA-D activity	90	Hodson, et al. 1977
Brook trout (embryo - 21 day), *Salvelinus fontinalis*	Lead chloride	44	38 days	Elevation of ALP and ACH activity	525	Christensen, 1975
Brook trout (12 mos), *Salvelinus fontinalis*	Lead chloride	44	56 days	Decrease of hemoglobin and inhibition of GOT activity	58	Christensen, et al. 1977
Goldfish (embryo, larva), *Carassius auratus*	Lead chloride	195	7 days	EC50 (death and deformity)	1,660	Birge, 1978
Goldfish (<12 mos), *Carassius auratus*	Lead nitrate	135	14 days	Inhibition of ALA-D activity	470	Hodson, et al. 1977

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Result (µg/L)*	Reference
Alga, <u>Dunaliella tertiolecta</u>	Tetramethyl lead	-	96 hrs	EC50	1,650	Marchetti, 1978
Alga, <u>Dunaliella tertiolecta</u>	Tetraethyl lead	-	96 hrs	EC50	150	Marchetti, 1978
Alga, <u>Chlorella stigmatophora</u>	Lead acetate	-	21 days	50% growth inhibition	700	Christensen, et al. 1979
Natural phytoplankton populations	Lead chloride	-	5 days	Reduced chlorophyll a	207	Hollibaugh, et al. 1980
Natural phytoplankton populations	Lead chloride	-	4 days	Reduced biomass	21	Hollibaugh, et al. 1980.
Macroalga, <u>Fucus serratus</u>	Lead acetate	-	-	45% growth inhibition	810	Stromgren, 1980
Ciliate protozoa, <u>Cristigera</u> sp.	Lead nitrate	-	12 hrs	Reduced growth rate by 8.5%	150	Gray & Ventilla, 1973
Ciliate protozoa, <u>Cristigera</u> sp.	Lead nitrate	-	12 hrs	Reduced growth rate by 11.7%	300	Gray & Ventilla, 1973
Polychaete worm, <u>Ophryotrocha diadema</u>	Lead acetate	-	96 hrs	LC50	14,100	Reish, et al. 1976
Polychaete worm, <u>Ophryotrocha diadema</u>	Lead acetate	-	21 days	Suppressed reproduction	1,000	Reish & Carr, 1978
Polychaete worm, <u>Ophryotrocha diadema</u>	Lead chloride	-	48 hrs	LC50	100,000	Parker, 1984
Polychaete worm, <u>Ctenodrilus serratus</u>	Lead acetate	-	21 days	Suppressed reproduction	1,000	Reish & Carr, 1978
Polychaete worm, <u>Capitella capitata</u>	Lead acetate	-	96 hrs	LC50	1,200	Reish, et al. 1976

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Result (µg/L)*	Reference
Shiner perch, *Cymatogaster aggregata*	Lead nitrate	-	-	27% inhibition of brain cholinesterase	7.8	Abou-Donia & Menzel, 1967

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

** In river water.

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Result (µg/L)*	Reference
Red abalone, *Haliotis rufescens*	Lead chloride	-	6 mos	Accumulated 21 µg/g wet wt while being fed a brown alga (*Egregia laevigata*) which was pretreated with 1 mg/L	-	Stewart & Schulz-Baldes, 1976
Blue mussel, *Mytilus edulis*	Lead chloride	-	40 days	LC50	30,000	Talbot, et al. 1976
Blue mussel, *Mytilus edulis*	Lead nitrate	-	150 days	LT50	500	Schulz-Baldes, 1972
Eastern oyster, *Crassostrea virginica*	Field study	-	1 yr	BCF = 326	-	Kopfler & Mayer, 1973
Oyster, Unspecified	Lead acetate	-	14 days	BCF = 1044	-	Stone, et al. 1981
Soft-shell clam, *Mya arenaria*	Lead nitrate	-	168 hrs	LC50	8,800	Eisler, 1977
American lobster, *Homarus americanus*	Lead nitrate	-	30 days	Reduced enzyme activity	50	Gould & Greig, 1983
Mud crab, *Rhithropanopeus harrisii*	Lead chloride	-	-	Delayed larval development	50	Benijts-Claus & Benijts, 1975
Fiddler crab, *Uca pugilator*	Lead nitrate	-	2 wks	BCF = 20	-	Weis, 1976
Sea urchin, *Arbacia punctulata*	Lead nitrate	-	-	Few gastrula developed	14	Waterman, 1937
Mummichog (embryo), *Fundulus heteroclitus*	Lead nitrate	-	-	Depressed axis formation	100	Weis & Weis, 1977
Mummichog (embryo), *Fundulus heteroclitus*	Lead nitrate	-	-	Retarded hatching	10,000	Weis & Weis, 1982

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