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Ambient Water Quality Criteria for

Nickel - 1986

AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR

NICKEL

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NOTICES

This document has been reviewed by the Criteria and Standards Division, Office of Water Regulations and Standards, U.S. Environmental Protection Agency, and approved for publication.

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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 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 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*

Nickel is one of the most common of the metals occurring in surface waters (Forstner 1984; Hutchinson et al. 1975; Kopp and Kroner 1967; Martin and Knauer 1972; Mathis and Cummings 1973; McCabe et al. 1970; Portman 1972; Solbe 1973; Trollope and Evans 1976; Young 1982). Although nickel can exist in oxidation states of -1, 0, +1, +2, +3, and +4, under usual conditions in surface waters the divalent cation greatly predominates and is generally considered the most toxic. Alkalinity, hardness, salinity, pH, temperature, and such complexing agents as humic acids influence the oxidation state, toxicity, and availability of the nickel in aquatic ecosystems.

Natural sources of the nickel in surface waters include weathering of rocks, inflow of particulate matter, and precipitation. Anthropogenic sources of nickel include the burning of coal and other fossil fuels and discharges from such industries as electroplating and smelting. Although fly ash can contain as much as 960 μg/g (Swaine 1980), lake restoration projects have experimented with the use of fly ash to remove nutrients.

Mechanisms of nickel toxicity are varied and complex (Mushak 1980), and, as with other heavy metals, significant effects occur at cell membranes and membranous tissues, such as gills. In fish, hematological effects such as hyperglycemia, lymphopenia, and erythrocytosis have been reported in association with nickel intoxication (Agrawal et al. 1979; Chaudhry 1984; Chaudhry and Nath 1985; Chaudry and Nath 1985; Gill and Pant 1981).

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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, and the response to public comment (U.S. EPA 1985a) is necessary in order to understand the following text, tables, and calculations.

Because of the variety of forms of nickel (Callahan et al. 1979; Nriagu 1980) and lack of definitive information about their relative toxicities, no available analytical measurement is known to be ideal for expressing aquatic life criteria for nickel. Previous aquatic life criteria for nickel (U.S. EPA 1980) were expressed in terms of total recoverable nickel (U.S. EPA 1983a), but this measurement is probably too rigorous in some situations. Acid-soluble nickel (operationally defined as the nickel 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 present for the following reasons:

1. This measurement is compatible with nearly all available data concerning toxicity of nickel to, and bioaccumulation of nickel 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 nickel. For example, results reported in terms of dissolved nickel would not have been used if the concentration of precipitated nickel had been substantial.
2. On samples of ambient water, measurement of acid-soluble nickel will probably measure all forms of nickel 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 nickel 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. Although this measurement (and many others) will measure soluble complexed forms of nickel, such as the EDTA complex of nickel, 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 nickel in aqueous effluents. Measurement of acid-soluble nickel probably will be applicable to effluents because it will measure precipitates, such as carbonate and hydroxide precipitates of nickel, 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 nickel might be used to determine whether the receiving water can decrease the concentration of acid-soluble nickel 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. 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 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 nickel, the analysis can be performed using either atomic absorption spectrophotometric or ICP-atomic emission spectrometric analysis (U.S. EPA 1983a), as with the total recoverable measurement.

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

Unless otherwise noted, all concentrations reported herein are expected to be essentially equivalent to acid-soluble nickel concentrations. All concentrations are expressed as nickel, not as the chemical tested. The criteria presented herein supersede previous national aquatic life-water quality criteria for nickel (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 1985b). The latest comprehensive literature search for information for this document was conducted in July, 1986; some more recent information might have been included.

Acute Toxicity to Aquatic Animals

Lind et al. (Manuscript) conducted studies on the effects of both hardness and TOC on the acute toxicity of nickel to both Daphnia pulicaria and the fathead minnow (Table 6). With both species, hardness was the only significantly correlated parameter. Nebeker et al. (1985) reported that rainbow trout were more sensitive when 12-months old than when 3-months old. Rehwoldt et al. (1973) observed that embryos were more sensitive than adult snails.

Many factors might affect the results of tests of the toxicity of nickel to aquatic organisms (Sprague 1985), but water quality criteria can quantitatively take into account such factors 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 nickel in fresh water, 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 (expressed as mg $CaCO_3$/L) is used here as a surrogate for the ions that affect the results of toxicity tests on nickel. 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. The four slopes are between 0.69 and 1.19 (see end of Table 1) and are close to the slope of 1.0 that is expected on the basis that nickel, calcium, magnesium, and carbonate all have a charge of two. An F-test showed that, under the assumption of equality of slopes, the probability of obtaining four slopes as dissimilar as these is P = 0.26. This was interpreted as indicating that it is not unreasonable to assume that the slopes for these four species are the same.

Where possible, the pooled slope of 0.8460 was used to adjust the acute values in Table 1 to hardness = 50 mg/L. Species Mean Acute Values were calculated as geometric means of the adjusted acute values. Genus Mean Acute Values at hardness = 50 mg/L were then calculated as geometric means of the available freshwater Species Mean Acute Values (Table 3). Of the eighteen genera for which freshwater acute values are available, the most sensitive genus, Daphnia, was 29 times more sensitive than the most resistant, Fundulus. The freshwater Final Acute Value for nickel at hardness = 50 mg/L was calculated to be 1,578 µg/L using the procedure described in the Guidelines and the Genus Mean Acute Values in Table 3. Thus, the freshwater Criterion Maximum Concentration (in µg/L) = $e^{(0.8460[\ln(\text{hardness})]+3.3612)}$.

The acute toxicity of nickel to saltwater organisms has been determined with 18 species of invertebrates and 4 species of fish (Table 1). The LC50s and EC50s for invertebrates range from 151.7 µg/L for juveniles of the mysid, Heteromysis formosa (Gentile et al. 1982) to 1,100,000 µg/L for late juvenile to adult stages of the clam, Macoma balthica (Bryant et al. 1985). Fish are not as sensitive or as resistant to nickel. The 96-hr LC50s range from 7,958 µg/L for larval stages of the Atlantic silverside, Menidia menidia (Cardin 1985) to 350,000 µg/L for adult stages of the mummichog, Fundulus heteroclitus (Eisler and Hennekey 1977).

Although data are limited, relationships might exist between both salinity and temperature and the toxicity of nickel to some saltwater species. For example, the LC50 for the mummichog is 55,000 µg/L at a salinity of 6.9 g/kg, and 175,000 µg/L at a salinity of 21.6 g/kg (Dorfman 1977). In a series of tests with the amphipod, Corophium volutator (Bryant et al. 1985), the LC50 increased with salinity at 5°C, 10°C, and 15°C. At salinities of 5, 10, and 15 g/kg, temperature did not seem to affect the LC50, but at salinities of 25 and 35 g/kg, the LC50 decreased as temperature increased. Bryant et al. (1985) found similar effects of salinity and temperature on nickel toxicity with the clam, Macoma balthica (Table 6). Regressions of toxicity on salinity for the above data show strong correlations. However, analysis of covariance reveals that the slopes for the individual species are too dissimilar ($P < 0.05$) to justify expressing nickel toxicity as a function of salinity.

Of the twenty saltwater genera for which acute values are available, the most sensitive genus, Heteromysis, was over 2,000 times more sensitive than the most resistant, Mya (Table 3). Acute values are available for more than one species in each of three genera, and the range of Species Mean Acute Values within each genus is less than a factor of 4.8. Genus Mean Acute Values for the four most sensitive genera, Heteromysis, Mercenaria, Mysidopsis, and Crassostrea, were within a factor of 7.8 even though the acute tests were conducted with juveniles of the crustaceans and with embryos of the bivalves. The saltwater Final Acute Value was calculated to be 149.2 µg/L, which is very close to the acute value for the most sensitive tested saltwater species.

Chronic Toxicity to Aquatic Animals

Data are available on the freshwater chronic toxicity of nickel to a cladoceran, a caddisfly, and two species of fish (Table 2). Nebeker et al. (1985) conducted two early life-stage tests beginning with rainbow trout embryos 4 hours after fertilization and one early life-stage test beginning with trout embryos 25 days after fertilization. In the first test, weight was significantly reduced by all tested concentrations including the lowest of 35 µg/L. In the second test, weight was significantly reduced by 62 and 431 µg/L, but not by 35, 134, and 238 µg/L, whereas survival was reduced only at nickel concentrations of 134 µg/L and higher. In the third test, weight was significantly reduced at 431 µg/L and higher, but the reduction in survival was significant only at 1,680 µg/L and higher.

Lazareva (1985) conducted a life-cycle test over successive generations with Daphnia magna and observed little change in sensitivity. Although survival time was the most sensitive parameter in one test, growth was consistently affected at a concentration of 10 µg/L. Lazareva predicted that 5 µg/L would affect the productivity of populations of Daphnia magna.

The influence of hardness on chronic toxicity of nickel was investigated by Chapman et al. (Manuscript). In life-cycle tests with Daphnia magna, they observed an increase in chronic value with increased hardness. Least squares regression of ln[chronic value] on ln[hardness] produced a slope of 2.3007 with wide confidence limits (Table 2). A similar regression with data for the fathead minnow produced a slope of 0.5706, but confidence limits could not be calculated because only two points were available for use in the regression. An F-test showed that, under the assumption of equality of slopes, the probability of obtaining two slopes as dissimilar as these is P = 0.19. This was interpreted as indicating that it is not unreasonable to assume that the two slopes are the same. The pooled slope is 1.3418 with 95% confidence limits of -1.3922 and 4.0760. The confidence limits on the pooled acute slope are well within the confidence limits on the pooled chronic slope.

The mysid, *Mysidopsis bahia*, is the only saltwater species with which an acceptable chronic test has been conducted on nickel (Table 2). Chronic exposure to nickel reduced survival and number of young at 141 µg/L and above but not at 61 µg/L and lower (Lussier et al. 1985). Thus the chronic value for nickel with this species is 92.74 µg/L and the acute-chronic ratio is 5.478.

The three available species mean acute-chronic ratios range from 5.478 to 35.58 and were all determined with species that are acutely sensitive to nickel (Table 3). The Final Acute-Chronic Ratio of 17.99 was calculated as the geometric mean of the three ratios. Division of the freshwater Final Acute Value by the Final Acute-Chronic Ratio results in a freshwater Final Chronic Value of 87.72 ug/L at hardness = 50 mg/L. Some data (Tables 2 and 6) concerning the chronic toxicity of nickel to rainbow trout indicate that embryos and larvae of this species might be affected at this concentration, whereas other data (Table 2) indicate that embryos and larvae of the species might not be adversely affected. Use of an acute-chronic ratio that is independent of hardness is equivalent to assuming that the chronic slope is equal to the acute slope. Thus the freshwater Final Chronic Value (in µg/L) = $e^{(0.8460[\ln(\text{hardness})]+1.645)}$. This value might not protect *Daphnia magna* in soft water.

Division of the saltwater Final Acute Value by 17.99 results in a saltwater Final Chronic Value of 8.293 µg/L, which is about a factor of eleven lower than the only chronic value that has been determined with a saltwater species. Three of the four acutely most sensitive saltwater species are in the same family as the species with which the saltwater acute-chronic ratio was determined. In addition, two other sensitive species are bivalve molluscs for which the acute values were obtained from tests on embryos and larvae.

Toxicity to Aquatic Plants

Data on the toxicity of nickel to aquatic plants are found in Table 4. Nickel concentrations resulting in a 40-60% reduction in growth of freshwater algae range from 50 µg/L for the green alga, Scenedesmus acuminatz, to 5,000 µg/L for the green algae, Ankistrodesmus falcatus and Chlorococcum sp. Wang and Wood (1984) indicate that toxicity of nickel to plants is pH dependent. Although lack of hardness values makes comparisons difficult, general comparison of data in Table 4 with chronic toxicity data in Table 2 suggests that nickel concentrations high enough to produce chronic effects on freshwater animals will also have deteriorative effects on freshwater algal populations.

Patrick et al. (1975) found that nickel decreased diatom diversity and caused a shift to green and blue-green algae. In their field study, Spencer and Greene (1981) also found an increase in blue-green algae. Using EDTA to manipulate Ni^{+2} concentrations, Spencer and Nichols (1983) reported algal growth to be inversely related to free divalent nickel and independent of total nickel concentrations.

Brown and Rattigan (1979) studied nickel toxicity to two freshwater vascular plants, duckweed and Elodea (Anacharis). Despite the presence of a thick cuticle, which protects it from many pollutants (e.g., herbicides), duckweed was much more susceptible to nickel than was Elodea. A similar EC50 was reported for duckweed by Wang (1986). Muramoto and Oki (1984) observed that the water hyacinth is quite resistant, with about a 30% reduction in growth at 4,000 and 8,000 µg/L.

Data on the toxicity of nickel to saltwater plants and algae are found in Tables 4 and 6. The test with the giant kelp, Macrocystis pyrifera, lasted four days and resulted in a 50% reduction in photosynthesis at 2,000 µg/L (Clendenning and North 1959). The lowest concentrations affecting growth of phytoplankton ranged from 17 to 1,800 µg/L and were salinity and temperature dependent (Wilson and Freeberg 1980). Concentrations that affect most saltwater plants apparently are higher than those that are chronically toxic to saltwater animals.

Bioaccumulation

Data are available on bioaccumulation of nickel by a freshwater alga, a cladoceran, and two species of fish (Table 5). The lowest factor, 0.8, was obtained for muscle of rainbow trout. All other studies where conducted on whole body samples and the factors ranged from 9.3 for the alga to 193 for the cladoceran. In studies with the fathead minnow, Lind et al. (Manuscript) found that the BCF decreased as the concentration of nickel in water increased. This same trend was observed by Hall (1982), who studied the accumulation of nickel in various tissues of Daphnia magna and used a model to describe uptake at different exposure concentrations.

Watras et al. (1985) reported a BCF with *Daphnia magna* of 11.6. Their study indicated that uptake of nickel directly from the water was much greater than uptake from food. They also suggested that little biomagnification occurs within the association of the cladoceran and algae. Jennett et al. (1982) examined physical and biological variables affecting uptake by algae. Although their study did not demonstrate that steady-state was attained, Taylor and Crowder (1983,1984) studied differential uptake of nickel by various portions of an emergent aquatic plant, the cattail. A field study with measured nickel concentrations in a stream produced average BCF of 803 for wild rainbow trout (*Salmo gairdneri*) (Dallinger and Kautzky 1985).

Data on bioaccumulation of nickel by saltwater organisms are available for two species of algae and two species of bivalves (Table 5). BCFs for algae collected from the field are 675 for the rockweed, *Fucus vesiculosis*, and 458.3 for *Ascophyllum nodosum* (Foster 1976). BCFs for bivalves exposed for 9 days in the laboratory were 472.7 and 328.6 for the blue mussel and 458.1 and 261.8 for the Eastern oyster (Zaroogian and Johnson 1984).

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

Other Data

Data in Table 6 suggest a high toxicity to nickel in the single-celled organisms. Bringmann and Kuhn (1959a,b;1977a;1979;1980a,b;1981) reported that concentrations of 2.5 to 1,500 µg/L resulted in incipient inhibition of algae, bacteria, and protozoans. Babich and Stotzky (1983) observed delayed effects after a 24-hr exposure.

Willford (1966) reported 48-hr LC50s for six fishes tested in the same water. Although the fish differed in size, neither this nor taxonomic differences produced a clear trend in relative toxicity. Blaylock and Frank (1979) observed LC50s for carp larva at 3 and 10.5 days to be 8,460 and 750 µg/L, respectively. Birge and coworkers obtained 28-day EC50s of 50, 60, and 90 µg/L with embyros and larvae of rainbow trout and a 7-day EC50 of 50 µg/L with embryos and larvae of the narrow-mouthed toad.

Shaw and Brown (1971) studied the effect of nickel on laboratory fertilization of rainbow trout eggs. They did not find a statistically significant effect at 1000 µg/L (hardness = 260 to 280 mg/L) and noted a stimulation in development after fertilization compared to controls.

Whitley and Sikora (1970) and Brkovic-Popovic and Popovic (1977b) studied effects on respiration in tubificid worms. Influence of nickel on thermal resistance of salmonids was examined by Becker and Wolford (1980). The effect of complexing agents on toxicity of nickel to carp was studied by Muramoto (1983). Smith-Sonneborn et al. (1983) studied the toxicity of nickel dust particles ingested by Paramecium. Anderson (1973) and Anderson and Weber (1975) derived an expression relating body size to sensitivity of the guppy.

In a field study, Havas and Hutchinson (1982) worked with acidified and control ponds and suggested that the lowered pH increased the concentrations of heavy metals such as nickel and stressed resident aquatic invertebrates. Keller and Pitblado (1984) and Yan et al. (1985) compared ambient nickel concentrations to aquatic community dynamics.

Available data that were not used directly in the derivation of saltwater criterion for nickel (Table 6) do not indicate a need to lower the criterion. In addition to affecting survival of saltwater animals, nickel affects growth, development, reproduction, and biochemical responses. A 19% reduction in growth of juvenile Pacific oysters, Crassostrea gigas, exposed to 10 µg/L for 14 days at a salinity of 34 g/kg was reported by Watling (1983). The ecological significance of this reduction is unknown, but after 14 days in clean water size was similar to that of the controls. Petrich and Reish (1979) found that 100 to 500 ug/L suppressed reproduction of a polychaete, Ctenodrilus serratus. Zaroogian et al. (1982) showed a significant reduction in ATP activity in the adductor muscle of the blue mussel, but not the Eastern oyster, after a 10-week exposure to 10 µg/L. Abnormal development of embryos of the sea urchins, Arbacia punctulata and Lytechinus pictus, occurred at several concentrations of nickel (Timourian and Watchmaker 1972; Waterman 1937), and concentrations as low as 58.69 µg/L depressed sperm motility in gametes of the purple urchin, Strongylocentrotus purpuratus (Timourian and Watchmaker 1977).

Unused Data

Some data on the effects of nickel on aquatic organisms were not used because the studies were conducted with species that are not resident in North America (e.g., Ahsanullah 1982; Ballester and Castellvi 1979; Baudouin and Scoppa 1974; Kanai and Wakabayashi 1984; Khangarot et al. 1982; McFeters et al. 1983; Saxena and Parashari 1983; Srivastava et al. 1985: Van Hoof and Nauwelaers 1984; Verma et al. 1981; Wilson 1983). Results (e.g., Kissa et al. 1984) 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 nickel was a component of a mixture (e.g., Alman and Bager 1984; Anderson 1983; Besser 1985; Cowgill et al. 1986, Doudoroff 1956; Doudoroff et al. 1966: Eisler 1977b; Hutchinson and

Sprague 1983,1986; Lopez-Avila et al. 1985; Markarian et al. 1980: Muska 1978; Muska and Weber 1977a,b; Phelps et al. 1981; Suloway et al. 1983; Stratton and Corke 1979b; Vymazal 1984; Weinstein and Anderson 1978; Wong and Beaver 1980; Wong et al. 1978,1982), an effluent (e.g., Abbe 1982; Blaise and Couture 1984; Cherry et al. 1979; Jay and Muncy 1979; Lewis 1986) or sediments (e.g., Malueg et al. 1984; Seeleye et al. 1982).

Babich and Stotzky (1985), Biddinger and Gloss (1984), Birge and Black (1980), Chapman et al. (1968), Doudoroff and Katz (1953), Eisler (1981), Jenkins (1980), Kaiser (1980), LeBlanc (1984), McKim (1977), Phillips and Russo (1978), Rai et al. (1981), Thompson et al. (1972), and U.S. EPA (1975) only contain data that have been published elsewhere. Christensen et al. (1985) reported computer simulated data only.
Data were not used if the organisms were exposed to nickel in food (e.g., Cowgill et al. 1985; Mansouri-Aliabadi and Sharp 1985; Windom et al. 1982). Results were not used if the test procedures were not adequately described (e.g., Bean and Harris 1977; Braginskiy and Shcherban 1978; Brown 1968; Jones 1939; Petukhov and Ninonenko 1982; See et al. 1974,1975; Shcherban 1977; Sirover and Loeb 1976; Soeder and Engelmann 1984; Wang et al. 1984). The 96-hr values reported by Buikema et al. (1974a,b) were subject to error because of possible reproductive interactions (Buikema et al. 1977). Michnowicz and Weaks (1984) conducted tests at too low a pH. Babich et al. (1986) only exposed cell cultures.

Results of some laboratory tests were not used because the tests were conducted in distilled or deionized water without addition of appropriate salts (e.g., Jones 1935; MacDonald et al. 1980; Shaw and Grushkin 1957) or were conducted in chlorinated or "tap" water (e.g., Grande and Andersen 1983; Janauer 1985). Dilution waters in studies by Mann and Fyfe (1984) and Stratton and Corke (1979a) contained excessive amounts of EDTA. Stokes (1975) and Whitton and Shehata (1982) used algae from waters containing high concentrations of nickel. The data of Gerhards and Weller (1977) on accumulation of nickel by algae were not used because the test concentrations of nickel adversely affected the growth of the algae. Dugan (1975) reported results in uptake studies only as counts of radio-labeled nickel.

Bringmann and Kuhn (1982) cultured Daphnia magna in one water and conducted tests in another. Tests conducted with too few test organisms (e.g., Applegate et al. 1957; Tarzwell and Henderson 1960) were not used.

Reports of the concentrations of nickel in wild aquatic organisms (e.g., Abo-Rady 1979; Amemiya and Nakayama 1984; Bailey and Stokes 1985; Bosserman 1985; Bradley and Morris 1986; Brezina and Arnold 1977; Bryan et al. 1983; Chapman 1985; Chassard-Bouchard and Balvay 1978; Dunstan et al. 1980; Eisler et al. 1978; Gordon et al. 1980; Guilizzoni 1980; Hall et al. 1978; Heit and Klasek 1985; Jenkins 1980; Kawamata et al. 1983; La Touche and Mix 1982; McDermott et al. 1976; McHardy and George 1985; Martin 1979; Mathis and Cummings 1973; Mears and Eisler 1977; O'Conner 1976; Ozimek 1985; Parsons et al. 1972; Pennington et al. 1982; Pulich 1980; Reynolds 1979; Stokes et al. 1985; Tong et al. 1974; Trollope and Evans 1976; Uthe and Bligh 1971; Van Coille and Rousseau 1974; Wachs 1982; Wehr and Whitton 1983; Wren et al. 1983) were not used to calculate bioaccumulation factors due to the absence or insufficient number of measurements of nickel in water.

Summary

Acute values with twenty-one freshwater species in 18 genera range from 1,101 μg/L for a cladoceran to 43,240 μg/L for a fish. Fishes and invertebrates are both spread throughout the range of sensitivity. Acute values with four species are significantly correlated with hardness.

Data are available concerning the chronic toxicity of nickel to two invertebrates and two fishes in fresh water. Data available for two species indicate that chronic toxicity decreases as hardness increases. The measured chronic values ranged from 14.77 µg/L with Daphnia magna in soft water to 526.7 µg/L with the fathead minnow in hard water. Five acute-chronic ratios are available for two species in soft and hard water and range from 14 to 122.

Nickel appears to be quite toxic to freshwater algae, with concentrations as low as 50 µg/L producing significant inhibition. Bioconcentration factors for nickel range from 0.8 for fish muscle to 193 for a cladoceran.

Acute values for twenty-three saltwater species in twenty genera range from 151.7 µg/L with juveniles of a mysid to 1,100,000 µg/L with juveniles and adults of a clam. The acute values for the four species of fish range from 7,598 to 350,000 µg/L. The acute toxicity of nickel appears to be related to salinity, but the form of the relationship appears to be species-dependent.

Mysidopsis bahia is the only saltwater species with which an acceptable chronic test has been conducted on nickel. Chronic exposure to 141 µg/L and greater resulted in reduced survival and reproduction. The measured acute-chronic ratio was 5.478.

Bioconcentration factors in salt water range from 261.8 with a oyster to 675 with a brown alga.

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 nickel does not exceed the numerical value given by $e^{(0.8460[\ln(\text{hardness})]+1.1645)}$ 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 $e^{(0.8460[\ln(\text{hardness})]+3.3612)}$ 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 nickel are 88, 160, and 280 μg/L, respectively, and the one-hour average concentrations are 790, 1400, and 2500 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 nickel does not exceed 8.3 μg/L more than once every three years on the average and if the one-hour average concentration does not exceed 75 μg/L more than once every three years on the average.

"Acid-soluble" is probably the best measurement at present for expressing criteria for metals and the criteria for nickel 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.

Three years is the Agency's best scientific judgment of the average amount of time aquatic ecosystems should be provided between excursions (U.S. EPA 1985b). The resiliencies of ecosystems and their abilities to recover differ greatly, however, and site-specific allowed excursion frequencies 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 (U.S. EPA 1985b). Limited data or other considerations might make their use impractical, in which case one must rely on a steady-state model (U.S. EPA 1986).

Table 1. Acute Toxicity of Nickel to Aquatic Animals

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
			FRESHWATER SPECIES				
Worm, *Nais* sp.	S, M	-	50	14,100	14,100	14,100	Rehwoldt et al. 1973
Snail (embryo), *Amnicola* sp.	S, M	-	50	11,400	11,400	-	Rehwoldt et al. 1973
Snail (adult), *Amnicola* sp.	S, M	-	50	14,300	14,300	12,770	Rehwoldt et al. 1973
Cladoceran, *Daphnia magna*	S, U	Nickel chloride	-	<317	-	-	Anderson 1948
Cladoceran, *Daphnia magna*	S, U	Nickel chloride	45.3	510	554.4	-	Biesinger and Christensen 1972
Cladoceran, *Daphnia magna*	S, M	Nickel nitrate	51.1	915	898.3	-	Call et al. 1983
Cladoceran, *Daphnia magna*	S, M	Nickel chloride	51	1,800	1,770	-	Chapman et al. Manuscript
Cladoceran, *Daphnia magna*	S, M	Nickel chloride	100	2,360	1,313	-	Chapman et al. Manuscript
Cladoceran, *Daphnia magna*	S, M	Nickel chloride	104	1,920	1,033	-	Chapman et al. Manuscript
Cladoceran, *Daphnia magna*	S, M	Nickel chloride	206	4,970	1,500	1,102	Chapman et al. Manuscript
Cladoceran, *Daphnia pulicaria*	S, M	Nickel sulfate	48	2,182	2,259	-	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	S, M	Nickel sulfate	48	1,813	1,877	-	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	S, M	Nickel sulfate	44	1,836	2,046	-	Lind et al. Manuscript

Table 1. (Continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (μg/L)**	Adjusted LC50 or EC50 (μg/L)***	Species Mean Acute Value (μg/L)****	Reference
Cladoceran, *Daphnia pulicaria*	S, M	Nickel sulfate	47	1,901	2,003	2,042	Lind et al. Manuscript
Amphipod, *Gammarus* sp.	S, M	-	50	13,000	13,000	13,000	Rehwoldt et al. 1973
Mayfly, *Ephemerella subvaria*	S, U	Nickel sulfate	42	4,000	4,636	4,636	Warnick and Bell 1969
Damselfly, Unidentified sp.	S, M	-	50	21,200	21,200	21,200	Rehwoldt et al. 1973
Stonefly, *Acroneuria lycorias*	S, U	Nickel sulfate	40	33,500	40,460	40,460	Warnick and Bell 1969
Caddisfly, Unidentified sp.	S, M	-	50	30,200	30,200	30,200	Rehwoldt et al. 1973
American eel, *Anguilla rostrata*	S, M	Nickel nitrate	53	13,000[†]	12,370	-	Rehwoldt et al. 1971
American eel, *Anguilla rostrata*	S, M	-	55	13,000	11,990	12,180	Rehwoldt et al. 1972
Rainbow trout (2 mos), *Salmo gairdneri*	F, M	Nickel nitrate	-	35,500	-	-	Hale 1977
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Nickel sulfate	-	20,100[†]	-	-	Anderson 1981
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Nickel sulfate	-	12,700[†]	-	-	Anderson 1981
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Nickel sulfate	-	28,000[†]	-	-	Anderson 1981
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Nickel sulfate	-	30,900[†]	-	-	Anderson 1981
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Nickel sulfate	-	16,900[†]	-	-	Anderson 1981

Table 1. (continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Nickel sulfate	-	15,900†	-	-	Anderson 1981
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Nickel sulfate	-	11,300†	-	-	Anderson 1981
Rainbow trout (juvenile), *Salmo gairdneri*	F, M	Nickel sulfate	-	11,100†	-	-	Anderson 1981
Rainbow trout (3 mos), *Salmo gairdneri*	F, M	Nickel chloride	27-39	10,000	14,210	-	Nebeker et al. 1985
Rainbow trout (3 mos), *Salmo gairdneri*	F, M	Nickel chloride	27-39	10,900	15,490	-	Nebeker et al. 1985
Rainbow trout (12 mos), *Salmo gairdneri*	F, M	Nickel chloride	27-39	8,900	12,650	-	Nebeker et al. 1985
Rainbow trout (12 mos), *Salmo gairdneri*	F, M	Nickel chloride	27-39	8,100	11,510	13,380	Nebeker et al. 1985
Goldfish (1-2 g), *Carassius auratus*	S, U	Nickel chloride	20	9,820	21,320	21,320	Pickering and Henderson 1966
Common carp (<20 cm), *Cyprinus carpio*	S, M	Nickel nitrate	53	10,600†	10,090	-	Rehwoldt et al. 1971
Common carp, *Cyprinus carpio*	S, M	-	55	10,400	9,594	9,839	Rehwoldt et al. 1972
Fathead minnow (1-2 g), *Pimephales promelas*	S, U	Nickel chloride	20	5,180	11,250	-	Pickering and Henderson 1966
Fathead minnow (1-2 g), *Pimephales promelas*	S, U	Nickel chloride	20	4,580	9,943	-	Pickering and Henderson 1966
Fathead minnow (1-2 g), *Pimephales promelas*	S, U	Nickel chloride	360	42,400	7,981	-	Pickering and Henderson 1966
Fathead minnow (1-2 g), *Pimephales promelas*	S, U	Nickel chloride	360	44,500	8,376	-	Pickering and Henderson 1966

Table 1. (continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
Fathead minnow (immature), *Pimephales promelas*	S, U	Nickel chloride	210	27,000	8,019	-	Pickering 1974
Fathead minnow (immature), *Pimephales promelas*	S, M	Nickel chloride	210	32,200	9,563	-	Pickering 1974
Fathead minnow (immature), *Pimephales promelas*	F, M	Nickel chloride	210	28,000	8,316	-	Pickering 1974
Fathead minnow (immature), *Pimephales promelas*	F, M	Nickel chloride	210	25,000	7,425	-	Pickering 1974
Fathead minnow, *Pimephales promelas*	F, M	Nickel sulfate	45	5,209	5,695	-	Lind et al. Manuscript
Fathead minnow, *Pimephales promelas*	F, M	Nickel sulfate	44	5,163	5,753	8,027	Lind et al. Manuscript
Banded killifish (<20 cm), *Fundulus diaphanus*	S, M	Nickel nitrate	53	46,200†	43,980	-	Rehwoldt et al. 1971
Banded killifish, *Fundulus diaphanus*	S, M	-	55	46,100	42,530	43,250	Rehwoldt et al. 1972
Guppy (6 mo), *Poecilia reticulata*	S, U	Nickel chloride	20	4,450	9,661	9,661	Pickering and Henderson 1966
White perch (<20 cm), *Morone americana*	S, M	Nickel nitrate	53	13,600†	12,950	-	Rehwoldt et al. 1971
White perch, *Morone americana*	S, M	-	55	13,700	12,640	12,790	Rehwoldt et al. 1972
Striped bass (fingerling), *Morone saxatilis*	S, M	Nickel nitrate	53	6,200†	5,902	-	Rehwoldt et al. 1971
Striped bass, *Morone saxatilis*	S, M	-	55	6,300	5,812	-	Rehwoldt et al. 1972
Striped bass (63 day), *Morone saxatilis*	S, U	Nickel chloride	40	3,900	4,710	-	Palawski et al. 1985

Table 1. (continued)

Species	Method*	Chemical	Hardness (mg/L as $CaCO_3$)	LC50 or EC50 (µg/L)**	Adjusted LC50 or EC50 (µg/L)***	Species Mean Acute Value (µg/L)****	Reference
Striped bass (63 day), *Morone saxatilis*	S, U	Nickel chloride	285	33,000	7,569	5,914	Palawski et al. 1985
Rock bass, *Ambloplites rupestris*	F, M	Nickel sulfate	26	2,480	4,312	4,312	Lind et al. Manuscript
Pumpkinseed (<20 cm), *Lepomis gibbosus*	S, M	Nickel nitrate	53	8,100[†]	7,710	-	Rehwoldt et al. 1971
Pumpkinseed, *Lepomis gibbosus*	S, M	-	55	8,000	7,380	7,544	Rehwoldt et al. 1972
Bluegill (1-2 g), *Lepomis macrochirus*	S, U	Nickel chloride	20	5,180	11,250	-	Pickering and Henderson 1966
Bluegill (1-2 g), *Lepomis macrochirus*	S, U	Nickel chloride	20	5,360	11,640	-	Pickering and Henderson 1966
Bluegill (1-2 g), *Lepomis macrochirus*	S, U	Nickel chloride	360	39,600	7,454	-	Pickering and Henderson 1966
Bluegill, *Lepomis macrochirus*	F, M	Nickel chloride	49	21,200	21,570	12,040	Cairns et al. 1981

Table 1. (continued)

Species	Method*	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)	Reference
			SALTWATER SPECIES			
Polychaete worm (adult), *Nereis arenaceodentata*	S, U	Nickel chloride	-	49,000	49,000	Petrich and Reish 1979
Polychaete worm (adult), *Nereis virens*	S, U	Nickel chloride	20	25,000	25,000	Eisler and Hennekey 1977
Polychaete worm (adult), *Ctenodrilus serratus*	S, U	Nickel chloride	-	17,000	17,000	Petrich and Reish 1979
Polychaete worm (adult), *Capitella capitata*	S, U	Nickel chloride	-	>50,000	>50,000	Petrich and Reish 1979
Mud snail (adult), *Nassarius obsoletus*	S, U	Nickel chloride	20	72,000	72,000	Eisler and Hennekey 1977
Eastern oyster (embryo), *Crassostrea virginica*	S, U	Nickel chloride	25	1,180	1,180	Calabrese et al. 1973
Clam, *Macoma balthica*	S, U	Nickel chloride	15 (5°C)	100,000	-	Bryant et al. 1985
Clam, *Macoma balthica*	S, U	Nickel chloride	25 (5°C)	380,000	-	Bryant et al. 1985
Clam, *Macoma balthica*	S, U	Nickel chloride	35 (5°C)	700,000	-	Bryant et al. 1985
Clam, *Macoma balthica*	S, U	Nickel chloride	15 (10°C)	95,000	-	Bryant et al. 1985
Clam, *Macoma balthica*	S, U	Nickel chloride	25 (10°C)	560,000	-	Bryant et al. 1985
Clam, *Macoma balthica*	S, U	Nickel chloride	35 (10°C)	1,100,000	-	Bryant et al. 1985
Clam, *Macoma balthica*	S, U	Nickel chloride	15 (15°C)	110,000	-	Bryant et al. 1985

Table 1. (continued)

Species	Method*	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)	Reference
Clam, *Macoma balthica*	S, U	Nickel chloride	25 (15°C)	180,000	-	Bryant et al. 1985
Clam, *Macoma balthica*	S, U	Nickel chloride	35 (15°C)	540,000	294,500	Bryant et al. 1985
Quahog clam (embryo), *Mercenaria mercenaria*	S, U	Nickel chloride	25	310	310	Calabrese and Nelson 1974
Soft-shell clam (adult), *Mya arenaria*	S, U	Nickel chloride	20	320,000	-	Eisler and Hennekey 1977
Soft-shell clam (adult), *Mya arenaria*	S, U	Nickel chloride	30	>50,000	320,000	Eisler 1977a
Copepod (adult), *Eurytemora affinis*	S, U	Nickel chloride	30	13,180	-	Lussier and Cardin 1985
Copepod (adult), *Eurytemora affinis*	S, U	Nickel chloride	30	9,593	11,240	Lussier and Cardin 1985
Copepod (adult), *Acartia clausi*	S, U	Nickel chloride	30	3,466	3,466	Lussier and Cardin 1985
Copepod (adult), *Nitocra spinipes*	S, U	Nickel chloride	7	6,000	6,000	Bengtsson 1978
Mysid (juvenile), *Heteromysis formosa*	S, M	Nickel chloride	30	151.7	151.7	Gentile et al. 1982
Mysid (juvenile), *Mysidopsis bahia*	F, M	Nickel chloride	30	508	508	Gentile et al. 1982; Lussier et al. 1985
Mysid (juvenile), *Mysidopsis bigelowi*	S, M	Nickel chloride	30	634	634	Gentile et al. 1982
Amphipod, *Corophium volutator*	S, U	Nickel chloride	5 (5°C)	5,000	-	Bryant et al. 1985
Amphipod, *Corophium volutator*	S, U	Nickel chloride	10 (5°C)	21,000	-	Bryant et al. 1985

Table 1. (continued)

Species	Method*	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)	Reference
Amphipod, Corophium volutator	S, U	Nickel chloride	15 (5°C)	18,000	-	Bryant et al. 1985
Amphipod, Corophium volutator	S, U	Nickel chloride	25 (5°C)	36,000	-	Bryant et al. 1985
Amphipod, Corophium volutator	S, U	Nickel chloride	35 (5°C)	54,000	-	Bryant et al. 1985
Amphipod, Corophium volutator	S, U	Nickel chloride	5 (10°C)	8,000	-	Bryant et al. 1985
Amphipod, Corophium volutator	S, U	Nickel chloride	10 (10°C)	15,000	-	Bryant et al. 1985
Amphipod, Corophium volutator	S, U	Nickel chloride	15 (10°C)	22,000	-	Bryant et al. 1985
Amphipod, Corophium volutator	S, U	Nickel chloride	25 (10°C)	24,000	-	Bryant et al. 1985
Amphipod, Corophium volutator	S, U	Nickel chloride	35 (10°C)	52,000	-	Bryant et al. 1985
Amphipod, Corophium volutator	S, U	Nickel chloride	5 (15°C)	5,600	-	Bryant et al. 1985
Amphipod, Corophium volutator	S, U	Nickel chloride	10 (15°C)	16,000	-	Bryant et al. 1985
Amphipod, Corophium volutator	S, U	Nickel chloride	15 (15°C)	18,000	-	Bryant et al. 1985
Amphipod, Corophium volutator	S, U	Nickel chloride	25 (15°C)	22,000	-	Bryant et al. 1985
Amphipod, Corophium volutator	S, U	Nickel chloride	35 (15°C)	34,000	18,950	Bryant et al. 1985
Hermit crab (adult), Pagurus longicarpus	S, U	Nickel chloride	20	47,000	47,000	Eisler and Hennekey 1977

Table 1. (continued)

Species	Method*	Chemical	Salinity (g/kg)	LC50 or EC50 (µg/L)**	Species Mean Acute Value (µg/L)	Reference
Starfish (adult), *Asterias forbesii*	S, U	Nickel chloride	20	150,000	150,000	Eisler and Hennekey 1977
Mummichog (adult), *Fundulus heteroclitus*	S, U	Nickel chloride	6.9	55,000	-	Dorfman 1977
Mummichog (adult), *Fundulus heteroclitus*	S, U	Nickel chloride	21.6	175,000	-	Dorfman 1977
Mummichog (adult), *Fundulus heteroclitus*	S, U	Nickel chloride	20	350,000	149,900	Eisler and Hennekey 1977
Atlantic silverside (larva), *Menidia menidia*	S, U	Nickel chloride	30	7,958	7,958	Cardin 1985
Tidewater silverside (juvenile), *Menidia peninsulae*	S, U	Nickel chloride	20	38,000	38,000	Hansen 1983
Striped bass (63 day), *Morone saxatilis*	S, U	Nickel chloride	1	21,000	21,000	Palawski et al. 1985
Spot (juvenile), *Leiostomus xanthurus*	S, U	Nickel chloride	21	70,000	70,000	Hansen 1983

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

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

*** Freshwater LC50s and EC50s were adjusted to hardness = 50 mg/L (as $CaCO_3$) using the pooled slope of 0.8460 (see text).

**** Freshwater Species Mean Acute Values are calculated at hardness = 50 mg/L (as $CaCO_3$).

† In river water.

Table 1. (continued)

Results of Covariance Analysis of Freshwater Acute Toxicity versus Hardness

Species	n	Slope	95% Confidence Limits	Degrees of Freedom
Daphnia magna	6	1.1810	0.3187, 2.0433	4
Fathead minnow	10	0.8294	0.6755, 0.9833	8
Striped bass	4	1.0459	0.7874, 1.3045	2
Bluegill	4	0.6909	-0.1654, 1.5472	2
All of above	24	0.8460*	0.7004, 0.9915	19

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* P = 0.26 for equality of slopes with 16 degrees of freedom.

Table 2. Chronic Toxicity of Nickel to Aquatic Animals

Species	Test*	Chemical	Hardness (mg/L as $CaCO_3$)	Limits (µg/L)**	Chronic Value (µg/L)	Reference
			FRESHWATER SPECIES			
Cladoceran, *Daphnia magna*	LC	Nickel chloride	51	10.2-21.4	14.77	Chapman et al. Manuscript
Cladoceran, *Daphnia magna*	LC	Nickel chloride	105	101-150	123.1	Chapman et al. Manuscript
Cladoceran, *Daphnia magna*	LC	Nickel chloride	205	220-578	356.6	Chapman et al. Manuscript
Cladoceran (1st generation), *Daphnia magna*	LC	Nickel sulfate	-	5-10	7.071	Lazareva 1985
Cladoceran (2nd generation), *Daphnia magna*	LC	Nickel sulfate	-	<5***	<5	Lazareva 1985
Cladoceran (3rd generation), *Daphnia magna*	LC	Nickel sulfate	-	5-10	7.071	Lazareva 1985
Cladoceran (4th generation), *Daphnia magna*	LC	Nickel sulfate	-	5-10	7.071	Lazareva 1985
Caddisfly, *Clistoronia magnifica*	LC	Nickel chloride	54	66-250	128.4	Nebeker et al. 1984
Rainbow trout, *Salmo gairdneri*	ELS	Nickel chloride	53	<35***	<35	Nebeker et al. 1985
Rainbow trout, *Salmo gairdneri*	ELS	Nickel chloride	52	62-134	91.15	Nebeker et al. 1985
Rainbow trout, *Salmo gairdneri*	ELS	Nickel chloride	49	134-431	240.3	Nebeker et al. 1985
Fathead minnow, *Pimephales promelas*	LC	Nickel chloride	210	380-730	526.7	Pickering 1974
Fathead minnow, *Pimephales promelas*	ELS	Nickel sulfate	44-45†	108.9-433.5	217.3	Lind et al. Manuscript

Table 2. (Continued)

Species	Test*	Chemical	Salinity (g/kg)	Limits (µg/L)**	Chronic Value (µg/L)	Reference
			SALTWATER SPECIES			
Mysid, *Mysidopsis bahia*	LC	Nickel chloride	30	61-141	92.74	Gentile et al. 1982; Lussier et al. 1985

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

** Results are based on measured concentrations of nickel.

*** Unacceptable effects occurred at all concentrations tested.

† Values from acute tests in Table 1.

Results of Regression Analysis of Freshwater Chronic Toxicity versus Hardness

Species	n	Slope	95% Confidence Limits	Degrees of Freedom
Daphnia magna	3	2.3007	-2.6551, 7.2568	1
Fathead minnow	2	0.5706	*	0
All of above	5	1.3418**	-1.3922, 4.0760	2

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* Cannot be calculated because degrees of freedom = 0.

** P = 0.19 for equality of slopes with 1 degree of freedom.

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*	51	1,800	14.77	122.4
Cladoceran, *Daphnia magna*	104-105	1,920	123.1	15.60
Cladoceran, *Daphnia magna*	205-206	4,970	356.6	13.94
Fathead minnow, *Pimephales promelas*	210	27,930*	526.7	53.03
Fathead minnow, *Pimephales promelas*	44-45	5,186**	217.3	23.87
Mysid, *Mysidopsis bahia*	30***	508	92.74	5.478

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* Geometric mean of four values in Table 1.

** Geometric mean of two values in Table 1.

*** Salinity (g/kg).

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		
18	43,250	Banded killifish, *Fundulus diaphanis*	43,250	-
17	40,460	Stonefly, *Acroneuria lycorias*	40,460	-
16	30,200	Caddisfly, Unidentified sp.	30,200	-
15	21,320	Goldfish, *Carassius auratus*	21,320	-
14	21,200	Damselfly, Unidentified sp.	21,200	-
13	14,100	Worm, *Nais* sp.	14,100	-
12	13,380	Rainbow trout, *Salmo gairdneri*	13,380	-
11	13,000	Amphipod, *Gammarus* sp.	13,000	-
10	12,770	Snail, *Amnicola* sp.	12,770	-
9	12,180	American eel, *Anguilla rostrata*	12,180	-
8	9,839	Common carp, *Cyprinus carpio*	9,839	-
7	9,661	Guppy, *Poecilia reticulata*	9,661	-
6	8,697	White perch, *Morone americana*	12,790	-
		Striped bass, *Morone saxatilis*	5,914	-

Table 3. (Continued)

Rank*	Genus Mean Acute Value (µg/L)**	Species	Species Mean Acute Value (µg/L)***	Species Mean Acute-Chronic Ratio****
5	9,530	Pumpkinseed, *Lepomis gibbosus*	7,544	-
		Bluegill, *Lepomis macrochirus*	12,040	-
4	8,027	Fathead minnow, *Pimephales promelas*	8,027	35.58[†]
3	4,636	Mayfly, *Ephemerella subvaria*	4,636	-
2	4,312	Rock bass, *Ambloplites rupestris*	4,312	-
1	1,500	Cladoceran, *Daphnia pulicaria*	2,042	-
		Cladoceran, *Daphnia magna*	1,102	29.86[††]
		SALTWATER SPECIES		
20	320,000	Soft-shell clam, *Mya arenaria*	320,000	-
19	294,500	Clam, *Macoma balthica*	294,500	-
18	150,000	Starfish, *Asterias forbesii*	150,000	-
17	149,900	Mummichog, *Fundulus heteroclitus*	149,900	-
16	72,000	Mud snail, *Nassarius obsoletus*	72,000	-
15	70,000	Spot, *Leiostomus xanthurus*	70,000	-

Table 3. (Continued)

Rank*	Genus Mean Acute Value (µg/L)**	Species	Species Mean Acute Value (µg/L)***	Species Mean Acute-Chronic Ratio****
14	>50,000	Polychaete worm, *Capitella capitata*	>50,000	-
13	47,000	Hermit crab, *Pagurus longicarpus*	47,000	-
12	35,000	Polychaete worm, *Nereis arenaceodentata*	49,000	-
		Polychaete worm, *Nereis virens*	25,000	-
11	21,000	Striped bass, *Morone saxatilis*	21,000	-
10	17,390	Atlantic silverside, *Menidia menidia*	7,958	-
		Tidewater silverside, *Menidia peninsulae*	38,000	-
9	17,000	Polychaete worm, *Ctenodrilus serratus*	17,000	-
8	18,950	Amphipod, *Corophium volutator*	18,950	-
7	11,240	Copepod, *Eurytemora affinis*	11,240	-
6	6,000	Copepod, *Nitocra spinipes*	6,000	-
5	3,466	Copepod, *Acartia clausi*	3,466	-
4	1,180	Eastern oyster, *Crassostrea virginica*	1,180	-

Table 3. (Continued)

Rank*	Genus Mean Acute Value (µg/L)**	Species	Species Mean Acute Value (µg/L)***	Species Mean Acute-Chronic Ratio****
3	567.5	Mysid, *Mysidopsis bahia*	508	5.478
		Mysid, *Mysidopsis bigelowi*	634	-
2	310	Quahog clam, *Mercenaria mercenaria*	310	-
1	151.7	Mysid, *Heteromysis formosa*	151.7	-

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* 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 the Final Acute Value is not unnecessarily lowered.

** Freshwater Genus Mean Acute Values are at hardness = 50 mg/L.

*** From Table 1; freshwater values are at hardness = 50 mg/L.

**** From Table 2.

† Geometric mean of two values in Table 2.

†† Geometric mean of three values in Table 2.

Table 3. (Continued)

Fresh water

Final Acute Value = 1,578 µg/L (at hardness = 50 mg/L)

Criterion Maximum Concentration = (1,578 µg/L) / 2 = 789.0 µg/L (at hardness = 50 mg/L)

Pooled Slope = 0.8460 (see Table 1)

ln(Criterion Maximum Intercept) = ln(789.0) - [slope x ln(50)]

= 6.6708 - (0.8460 x 3.9120) = 3.3612

Criterion Maximum Concentration = $e^{(0.8460[\ln(\text{hardness})]+3.3612)}$

Final Acute-Chronic Ratio = 17.99 (see text)

Final Chronic Value = (1,578 µg/L) / 17.99 = 87.72 µg/L (at hardness = 50 mg/L)

Assumed Chronic Slope = 0.8460 (see text)

ln(Final Chronic Intercept) = ln(87.72) - [slope x ln(50)]

= 4.4741 - (0.8460 x 3.9120) = 1.1645

Final Chronic Value = $e^{(0.8460[\ln(\text{hardness})]+1.1645)}$

Salt water

Final Acute Value = 149.2 µg/L

Criterion Maximum Concentration = 149.2 / 2 = 74.60 µg/L

Final Acute-Chronic Ratio = 17.99 (see text)

Final Chronic Value = (149.2 µg/L) / 17.99 = 8.293 µg/L

Table 4. Toxicity of Nickel to Aquatic Plants

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)*	Reference
		FRESHWATER SPECIES				
Blue-green alga, *Anabaena flos-aquae*	Nickel nitrate	-	14	84% reduction in growth	600	Spencer and Greene 1981
Blue-green alga, *Microcystis aeruginosa*	Nickel chloride	-	8	Incipient inhibition	5	Bringmann and Kuhn 1978a,b
Green alga, *Ankistrodesmus falcatus*	Nickel chloride	-	10	45% reduction in growth	5,000	Devi Prasad and Devi Prasad 1982
Green alga, *Ankistrodesmus falcatus*	Nickel nitrate	-	14	98% reduction in growth	100	Spencer and Greene 1981
Green alga, *Ankistrodesmus falcatus* var. *acicularis*	Nickel nitrate	-	14	42% reduction in growth	100	Spencer and Greene 1981
Green alga, *Chlamydomonas eugametos*	Nickel nitrate or Nickel sulfate	47.5	12	91% reduction in growth	700**	Hutchinson 1973; Hutchinson and Stokes 1975
Green alga, *Chlorella vulgaris*	Nickel nitrate or Nickel sulfate	47.5	12	53% reduction in growth	300**	Hutchinson 1973; Hutchinson and Stokes 1975
Green alga, *Chlorococcum* sp.	Nickel chloride	-	10	52% reduction in growth	5,000	Devi Prasad and Devi Prasad 1982
Green alga, *Haematococcus capensis*	Nickel nitrate or Nickel sulfate	47.5	12	85% reduction in growth	300**	Hutchinson 1973; Hutchinson and Stokes 1975
Green alga, *Pediastrum tetras*	Nickel nitrate	-	14	Increased growth	100	Spencer and Greene 1981
Green alga, *Scenedesmus acuminata*	Nickel nitrate or Nickel sulfate	47.5	12	54% reduction in growth	50**	Hutchinson 1973; Hutchinson and Stokes 1975

Table 4. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration (days)	Effect	Concentration (µg/L)*	Reference
Green alga, *Scenedesmus acuminata*	Nickel nitrate or Nickel sulfate	47.5	13	Reduced growth	500	Stokes et al. 1973; Hutchinson and Stokes 1975
Green alga, *Scenedesmus dimorphus*	Nickel nitrate	-	14	30% reduction in growth	100	Spencer and Greene 1981
Green alga, *Scenedesmus obliquus*	Nickel chloride	-	10	47% reduction in growth	3,000	Devi Prasad and Devi Prasad 1982
Green alga, *Scenedesmus quadricauda*	Nickel chloride	-	8	Incipient inhibition	1,300	Bringmann and Kuhn 1977a; 1978a,b; 1979; 1980b
Green alga, *Scenedesmus quadricauda*	Nickel nitrate	-	14	60% reduction in growth	100	Spencer and Greene 1981
Diatom, *Navicula pelliculosa*	Nickel nitrate	14.96	14	82% reduction in growth	100	Fezy et al. 1979
Duckweed, *Lemna minor*	Nickel chloride	-	28	EC50	340	Brown and Rattigan 1979
Duckweed, *Lemna minor*	-	-	4	EC50 (growth)	450	Wang 1986
Macrophyte, *Elodea (Anacharis) canadensis*	Nickel chloride	-	28	EC50	2,800	Brown and Rattigan 1979
Water hyacinth, *Eichhornia crassipes*	Nickel chloride	12	38	30% reduction in growth	4,000	Muramoto and Oki 1984
Water hyacinth, *Eichhornia crassipes*	Nickel chloride	12	38	29% reduction in growth	8,000	Muramoto and Oki 1984
			SALTWATER SPECIES			
Giant kelp (young fronds), *Macrocystis pyrifera*	-	4	-	EC50 (reduction in photosynthesis)	2,000	Clendenning and North 1959

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

Table 5. Bioaccumulaton of Nickel by Aquatic Organisms

Species	Chemical	Concentration in Water (µg/L)*	Hardness (mg/L as $CaCO_3$)	Duration (days)	Tissue	BCF or BAF**	Reference
			FRESHWATER SPECIES				
Green alga, *Scenedesmus acuminata*	Nickel nitrate or Nickel sulfate	1,000	-	6	Whole body	9.3	Hutchinson and Stokes 1975
Water hyacinth, *Eichhornia crassipes*	Nickel chloride	1,000	38	12	Root tops	256.0 174.2	Muramoto and Oki 1984
Water hyacinth, *Eichhornia crassipes*	Nickel chloride	4,000	38	12	Root tops	438.2 500.3	Muramoto and Oki 1984
Water hyacinth, *Eichhornia crassipes*	Nickel chloride	8,000	38	12	Root tops	335.5 576.2	Muramoto and Oki 1984
Cladoceran, *Daphnia magna*	^{63}Ni in 0.1M HCl	-	-	-	Whole body	100	Hall 1978
Cladoceran, *Daphnia magna*	-	50	20.1	3.75	Whole body	192***	Hall 1982
Cladoceran, *Daphnia magna*	-	750	20.1	3.75	Whole body	123***	Hall 1982
Cladoceran, *Daphnia magna*	Nickel chloride	58.7	-	13	Whole body	11.6	Watras et al. 1985
Rainbow trout, *Salmo gairdneri*	Nickel chloride	1,000	320	180	Muscle	0.8	Calamari et al. 1982
Fathead minnow, *Pimephales promelas*	Nickel sulfate	21	-	30	Whole body	106	Lind et al. Manuscript
Fathead minnow, *Pimephales promelas*	Nickel sulfate	44.4	-	30	Whole body	79	Lind et al. Manuscript
Fathead minnow, *Pimephales promelas*	Nickel sulfate	108.9	-	30	Whole body	47	Lind et al. Manuscript
			SALTWATER SPECIES				
Rockweed, *Fucus vesiculosis*	-	1.2	-	Field collections	Whole plant	675†	Foster 1976

Table 5. (Continued)

Species	Chemical	Concentration in Water (µg/L)*	Hardness (mg/L as $CaCO_3$)	Duration (days)	Tissue	BCF or BAF**	Reference
Brown macroalga, *Ascophyllum nodosum*	-	1.2	-	Field collections	Whole plant	458.3†	Foster 1976
Blue mussel, *Mytilus edulis*	Nickel sulfate	4.4	-	84	Soft parts	472.7	Zaroogian and Johnson 1984
Blue mussel, *Mytilus edulis*	Nickel sulfate	10.0	-	84	Soft parts	328.6	Zaroogian and Johnson 1984
Eastern oyster, *Crassostrea virginica*	Nickel sulfate	4.2	-	84	Soft parts	458.1	Zaroogian and Johnson 1984
Eastern oyster, *Crassostrea virginica*	Nickel sulfate	9.9	-	84	Soft parts	261.8	Zaroogian and Johnson 1984

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* Measured concentration of nickel.

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

*** Estimated from graph.

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

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

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
			FRESHWATER SPECIES			
Alga, *Chlorella pyrenoidosa*	-	-	24 hr	Reduced growth	88	Gerhards and Weller 1977
Green alga, *Scenedesmus quadricauda*	Nickel chloride	-	96 hr	Incipient inhibition (river water)	1,500	Bringmann and Kuhn 1959a,b
Green alga, *Scenedesmus quadricauda*	Nickel ammonium sulfate	-	96 hr	Incipient inhibition (river water)	900	Bringmann and Kuhn 1959a,b
Alga, (mixed population)	Nickel nitrate	87-99	≤53 days	Decrease in diatom diversity; shift to green and blue-green algae	2-8.6	Patrick et al. 1975
Blue-green alga, *Anabaena cylindrica*	Nickel sulfate	-	5 days	No effect on doubling time (in light)	15.1	Daday et al. 1985
Blue-green alga, *Anabaena cylindrica*	Nickel sulfate	-	5 days	13% reduction in doubling time (in dark)	15.1	Daday et al. 1985
Blue-green alga, *Anabaena cylindrica*	Nickel chloride	-	30 hr	BCF = 680.5 (in light)	-	Campbell and Smith 1986
Blue-green alga, *Anabaena cylindrica*	Nickel chloride	-	30 hr	BCF = 375.0 (in dark)	-	Campbell and Smith 1986
Blue-green alga, *Nostoc linckia*	Nickel chloride	-	24 hr	EC50 (nitrate reduction)	1,885	Kumar et al. 1985
Blue-green alga, *Nostoc linckia*	Nickel chloride	-	24 hr	EC50 (ammonia uptake)	1,141	Kumar et al. 1985
Blue-green alga, *Nostoc muscorum*	Nickel chloride	-	21 days	EC50 (survival)	235.1	Rai and Raizada 1985
Bacterium, *Aeromonas sobria*	Nickel chloride	40	24 hr**	Reduction in abundance	5	Babich and Stotzky 1983

Table 6. (continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Bacterium, *Bacillus brevis*	Nickel chloride	40	24 hr**	Reduction in abundance	5	Babich and Stotzky 1983
Bacterium, *Bacillus cereus*	Nickel chloride	40	24 hr**	Reduction in abundance	5	Babich and Stotzky 1983
Bacterium, *Escherichia coli*	Nickel chloride	-	-	Incipient inhibition	100	Bringmann and Kuhn 1959a
Bacterium, *Escherichia coli*	Nickel ammonium sulfate	-	-	Incipient inhibition	100	Bringmann and Kuhn 1959a
Bacterium, *Pseudomonas putida*	Nickel chloride	-	16 hr	Incipient inhibition	2.5 (3.0)	Bringmann and Kuhn 1977a; 1979; 1980b
Bacterium, *Serratia marcescens*	Nickel chloride	40	24 hr**	Reduction in abundance	10	Babich and Stotzky 1983
Bacterium, *Nitrosomonas europaea*	-	9	-	No growth	400	Sato et al. 1986
Mixed heterotrophic bacteria	Nickel chloride	-	0.5 hr	EC50 (survival)	42.9	Albright et al. 1972
Protozoan, *Entosiphon sulcatum*	Nickel chloride	-	72 hr	Incipient inhibition	140	Bringmann 1978; Bringmann and Kuhn 1979; 1980b; 1981
Protozoan, *Microregma heterostoma*	Nickel chloride	-	28 hr	Incipient inhibition	50	Bringmann and Kuhn 1959b
Protozoan, *Microregma heterostoma*	Nickel ammonium sulfate	-	28 hr	Incipient inhibition	70	Bringmann and Kuhn 1959b
Protozoan, *Chilomonas paramecium*	Nickel chloride	-	48 hr	Incipient inhibition	820	Bringmann et al. 1980; Bringmann and Kuhn 1981
Protozoan, *Uronema parduezi*	Nickel chloride	-	20 hr	Incipient inhibition	42	Bringmann and Kuhn 1980a, 1981

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Tubificid worm, *Tubifex tubifex*	Nickel sulfate	34.2	48 hr	LC50	8.70 7.00	Brkovic-Popovic and Popovic 1977a
Cladoceran, *Daphnia magna*	Nickel chloride	-	48 hr	EC50 (river water)	6,000	Bringmann and Kuhn 1959a,b
Cladoceran, *Daphnia magna*	Nickel ammonium sulfate	-	48 hr	EC50 (river water)	6,000	Bringmann and Kuhn 1959a,b
Cladoceran, *Daphnia magna*	Nickel chloride	288	24 hr	EC50 (swimming)	11,000	Bringmann and Kuhn 1977b
Cladoceran, *Daphnia magna*	Nickel chloride	45.3	48 hr	EC50 (immobilization) (fed)	1,120	Biesinger and Christensen 1972
Cladoceran, *Daphnia magna*	Nickel chloride	45.3	21 days	EC50 (immobilization)	130	Biesinger and Christensen 1972
Cladoceran, *Daphnia magna*	Nickel chloride	45.3	21 days	16% reproductive impairment	30	Biesinger and Christensen 1972
Cladoceran, *Daphnia magna*	Nickel chloride	-	72 hr	BCF = 0.823 BCF = 0.526 BCF = 1.83 BCF = 2.20 BCF = 1.17	1,855 1,115 185.5 58.70 18.50	Watras et al. 1985
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	25	48 hr	LC50 (TOC = 39 mg/L)	2,171	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	28	48 hr	LC50 (TOC = 15 mg/L)	1,140	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	28	48 hr	LC50 (TOC = 13 mg/L)	1,034	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	29	48 hr	LC50 (TOC = 13 mg/L)	697	Lind et al. Manuscript

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	73	48 hr	LC50 (TOC = 28 mg/L)	3,414	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	74	48 hr	LC50 (TOC = 28 mg/L)	2,325	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	84	48 hr	LC50 (TOC = 32 mg/L)	3,014	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	86	48 hr	LC50 (TOC = 34 mg/L)	3,316	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	89	48 hr	LC50 (TOC = 18 mg/L)	2,042	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	89	48 hr	LC50 (TOC = 34 mg/L)	2,717	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	100	48 hr	LC50 (TOC = 34 mg/L)	3,757	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	114	48 hr	LC50 (TOC = 27 mg/L)	3,156	Lind et al. Manuscript
Cladoceran, *Daphnia pulicaria*	Nickel sulfate	120	48 hr	LC50 (TOC = 33 mg/L)	3,607	Lind et al. Manuscript
Midge, *Chironomus* sp.	-	50	96 hr	LC50	8,600	Rehwoldt et al. 1973
Coho salmon (yearling), *Oncorhynchus kisutch*	Nickel chloride	90	144 hr	100% survival	5,000	Lorz et al. 1978
Rainbow trout (0.5-0.9 g), *Salmo gairdneri*	Nickel sulfate	42	48 hr	LC50	35,730	Willford 1966
Rainbow trout (1 yr), *Salmo gairdneri*	Nickel sulfate	240	48 hr	LC50	32,000	Brown and Dalton 1970

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Rainbow trout (embryo, larva), *Salmo gairdneri*	Nickel chloride	104 (92-110)	28 days	EC50 (death and deformity)	50	Birge 1978; Birge and Black 1980; Birge et al. 1978,1979,1980,1981
Rainbow trout (embryo, larva), *Salmo gairdneri*	Nickel chloride	125	28 days	EC50 (death and deformity)	60	Birge et al. 1981
Rainbow trout (embryo, larva), *Salmo gairdneri*	Nickel chloride	174	28 days	EC50 (death and deformity)	90	Birge et al. 1981
Rainbow trout, *Salmo gairdneri*	Nickel sulfate	240	3.5 days	Decreased gill diffusion	2,000	Hughes et al. 1979
Rainbow trout (adult), *Salmo gairdneri*	Nickel chloride	320	6 mo	Increase in liver proteolytic activity of males	1,000	Arillo et al. 1982
Rainbow trout (10 g), *Salmo gairdneri*	Nickel chloride	28.4	20 min	Avoidance threshold	23.9	Giattina et al. 1982
Rainbow trout, *Salmo gairdneri*	Nickel sulfate	22.5	48 hr	LC50	54,963	Bornatowicz 1983
Rainbow trout (5 days post hatch), *Salmo gairdneri*	Nickel chloride	50	38 days	LC50	1,400	Nebeker et al. 1985
Brown trout (0.8-1.2 g), *Salmo trutta*	Nickel sulfate	42	48 hr	LC50	60,290	Willford 1966
Brook trout (0.4-0.6 g), *Salvelinus fontinalis*	Nickel sulfate	42	48 hr	LC50	54,040	Willford 1966
Lake trout (2.5-3.2 g), *Salvelinus namaycush*	Nickel sulfate	42	48 hr	LC50	16,750	Willford 1966

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Goldfish, *Carassius auratus*	Nickel chloride	-	19-50 hr 200-210 hr	LT LT	100,000 10,000	Ellis 1937
Goldfish (embryo, larva), *Carassius auratus*	Nickel chloride	195	7 days	EC50 (death and deformity)	2,140	Birge 1978
Goldfish (embryo, larva), *Carassius auratus*	Nickel chloride	93-105	7 days	EC50 (death and deformity)	2,780	Birge and Black 1980; Birge et al. 1981
Common carp (embryo), *Cyprinus carpio*	Nickel sulfate	128	72 hr	LC50	6,100	Blaylock and Frank 1979
Common carp (larva), *Cyprinus carpio*	Nickel sulfate	128	72 hr 257 hr	LC50	8,460 750	Blaylock and Frank 1979
Common carp (embryo), *Cyprinus carpio*	Nickel sulfate	360	-	EC50 (hatch)	22,000	Kapur and Yadav 1982
Fathead minnow, *Pimephales promelas*	Nickel sulfate	28	96 hr	LC50 (TOC = 14 mg/L)	2,923	Lind et al. Manuscript
Fathead minnow, *Pimephales promelas*	Nickel sulfate	29	96 hr	LC50 (TOC = 12 mg/L)	2,916	Lind et al. Manuscript
Fathead minnow, *Pimephales promelas*	Nickel sulfate	77	96 hr	LC50 (TOC = 32 mg/L)	12,356	Lind et al. Manuscript
Fathead minnow, *Pimephales promelas*	Nickel sulfate	86	96 hr	LC50 (TOC = 15 mg/L)	5,383	Lind et al. Manuscript
Fathead minnow, *Pimephales promelas*	Nickel sulfate	89	96 hr	LC50 (TOC = 33 mg/L)	17,678	Lind et al. Manuscript
Fathead minnow, *Pimephales promelas*	Nickel sulfate	91	96 hr	LC50 (TOC = 30 mg/L)	8,617	Lind et al. Manuscript
Channel catfish (1.2-1.5 g), *Ictalurus punctatus*	Nickel sulfate	42	48 hr	LC50	36,840	Willford 1966
Channel catfish, *Ictalurus punctatus*	Nickel chloride	93-105	7 days	EC50 (death and deformity)	710	Birge and Black 1980; Birge et al. 1981

Table 6. (Continued)

Species	Chemical	Hardness (mg/L as $CaCO_3$)	Duration	Effect	Concentration (µg/L)*	Reference
Guppy, *Poecilia reticulata*	Nickel sulfate	260	96 hr	LC50 (high solids)	34,900	Khangarot 1981
Guppy (184 mg), *Poecilia reticulata*	Nickel chloride	260	48 hr	LC50	37,000	Khangarot et al. 1981
Bluegill (0.7-1.1 g), *Lepomis macrochirus*	Nickel sulfate	42	48 hr	LC50	110,500	Willford 1966
Largemouth bass (embryo, larva), *Micropterus salmoides*	Nickel chloride	93-105	8 days	EC50 (death and deformity)	2,020 (2,060)	Birge and Black 1980; Birge et al. 1978, 1981
Narrow-mouthed toad (embryo, larva), *Gastrophryne carolinensis*	Nickel chloride	195	7 days	EC50 (death and deformity)	50	Birge 1978; Birge et al. 1979
Narrow-mouthed toad (embryo, larva), *Gastrophryne carolinensis*	Nickel chloride	95-103	7 days	EC50 (death and deformity)	50	Birge and Black 1980
Fowler's toad, *Bufo fowleri*	Nickel chloride	93-105	7 days	EC50 (death and deformity)	11,030	Birge and Black 1980
Marbled salamander (embryo, larva), *Ambystoma opacum*	Nickel chloride	93-105	8 days	EC50 (death and deformity)	420 (410)	Birge and Black 1980; Birge et al. 1978

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
			SALTWATER SPECIES			
Golden brown alga, *Isochrysis galbana*	-	28	2 days	Lowest concentration reducing chlorophyll *a*	500	Wilson and Freeberg 1980
Golden brown alga, *Isochrysis galbana*	-	28	9 days	Lowest concentration reducing cell numbers	80	Wilson and Freeberg 1980
Diatom, *Phaeodactylum tricornutum*	Nickel chloride	26	7 days	Reduced growth	1,000	Skaar et al. 1974
Diatom, *Thalassiosira pseudonana*	-	14	2 days	Chlorophyll *a* reduced about 65% at 12°C	100	Wilson and Freeberg 1980
Diatom, *Thalassiosira pseudonana*	-	14	2 days	Chlorophyll *a* reduced about 65% at 16°C	31	Wilson and Freeberg 1980
Diatom, *Thalassiosira pseudonana*	-	14	2 days	Chlorophyll *a* reduced about 65% at 20°C	28	Wilson and Freeberg 1980
Diatom, *Thalassiosira pseudonana*	-	14	2 days	Chlorophyll *a* reduced about 65% at 24°C	17	Wilson and Freeberg 1980
Diatom, *Thalassiosira pseudonana*	-	14	2 days	Chlorophyll *a* reduced about 65% at 28°C	80	Wilson and Freeberg 1980
Diatom, *Thalassiosira pseudonana*	-	28	2 days	Chlorophyll *a* reduced about 65% at 12°C	72	Wilson and Freeberg 1980
Diatom, *Thalassiosira pseudonana*	-	28	2 days	Chlorophyll *a* reduced about 65% at 16°C	140	Wilson and Freeberg 1980

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Diatom, *Thalassiosira pseudonana*	-	28	2 days	Chlorophyll *a* reduced about 65% at 20°C	30	Wilson and Freeberg 1980
Diatom, *Thalassiosira pseudonana*	-	28	2 days	Chlorophyll *a* reduced about 65% at 24°C	21	Wilson and Freeberg 1980
Diatom, *Thalassiosira pseudonana*	-	28	2 days	Chlorophyll *a* reduced about 65% at 28°C	18	Wilson and Freeberg 1980
Diatom, *Thalassiosira pseudonana*	-	28	2 days	Lowest concentration reducing chlorophyll *a*	100	Wilson and Freeberg 1980
Dinoflagellate, *Glenodinium halli*	-	28	5 days	Reduced chlorophyll *a* and population numbers in chemostat cultures	50	Wilson and Freeberg 1980
Dinoflagellate, *Glenodinium halli*	-	28	2 days	Lowest concentration reducing chlorophyll *a*	200	Wilson and Freeberg 1980
Dinoflagellate, *Gymnodinium splendens*	-	28	2 days	Chlorophyll *a* reduced about 65% at 16°C	1,000	Wilson and Freeberg 1980
Dinoflagellate, *Gymnodinium splendens*	-	28	2 days	Chlorophyll *a* reduced about 65% at 20°C	950	Wilson and Freeberg 1980
Dinoflagellate, *Gymnodinium splendens*	-	28	2 days	Chlorophyll *a* reduced about 65% at 24°C	560	Wilson and Freeberg 1980

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)[a]	Reference
Dinoflagellate, *Gymnodinium splendens*	-	28	2 days	Chlorophyll *a* reduced about 65% at 28°C	130	Wilson and Freeberg 1980
Dinoflagellate, *Gymnodinium splendens*	-	28	2 days	Chlorophyll *a* reduced about 65% at 30°C	1,800	Wilson and Freeberg 1980
Dinoflagellate, *Gymnodinium splendens*	-	14	2 days	Chlorophyll *a* reduced about 65% at 16°C	1,800	Wilson and Freeberg 1980
Dinoflagellate, *Gymnodinium splendens*	-	14	2 days	Chlorophyll *a* reduced about 65% at 30°C	400	Wilson and Freeberg 1980
Dinoflagellate, *Gymnodinium splendens*	-	28	2 days	Lowest concentration reducing chlorophyll *a*	200	Wilson and Freeberg 1980
Polychaete worm (adult), *Ctenodrilus serratus*	Nickel chloride	-	28 days	Inhibited reproduction	100-500	Petrich and Reish 1979
Blue mussel, *Mytilus edulis*	Nickel chloride	29-32	10 weeks	ATP reduced; no effect on AEC	10	Zaroogian et al. 1982
Pacific oyster (juvenile), *Crassostrea gigas*	Nickel chloride	34	14 days	19% reduction in growth	20	Watling 1983
Eastern oyster (larva), *Crassostrea virginica*	Nickel chloride	24±2	12 days	LC50	1,200	Calabrese et al. 1977
Eastern oyster (larva), *Crassostrea virginica*	Nickel chloride	24±2	12 days	54.8% reduction in growth	1,200	Calabrese et al. 1977
Eastern oyster, *Crassostrea virginica*	Nickel chloride	29-32	10 weeks	No effect on AEC and components	10	Zaroogian et al. 1982
Clam (larva), *Mulina lateralis*	Nickel chloride	35	48 hr	Reduced calcium uptake	2,000	Ho and Zubkoff 1983

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Quahog clam (larva), *Mercenaria mercenaria*	Nickel chloride	24±2	8-10 days	LC50 No growth	5,700 5,700	Calabrese et al. 1977
Common Pacific littleneck (adult), *Protothaca staminea*	Nickel nitrate	31	48 hr	BCF = 4.3 (gill)	-	Hardy and Roesijadi 1982
Common Pacific littleneck (adult), *Protothaca staminea*	Nickel nitrate	31	48 hr	BCF = 4.0 (whole clam)	-	Hardy and Roesijadi 1982
Copepod (adult), *Pseudodiaptomus coronatus*	Nickel chloride	30	72 hr	LC50	14,570	Lussier and Cardin 1985
Copepod (adult), *Acartia clausi*	Nickel chloride	30	72 hr	LC50	6,006	Lussier and Cardin 1985
Copepod (adult), *Acartia tonsa*	Nickel chloride	30	72 hr	LC50	747	Lussier and Cardin 1985
Pink shrimp (adult), *Pandalus montagui*	Nickel sulfate	-	48 hr	LC50	56,880	Portmann 1968
Green crab (adult), *Carcinus maenas*	Nickel sulfate	-	48 hr	LC50	170,600	Portmann 1968
Sea urchin (embryo), *Arbacia punctulata*	Nickel chloride	-	21 hr	Stunted development	7,562	Waterman 1937
Sea urchin (embryo), *Arbacia punctulata*	Nickel chloride	-	42 hr	>50% mortality	7,562	Waterman 1937
Sea urchin (embryo), *Lytechinus pictus*	Nickel chloride	-	18-26 hr	Totally arrested development	586,900	Timourian and Watchmaker 1972
Sea urchin (embryo), *Lytechinus pictus*	Nickel chloride	-	48 hr	Abnormal development	586.9	Timourian and Watchmaker 1972

Table 6. (Continued)

Species	Chemical	Salinity (g/kg)	Duration	Effect	Concentration (µg/L)*	Reference
Sea urchin (gamete), Strongylocentrotus purpuratus	-	-	300 min	Depressed sperm motility	58.69	Timourian and Watchmaker 1977

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

** Incubated for 2 to 4 days after exposure.

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