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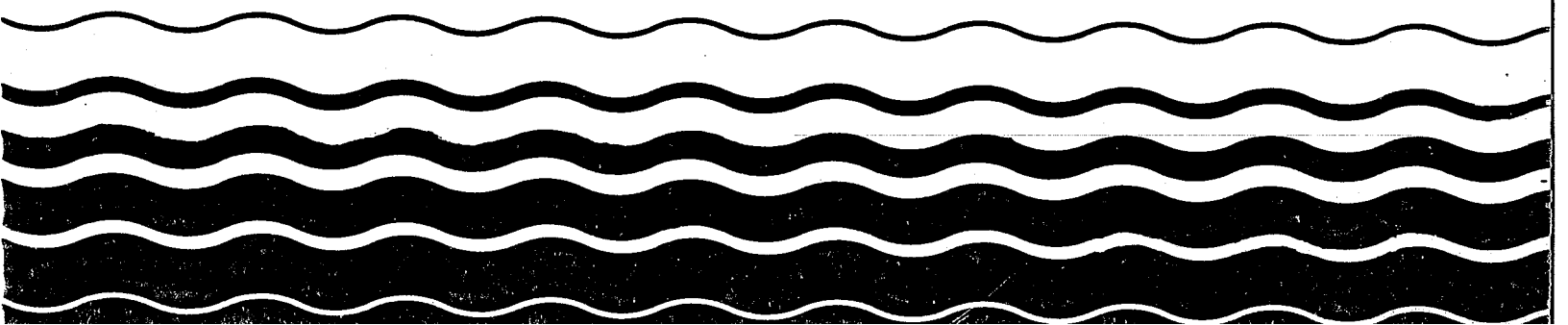
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Water



Ambient Water Quality Criteria for Ammonia (Saltwater)-1989



AMBIENT AQUATIC LIFE WATER QUALITY CRITERIA FOR AMMONIA
(SALT WATER)

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF RESEARCH AND DEVELOPMENT
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NOTICES

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

Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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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 which might be expected from the presence of pollutants in any body of water, including ground water. This document is a revision of proposed criteria based upon a consideration of comments received from other Federal agencies, State agencies, special interest groups, and individual scientists. Criteria contained in this document replace any previously published EPA aquatic life criteria for the same pollutants.

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 concentration in ambient waters within that state. Water quality criteria adopted in State water quality standards could have the same numerical values as the 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 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.

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CONTENTS

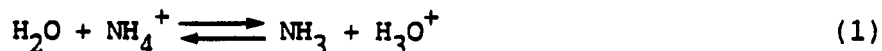
Foreword.....	iii
Acknowledgments.....	iv
Tables.....	vi
Introduction.....	1
Acute Toxicity to Saltwater Animals.....	7
Chronic Toxicity to Saltwater Animals.....	14
Toxicity to Aquatic Plants.....	17
Other Data.....	18
Unused Data.....	22
Summary.....	24
National Criteria.....	27
References.....	48

TABLES

1. Acute Toxicity of Ammonia to Saltwater Animals.....	32
2. Chronic Toxicity of Ammonia to Aquatic Animals.....	39
3. Ranked Genus Mean Acute Values with Species Mean Acute- Chronic Ratios.....	43
4. Other Data on Effects of Ammonia on Saltwater Organisms...	45

INTRODUCTION*

In aqueous solutions, the ammonium ion dissociates to un-ionized ammonia and the hydrogen ion. The equilibrium equation can be written:



The total ammonia concentration is the sum of NH_3 and NH_4^+ .

The toxicity of aqueous ammonia solutions to aquatic organisms is primarily attributable to the un-ionized form, the ammonium ion being less toxic (Armstrong et al. 1978; Chipman 1934; Tabata 1962; Thurston et al. 1981; Wuhrmann et al. 1947; Wuhrmann and Woker 1948). It is necessary, therefore, to know the percentage of total ammonia which is in the un-ionized form in order to establish the corresponding total ammonia concentration toxic to aquatic life. The percentage of un-ionized ammonia (UIA) can be calculated from the solution pH and pK_a^* , the negative log of stoichiometric dissociation,

$$\% \text{ UIA} = 100 [1 + 10^{(\text{pK}_a^* - \text{pH})}]^{-1} \quad (2)$$

The stoichiometric dissociation constant is defined:

$$\text{K}_a^* = \frac{[\text{NH}_3] [\text{H}^+]}{[\text{NH}_4^+]} \quad (3)$$

where the brackets represent molal concentrations. K_a^* is a function of the temperature and ionic strength of the solution.

* 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 1985c), is necessary in order to understand the following text, tables, and calculations.

Whitfield (1974) developed theoretical models to determine the pK_a^* of the ammonium ion in seawater. He combined his models with the infinite dilution data of Bates and Pinching (1949) to define general equations for the pK_a^* of ammonium ion as a function of salinity and temperature.

Whitfield's models allow reasonable approximations of the percent un-ionized ammonia in sea water and have been substantiated experimentally by Khoo et al. (1977). Hampson's (1977) program for Whitfield's full seawater model has been used to calculate the un-ionized ammonia fraction of measured total ammonia concentrations in toxicity studies conducted by EPA and also in the derivation of most other acute and chronic ammonia values which contribute to the criteria. The equations for this model are:

$$\% \text{ UIA} = 100 [1 + 10 (X + 0.0324 (298-T) + 0.0415 P/T - \text{pH})]^{-1} \quad (4)$$

where

P = 1 ATM for all toxicity testing reported to date;

T = temperature ($^{\circ}\text{K}$);

X = pK_a^S or the stoichiometric acid hydrolysis constant of ammonium ions in saline water based on I,

$$I = 19.9273 S (1000 - 1.005109 S)^{-1} \quad (5)$$

where

I = molal ionic strength of the sea water;

S = salinity (g/kg).

The Hampson program calculates the value for I for the test salinity (Eq. 5), finds the corresponding pK_a^S , then calculates % UIA (Eq. 4).

The major factors influencing the degree of ammonia dissociation are pH and temperature. Both correlate positively with un-ionized ammonia. Salinity, the least influential of the three water quality factors that control the fraction of un-ionized ammonia, is inversely correlated.

In ammonia toxicity testing, the pH is normally calibrated using low ionic strength National Bureau of Standards (NBS) buffers. In contrast, Khoo et al. (1977) used the free hydrogen ion sea water scale (ph(F)) in their measurements of ammonium ion hydrolysis in sea water. While the ph(F) scale is desirable from the thermodynamic standpoint, these seawater buffers are not available from a central source, precluding their use in toxicity testing. Calibration of pH with NBS buffers does contribute an error in the calculation of % un-ionized ammonia, although, fortuitously the error is small, presumably due to a compensation of the liquid junction potential by changes in activity coefficients (Bates and Culberson 1977). Millero (1986) found the pH(NBS) scale to overestimate pH relative to the free hydrogen ion scale by 0.02 pH unit at 30 g/kg salinity, 0.045 unit at 20 g/kg and 0.075 unit at 10 g/kg. The residual junction potential is a property of the reference electrode used and may vary \pm 0.03 pH unit with salinity, time, and electrode type (Whitfield et al. 1985).

Controlling pH in salt water ammonia toxicity tests is difficult. Ammonium salt solutions are acidic, but are slow to reach equilibrium in sea water. Consequently, pH typically declines during toxicity tests and the decline may be amplified by metabolism of test organisms. Also, tests conducted above or below the seawater equilibrium pH (7.8-8.2) experience strong shifts toward the buffered state. Inconsistency in degree of control of test pH is a major source of variability in ammonia toxicity studies

especially in sea water. A ± 0.1 pH unit variance would result in a misestimation of the NH_3 effect concentration of about $\pm 25\%$ at pH 8 and 25°C .

A number of analytical methods are available for direct determination of total ammonia concentrations in aqueous solutions (Richards and Healey 1984). Once total ammonia is measured, and the pH, salinity and temperature of the solution determined, the concentration of NH_3 present can be calculated based on the ammonia-seawater equilibrium expression.

Ammonia concentrations have been reported in a variety of forms in the aquatic toxicity literature, such as NH_3 , NH_4^+ , $\text{NH}_3\text{-N}$, NH_4OH , NH_4Cl and others. The use in the literature of the terms NH_3 , $\text{NH}_3\text{-N}$, or ammonia-nitrogen may not necessarily mean un-ionized ammonia, but may be the author's way of expressing total ammonia. Compounds used in the ammonia toxicity tests summarized here are NH_4Cl , NH_4NO_3 and $(\text{NH}_4)_2\text{SO}_4$.

Throughout the remainder of this document, all quantitative ammonia data have been expressed in terms of mg/L un-ionized ammonia for ease in discussion and comparison, and since un-ionized ammonia is the principal toxic form. Ammonia concentrations reported by authors are given as reported if the author(s) provided data expressed as mg NH_3 /L, or converted to mg/L if reported in other units. If authors reported only total ammonia, or if they calculated NH_3 concentration by a unique method (e.g., EA Eng. 1986), the total ammonia value and reported pH, temperature, and salinity conditions were used to calculate mg NH_3 /L, per the Hampson (1977) program. This approach produces NH_3 values that are consistently derived.

Some literature cited in this document fail to provide NH_3 concentrations or total ammonia concentrations along with sufficient pH, temper-

ature, and salinity data to enable calculation of NH_3 concentrations; such papers were not used but are cited under "Unused Data". In some instances information missing in published papers on experimental conditions was obtained through correspondence with authors; data obtained in this manner are so indicated by footnotes and are available from U.S. EPA, ERL, Narragansett.

A number of criteria documents, review articles and books dealing with ammonia as an aquatic pollutant are available. Armstrong (1979), Becker and Thatcher (1973), Colt and Armstrong (1981), Epler (1971), Hampson (1976), Liebmann (1960), McKee and Wolf (1963), Steffens (1976), and Tsai (1975) have published summaries of ammonia toxicity. Literature reviews, including factors affecting ammonia toxicity and physiological consequences of ammonia toxicity to aquatic organisms, have been published by Kinne (1976), Lloyd (1961), Lloyd and Herbert (1962), Lloyd and Swift (1976), Visek (1968), and Warren (1962). Literature reviews of ammonia toxicity information relating to criteria recommendations have been published by Alabaster and Lloyd (1980), European Inland Fisheries Advisory Commission (1970), National Academy of Sciences and National Academy of Engineering (1974), National Research Council (1979), U.S. Environmental Protection Agency (1976, 1980, 1985a), U.S. Federal Water Pollution Control Administration (1968), Willingham (1976), and Willingham et al. (1979).

The criteria presented herein supersede previous saltwater aquatic life water quality criteria for ammonia 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 1983a), which may include not only site-specific criterion

concentrations and mixing zone considerations (U.S. EPA, 1983b), but also site-specific durations of averaging periods and site-specific frequencies of allowed exceedences (U.S. EPA 1985b). This criterion does not apply to saltwater lakes. These water bodies may require development of site-specific water quality criteria. The latest comprehensive literature search for information for this document was conducted in June, 1986; some more recent information has been included.

ACUTE TOXICITY TO SALTWATER ANIMALS

The acute toxicity of ammonia to saltwater animals has been studied in crustaceans, bivalve mollusks, and fishes. Acute values are summarized in Table 1 for 21 species in 18 genera. The winter flounder, Pseudopleuronectes americanus, represents the most sensitive genus, with a Species Mean Acute Value (SMAV) of 0.492 (Cardin 1986). Fourteen (eight fish, five crustaceans and one mollusc) of the remaining 17 genera have Genus Mean Acute Values within the order of magnitude of that for the winter flounder. The three most tolerant species are mollusks. The SMAVs are 19.1 mg/L for the Eastern oyster, Crassostrea virginica, 5.36 mg/L for the quahog clam, Mercenaria mercenaria, and 3.08 mg/L for the brackish water clam, Rangia cuneata. Except for these mollusks, there is no phyletic pattern in acute sensitivity to ammonia. Fishes and crustaceans are well represented among both the more sensitive and the more tolerant species tested.

Few consistent trends or patterns are evident in the acute toxicity values cited in Table 1 with respect to biological or environmental variables. Contributing to this, in part, is test variability. This is evident in multiple tests with the same species, even when conducted under closely comparable conditions. Variability in acute toxicity values for ammonia may reflect differences in condition of the test organisms, changes in the exposure conditions during testing, particularly pH, and variance incurred through calculation of un-ionized ammonia concentrations. As noted in the Introduction, pH has a strong influence on the concentration of un-ionized ammonia in water, such that a variation of ± 0.1 pH unit during the test may result in $\pm 25\%$ variation in the NH_3 exposure concentration. The NH_3 exposure concentrations are calculated values dependent on accurate

measurement of exposure pH. However, pH monitoring during a test may not always detect potentially significant pH excursions. Also, non-systematic errors on the order of ± 0.03 pH unit may also occur with seawater pH measurements due to variation in the liquid junction potential between and within electrode pairs. In addition to these sources of error, interpretation of test results should consider known replicability of toxicity tests. Intra- and inter-laboratory comparisons of acute toxicity test results using saltwater species show LC50s may differ by as much as a factor of two for the same chemical tested with the same species (Hansen 1984; Schimmel 1986). In light of all these sources of variability, LC50s for un-ionized ammonia are in this document considered similar unless they differ by at least a factor of two.

Few marked differences are evident in the acute toxicity of ammonia with respect to differences in life stage or size of the test organism. Yolk-sac larval striped bass (Morone saxatilis) seem slightly less sensitive to un-ionized ammonia (LC50s = 0.70 and 1.09 mg/L) than 9 or 10 day old post-yolk sac larvae (LC50s = 0.33 and 0.58 mg/L) (Poucher 1986). Juvenile striped bass also seem less sensitive than post yolk-sac larvae (LC50s range from 0.91 to 1.68 mg/L) in tests by EA Eng. (1986) and Hazel et al. (1971). Acute values for striped mullet (Mugil cephalus) suggest a factor of two decrease in sensitivity (LC50 = 1.19 vs. 2.38 mg/L) to ammonia with increase in weight from 0.7 to 10.0g (Venkataramiah et al. 1981). Larval grass shrimp (Palaemonetes pugio) appear to be more acutely sensitive (LC50 = 1.06) (EA Eng. 1986) than juveniles and adults (LC50 = 2.57) (Fava et al. 1984), although the contrasting life stages were tested at different salinities. A slight decrease in the acute sensitivity of Eastern oysters, Crassostrea

virginica, is evident between 13 and 17 mm (LC50 = 8.6 to 15 mg/l) and 42 to 62 mm (LC50 = 24 to 43 mg/L) (Epifano and Srna 1975). No size related difference in acute sensitivity to ammonia was seen between 4.7 to 5.2 mm and 28 to 32 mm quahog clams, (Mercenaria mercenaria) (Epifanio and Srna 1975).

Several data sets in Table 1 permit an evaluation of the influence of salinity, temperature and pH on the acute toxicity of ammonia to saltwater animals. Few differences are evident in acute toxicity at different salinities in tests with similar life stages and similar pH and temperature conditions. Mysids (Mysidopsis bahia) have overlapping LC50s at four salinities in tests at pH > 7.8 and 25°C. At 10 to 11 g/kg salinity, NH₃ LC50s range from 1.04 to 3.19 mg/L; at 20 g/kg, 2.82 to 2.87 mg/L; at 30 g/kg, 1.47 to 3.41 mg/L (Cardin 1986); and at 14 to 18 g/kg, 0.92 to 1.68 mg/L (EA Eng. 1986). At pH 7.0, the LC50 was lower at a low salinity by a factor of 2.2 (Cardin 1986) (LC50 = 0.23 mg/L at 11 g/kg; 0.50 and 0.54 mg/L at 31 g/kg salinity). Acute values for larval inland silversides (Menidia beryllina) tested at pH 8 and 25°C are approximately a factor of 2 lower at 11 g/kg salinity with the LC50 = 0.88 mg/L, relative to 1.94 mg/L at 19 g/kg and 1.77 mg/L at 30 g/kg salinity (Poucher 1986). However, at pH 7 and 9, the LC50s for these larvae are slightly higher at 11 g/kg than at 31 g/kg salinity (by a factor of 1.7 and 1.5, respectively, comparing flow through test values only). Atlantic silverside (Menidia menidia) juveniles at pH 8 and ≥ 20°C have NH₃ LC50s ranging from 0.97 to 1.24 mg/L at 9 to 10 g/kg salinity (EA Eng. 1986) which corresponds well with the 0.98 mg/L value reported at 30 g/kg salinity by Fava et al. (1984). Acute values overlap for two fishes tested at low and high salinities by Hazel et al. (1971). For the three spined stickleback (Gasterosteus aculeatus), LC50s range from 2.09 to

2.75 mg/L at approximately 11 g/kg salinity and 1.68 to 5.6 mg/L at approximately 34 g/kg. With juvenile striped bass (Morone saxatilis), LC50s are 0.91 (EA Eng. 1986) and 1.0 to 1.68 mg/L at approximately 11 g/kg salinity; 0.75 and 1.4 mg/L at approximately 34 g/kg (Hazel et al. 1971).

Temperature also has little influence on the acute toxicity of ammonia with most saltwater animals tested. Acute values for thermally acclimated larval inland silverside (Menidia beryllina) tested at three temperatures and at similar pH and salinity (8.0 pH; 31 g/kg salinity) differ by less than a factor of 2. For this species tested at 18°C, the LC50 is 0.98 mg/L; at 25°C, LC50s are 1.75 and 1.77 mg/L; and at 32.5°C, the LC50 is 1.7 mg/L (Poucher 1986). The LC50 for thermally acclimated larval sheepshead minnow (Cyprinodon variegatus) at 13°C is 2.10 mg/L; at 25°C, 2.79 mg/L; and at 32.5°C, 3.5 mg/L (Poucher 1986). Acute values for juvenile striped bass (Morone saxatilis) tested at 15°C and 23°C overlap when tested at approximately 11 g/kg salinity and differ by less than a factor of 2 at approximately 34 g/kg salinity (Hazel et al. 1971). With three spined stickleback (Gasterosteus aculeatus) there was little difference in sensitivity to NH_3 at 15°C (LC50 = 2.75 mg/L) and 23°C (LC50 = 2.09 mg/L) at approximately 11 g/kg salinity, but in tests at approximately 34 g/kg, sensitivity was about 2 times greater at the higher temperature (at 23°C, LC50 = 1.68 and 2.7 mg/L; at 15°C, LC50 = 4.35 and 5.6 mg/L) (Hazel et al. 1971).

Several data sets on the effect of pH on the toxicity of un-ionized ammonia suggest that, unlike the data on freshwater species, the pH-toxicity relationship is not consistent between species. Text Table 1 summarizes LC50s of acute tests conducted at different pH conditions. Results are

Text Table 1.

Acute Toxicity of Un-ionized Ammonia to the Prawn (*Macrobrachium rosenbergii*), Mysid (*Mysidopsis bahia*), Larval Inland Silverside (*Menidia beryllina*), and Juvenile Atlantic Silverside (*Menidia menidia*), at Different pH Conditions. Toxicity expressed as LC50, mg NH₃/L. Flow-through test results underlined, mean temperature and salinity conditions indicated.

pH	Prawn (Armstrong et al. 1978)	Mysid (Cardin 1986)	(Cardin 1986)	(EA Eng. 1986)	Inland Silverside (Poucher 1986)	(Poucher 1986)	Atlantic (EA Eng. 1986)
	28°C, 12 g/kg	24.5°C, 11g/kg	25°C, 31 g/kg	20°C, 31 g/kg	25°C, 11 g/kg	25°C, 31 g/kg	22°C, 9.5 g/kg
6.5-6.9	0.38	-	-	-	-	-	-
7.0-7.4	-	<u>0.28</u>	<u>0.50</u> , 0.54	0.27	<u>1.64</u>	<u>0.93</u> , <u>0.97</u> , <u>1.06</u>	0.97
7.5-7.9	0.95	1.18	1.47	0.40, 0.92, 1.0	-	1.40	<u>1.05</u> , 1.32
8.0-8.4	1.3	<u>1.04</u> , 3.19	<u>1.70</u> , 2.49 <u>2.98</u> , 3.41	0.76	<u>0.88</u>	<u>1.77</u> , 1.75	0.97, 1.07, 1.10, 1.24
8.5-8.9	-	-	<u>2.76</u> , 0.77	1.51, 1.68	-	1.08	1.47
9.0-9.4	-	<u>2.02</u>	-	-	<u>1.16</u>	<u>0.75</u> , 0.49	1.21

segregated by the temperature and salinity conditions of the tests to preclude variability from these sources; LC50s also are listed by author so any interlaboratory variability may be recognized. For the two invertebrate species, the acute sensitivity to NH_3 is greater (> factor 2) at low pH for the prawn (pH 6.83) (Armstrong et al. 1978) and for the mysid (pH 7.0) (Cardin 1986; EA Eng. 1986), than at higher pH values. This response with mysids was consistent at low and high salinity. The two fishes tested differ from the mysid and prawn in their response to pH. Larval inland silverside (Menidia beryllina) do show increased acute sensitivity to ammonia as pH decreases from 8 to 7, but differ from the mysid response at pH 9.0, with appreciably increased sensitivity (> factor of 2) in 31 g/kg salinity. In contrast, in 11 g/kg salinity water, inland silverside have a nearly two-fold decrease in acute sensitivity at pH 7.0, while mysids have a two-fold increase in acute sensitivity at pH 7.0. A further contrast exists in the response of juvenile Atlantic silverside (Menidia menidia), with test pH over the range of 7.0 to 9.0 having little effect on the acute toxicity of ammonia (EA Eng. 1986). The influence of pH on ammonia toxicity in these two saltwater fishes is also a marked contrast with the response of several freshwater fishes (Erickson 1985) and may reflect basic differences in osmotic and ionic regulatory physiology which could influence their response to elevated external ammonia concentrations of over a range of pH, salinity and temperature conditions.

EPA believes that the data available on all water quality-toxicity relationships for un-ionized ammonia are insufficient to conclude that any of these factors, when acting alone, has a consistent major influence on NH_3 toxicity in salt water. Therefore, a water quality dependent function was

not derived for the Final Acute Value for saltwater organisms and Genus Mean Acute Values (Table 3) have been used to calculate the Final Acute Value.

The 18 available saltwater Genus Mean Acute Values range from 0.492 mg NH₃/L for Pseudopleuronectes to 19.102 mg NH₃/L for Crassostrea, a factor of less than 100. Acute values are available for more than one species in three genera. The range of Species Mean Acute Values within two of these genera is less than a factor of 1.2; in the remaining genus, they differ by a factor of 4.5. Eighty-eight percent of the Genus Mean Acute Values were within a factor of ten and 71 percent were a factor of five of the acute value for Pseudopleuronectes. A saltwater Final Acute Value of 0.465 mg NH₃/L was obtained using the Genus Mean Acute Values in Table 3 and the calculation procedure described in the Guidelines. This value is slightly lower than Species Mean Acute Value of 0.492 mg/L for winter flounder.

CHRONIC TOXICITY TO SALTWATER ANIMALS

Chronic toxicity tests have been conducted on ammonia with twelve freshwater and saltwater species of aquatic organisms (Table 2). Of the ten freshwater species tested, two are cladocerans and eight are fishes. The details of the results of the freshwater tests are discussed in the "Ambient Water Quality Criteria for Ammonia - 1984" (U.S. EPA 1985a). In saltwater, a life-cycle toxicity test has been conducted with the mysid, Mysidopsis bahia, and an early life-stage test has been completed with the inland silverside, Menidia beryllina (Table 2).

The effect of ammonia on survival, growth and reproduction of M. bahia was assessed in a life-cycle toxicity test lasting 32 days (Cardin 1986). Survival was reduced to 35 percent of that for controls and length of males and females was significantly reduced in 0.331 mg NH₃/L. Although reproduction was markedly diminished in this concentration, it did not differ significantly from controls. Lengths of females were significantly reduced in 0.163 mg/L, but this is not considered biologically significant since reproduction was not affected. No significant effects on mysids were detected at 0.092 mg/L. The chronic limits are 0.163 and 0.331 mg/L for a chronic value of 0.232. The Acute Value from a flow-through test conducted at similar conditions (7.95 pH, 26.5°C, 30.5 g/kg salinity) with M. bahia is 1.70 mg/L which results in an acute-chronic ratio of 7.2 with this species.

The effect of ammonia on survival and growth of the inland silverside (Menidia beryllina) was assessed in an early life-stage test lasting 28 days (Poucher 1986). Fry survival was reduced to 40 percent in 0.38 mg NH₃/L, relative to 93% survival of control fish, which is a significant difference. Average weights of fish surviving in concentrations > 0.074 mg/L were

significantly less than weights of controls, an effect which persisted as the concentrations of ammonia increased. No significant effects were detected in silversides exposed to 0.050 mg/L. Thus, the chronic limits are 0.050 and 0.074 mg/L for a chronic value of 0.061 mg/L. The acute value, derived as the geometric mean of flow-through tests with this fish at full strength sea water between pH 7.0 and 8.0, is 1.30 mg/L, resulting in an acute-chronic ratio of 21.3.

Acute-chronic ratios are available for ten freshwater and two saltwater species (Table 2). Ratios for the saltwater species are 7.2 for the mysid and 21.3 for inland silversides. These saltwater species have similar acute sensitivities to ammonia, with LC50s near the median for the 21 saltwater species tested. The acute-chronic ratios for the freshwater species vary from 1.4 to 53, so they should not be directly applied to the derivation of a Final Chronic Value. Guidance on how to interpret and apply ratios from tests with freshwater species to derive the freshwater criterion for ammonia has been detailed in U.S. EPA 1985a which should be consulted. This document concludes that: (1) acute-chronic ratios of freshwater species appear to increase with decrease in pH; (2) data on temperature effects on the ratios are lacking; and (3) acute-chronic ratios for the most acutely and chronically sensitive species are technically more applicable when trying to define concentrations chronically acceptable to acutely sensitive species. Therefore, mean acute-chronic ratios were selected from freshwater tests with species whose chronic sensitivity was less than or equal to the median conducted at pH > 7.7. These included the channel catfish, with a mean acute-chronic ratio of 10; bluegill, 12; rainbow trout, 14; and fathead minnow, 20. The mean acute-chronic ratios for these four freshwater and the

two saltwater species are within a factor of 3. The geometric mean of these six values, 13.1, which divided into the Final Acute Value of 0.465 mg/L yields the Final Chronic Value of 0.035 mg NH_3 /L.

TOXICITY TO AQUATIC PLANTS

Nitrogen in the saltwater environment is an important nutrient affecting primary production, the composition of phytoplankton, macroalgal and vascular plant communities, and the extent of eutrophication. Ammonia is an important part of nitrogen metabolism in aquatic plants, but excess ammonia is toxic to saltwater plants (Table 4). Limited data on mixed populations of saltwater benthic microalgae (Admiraal 1977) show that ammonia is more toxic at high than at low pH (Admiraal 1977). This suggests that toxicity may be primarily due to NH_3 rather than NH_4^+ .

Information on the toxicity of ammonia to saltwater plants is limited to tests on ten species of benthic diatoms and on the red macroalgal species, Champia parvula. A concentration of 0.247 mg NH_3/L retarded growth of seven species of benthic diatoms (Admiraal 1977). A concentration of 0.039 mg/L reduced reproduction of Champia parvula gametophytes; no effect was observed at 0.005 mg/L (Thursby 1986). Tetrasporophytes of C. parvula exposed to 0.005 to 0.026 mg/L for 14 days reproduced less but grew faster; no effect was observed at 0.003 mg/L.

OTHER DATA

A number of researchers have studied the effects of ammonia under test conditions that differed from those applicable to acute and chronic test requirements as specified in the Guidelines (Table 4). Animals studied included rotifers, nemertine worms, echinoderms, mollusks, arthropods, polychaetes, and fishes. Concentrations affecting the species tested are generally greater than the Final Acute Value and are all greater than the Final Chronic Value.

Among the lower invertebrates, Brown (1974) found the time to 50 percent mortality of the nemertine worm, Cerebratulus fuscus, exposed to 2.3 mg NH_3/L is 106 minutes. In the rotifer, Brachionus plicatilis, the 24-hr LC_{50} is 20.9 mg NH_3/L , the net reproduction rate was reduced 50 percent by 9.6 mg/L, and the intrinsic rate of population increase was reduced 50 percent by 16.2 mg/L (Yu and Hirayama 1986).

In tests with mollusks, the rate of removal of algae (Isochrysis galbana) from suspension (filtration rate) was reduced > 50% during a 20-hr exposure to 0.16 and 0.32 mg NH_3/L in juvenile and adult quahog clam (Mercenaria mercenaria) and to 0.08 mg/L in juvenile eastern oysters (Crassostrea virginica) (Epifanio and Srna 1975). The rate of ciliary beating in the mussel, Mytilus edulis, is reduced from 50 percent to complete inhibition in < 1 hour by 0.097 to 0.12 mg/L (Anderson et al. 1978). Excretion of ammonia is inhibited in channeled whelk (Busycon canaliculatum), common rangia (Rangia cuneata), and a nereid worm (Nereis succinea) exposed to sublethal concentrations of 0.37, 0.85 and 2.7 mg/L, respectively (Mangum et al. 1978). The authors conclude that ammonia crosses the excretory epithelium in the ionized form, and that process is linked to

Na^+ and K^+ ATPases. In the common bloodworm (Glycera dibrachiata), Sousa et al. (1977) found no competition exists between NH_3 and oxygen in binding hemoglobin.

Ammonium chloride (about 0.01 mg NH_3/L) exposure of unfertilized eggs of the sea urchins, Lytechinus pictus, Strongylocentrotus purpuratus, and S. drobachiensis increased the amount and rate of release of "fertilization acid" above that occurring post-insemination (Johnson et al. 1976; Paul et al. 1976). Exposure of unfertilized sea urchin (L. pictus) eggs to NH_4Cl resulted in stimulation of the initial rate of protein synthesis, an event that normally follows fertilization (Winkler and Grainger 1978). Activation of unfertilized L. pictus eggs by NH_4Cl exposure (ranging from 0.005 to 0.1 mg NH_3/L) was demonstrated by an increase in intracellular pH (Shen and Steinhardt 1978; Steinhardt and Mazia 1973). Ammonia treatment activated phosphorylation of thymidine and synthesis of histones in unfertilized eggs of the sea urchin S. purpuratus (Nishioka 1976). Premature chromosome condensation was induced by ammonia treatment of eggs of L. pictus and S. purpuratus (Epel et al. 1974; Krystal and Poccia 1979; Wilt and Mazia 1974). Ammonium chloride treatment (0.01 mg NH_3/L) of S. purpuratus and S. drobachiensis fertilized eggs resulted in absence of normal calcium uptake following insemination, but did not inhibit calcium uptake if ammonia treatment preceded insemination (Paul and Johnston 1978).

In exposures of crustaceans, the 7-day LC_{50} is 0.666 mg NH_3/L for the copepod, Eucalanus elongatus, while 38 percent of the E. pileatus died after 7 days in 0.706 mg/L (Venkataramiah et al. 1982). No sargassum shrimp (Latreutes fucorum) died after 21 days in ≤ 0.44 mg/L (Venkataramiah et al. 1982). The EC_{50} based on reduction in growth of white shrimp (Penaeus

setiferus) after three weeks of exposure is 0.72 mg/L (Wickens 1976). The eight-day LC50 is 1.79 mg/L for the American lobster (Homarus americanus) (Delistraty et al. 1977). When blue crabs (Callinectes sapidus) were moved from water of 28 g/kg salinity to water of 5 g/kg, a doubling of ammonia excretion rate occurred; addition of excess NH_4Cl to the low salinity water inhibited ammonia excretion and decreased net acid output (Mangum et al. 1976). Wickins (1976) found that the time to 50 percent mortality for the prawn, Macrobrachium rosenbergii, decreased from 1700 minutes at 1.7 mg/L to 560 minutes at 3.4 mg/L. In a six-week test with this prawn, growth was reduced 32 percent at 0.12 mg/L (Wickins 1976).

The relationship between decrease in toxicity of un-ionized ammonia with increase in pH seen in 96-hour tests with the prawn (Macrobrachium rosenbergii) is also exhibited in data from tests lasting 24 and 144 hours (Table 4) (Armstrong et al. 1978). Prawns were three times more sensitive to NH_3 at pH 6.83 than at 7.6. Above pH 7.6, the decrease in acute toxicity was not as great, declining only by a factor of 1.7 at pH 8.34. A similar effect of low pH was seen with growth of the prawn, which after seven days at pH 7.60 was reduced in 0.63 mg/L and at pH 6.83 by 0.11 mg/L (Armstrong et al. 1978).

Few "other data" are available on the effects of ammonia on saltwater fishes (Table 4). In three saltwater tests lasting 24 hours, the LC50s for chinook salmon (Oncorhynchus tshawytscha) ranged from 1.15 to 2.19 mg NH_3 /L (Harader and Allen 1983). The 24-hr LC50s from two tests with Atlantic salmon (Salmo salar) were 0.115 and 0.28 mg/L (Alabaster et al. 1979). Mortality of the Atlantic silverside (Menidia menidia) was higher in 0.44 mg/L than the 43 percent control mortality in a 28-day early life-stage test

(EA Eng. 1986). The 96-hr LC50 for white perch (Morone americana) was 0.2 mg/L in a test at pH 6.0, although this pH is rare in natural salt waters (Stevenson 1977).

UNUSED DATA

Studies conducted with species that are not resident to North America were not used (Alderson 1979; Arizzi and Nicotra 1980; Brown and Currie 1973; Brownell 1980; Chin 1976; Currie et al. 1973; Greenwood and Brown 1974; Inamura 1951; Nicotra and Arizzi 1980; Oshima 1931; Reddy and Menon 1979; Sadler 1981; Yamagata and Niwa 1982). Other data were not used because exposure concentrations were not reported for un-ionized ammonia and/or data on salinity, temperature, and pH necessary to calculate NH_3 concentrations were not available (Binstock and Lecar 1969; Lindén et al. 1978; Oshima 1931; Pinter and Provasoli 1963; Provasoli and McLaughlin 1963; Sigel et al. 1972; Sousa et al. 1974; Thomas et al. 1980; Zgurovskaya and Kustenko 1968). Data of Hall et al. (1978) were not used since the form of ammonia reported in the results is not stated. Data were also not used if ammonia was a component of an effluent (Miknea 1978; Natarajan 1970; Okaichi and Nishio 1976; Rosenberg et al. 1967; Thomas et al. 1980; Ward et al. 1982). Data reported by Sullivan and Ritacco (1985) were not used because the pH was highly variable between treatments. Data from a report by Curtis et al. (1979) were not used because the salt tested, ammonium fluoride, might have dual toxicity. Data reported by Katz and Pierro (1967) were not used because test exposure time and salinity cited in the summary data table and appendix do not agree. Results of a field study by Shilo and Shilo (1953, 1955) were not used since the ammonia concentration was highly variable. The Ministry of Technology, U.K. (1963) report was not used because the ammonia toxicity data were previously published elsewhere and the relevant information is cited in this document. References were not used if they relate more to ammonia metabolism in saltwater species than to ammonia toxicity; e.g., Bartberger

and Pierce, Jr. 1976; Cameron 1986; Girard and Payan 1980; Goldstein and Forster 1961; Goldstein et al. 1964; Grollman 1929; Hays et al. 1977; McBean et al. 1966; Nelson et al. 1977; Read 1971; Raguse-Degener et al. 1980; Schooler et al. 1966; Wood 1958. Publications reporting the effects of ammonia as a nutrient in stimulation of primary production were not used, e.g., Byerrum and Benson (1975).

SUMMARY

All of the following concentrations are un-ionized ammonia (NH_3) because NH_3 , not the ammonium ion (NH_4^+), has been demonstrated to be the more toxic form of ammonia. Data used in deriving the criteria are predominantly from tests in which total ammonia concentrations were measured.

Data available on the acute toxicity of ammonia to 21 saltwater animals in 18 genera showed LC50 concentrations ranging from 0.23 to 43 mg NH_3 /L. The winter flounder, Pseudopleuronectes americanus, is the most sensitive species, with a mean LC50 of 0.492 mg/L. The mean acute sensitivity of 88 percent of the species tested is within a factor of ten of that for the winter flounder. Fishes and crustaceans are well represented among both the more sensitive and more resistant species; mollusks are generally resistant.

Water quality, particularly pH and temperature, but also salinity, affects the proportion of un-ionized ammonia. With freshwater species, the relationship between the toxicity of un-ionized ammonia and pH and temperature is similar for most species and was used to derive pH and temperature dependent freshwater criteria for NH_3 . For saltwater species, the available data provide no evidence that temperature or salinity have a major or consistent influence on the toxicity of NH_3 . Hydrogen ion concentration does increase toxicity of NH_3 at pH below 7.5 in some, but not all species tested; above pH 8, toxicity may increase, decrease, or be little altered as pH increases, depending on species.

The chronic effects of ammonia have been evaluated in tests with two saltwater and ten freshwater species. In a life-cycle test with a mysid, adverse effects were observed at 0.331 mg NH_3 /L but not at 0.163 mg/L. In an early life-stage test with inland silversides, adverse effects were observed

at 0.074 mg/L NH_3 but not at 0.050 mg/L. Acute-chronic ratios are available for 12 species and range from 1.4 to 53. Ratios for the four most sensitive freshwater species, tested at pH values greater than 7.7, and for the two saltwater species tested, range from 7.2 to 21.3.

Available data on the toxicity of un-ionized ammonia to plants suggests significant effects may occur in benthic diatoms exposed to concentrations only slightly greater than those acutely lethal to salt-water animals. Ammonia at concentrations slightly less than those chronically toxic to animals may stimulate growth and reduce reproduction of a red macroalgal species.

The key research needs that should be addressed in order to provide a more complete assessment of toxicity of ammonia to saltwater species are: (1) assess reported pH-toxicity relationships and test other species by conducting additional acute toxicity tests using flow-through techniques and continuous pH control both with and without pH acclimation; (2) determine the effects of water quality variables on acute-chronic ratios by conducting life-cycle and early life stage tests with saltwater species; (3) investigate temperature influence by additional acute toxicity tests with species that can tolerate both low and high temperature extremes; (4) test the effects of constant total ammonia exposure and cyclic water quality charges to mimic potential tidal and diel shifts in salinity and pH; (5) test the effects of fluctuating and intermittent exposures with a variety of species; and (6) investigate the role of other water quality variables on ammonia toxicity; e.g., dissolved oxygen and chlorine; and (7) investigate the contribution of NH_4^+ to the toxicity of aqueous ammonia solutions to better resolve how the

ammonia criterion should be expressed if pH dependence continues to be demonstrated.

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, saltwater aquatic organisms should not be affected unacceptably if the four-day average concentration of un-ionized ammonia does not exceed 0.035 mg/L more than once every three years on the average and if the one-hour average concentration does not exceed 0.233 mg/L more than once every three years on the average. Because sensitive saltwater animals appear to have a narrow range of acute susceptibilities to ammonia, this criterion will probably be as protective as intended only when the magnitudes and/or durations of excursions are appropriately small.

Criteria concentrations based on total ammonia for the pH range of 7.0 to 9.0, temperature range of 0 to 35°C, and salinities of 10, 20 and 30 g/kg are provided in Text Tables 2 and 3. These values were calculated by Hampson's (1977) program of Whitfield's (1974) model for hydrolysis of ammonium ions in sea water.

Three years is the Agency's best scientific judgment of the average amount of time aquatic ecosystems should be provided between excursions. The ability of ecosystems to recover differ greatly.

Site-specific criteria may be established if adequate justification is provided. This site-specific criterion may include not only site-specific criteria concentrations, and mixing zone considerations (U.S. EPA, 1983b), but also site-specific durations of averaging periods and site-specific frequencies of allowed exceedences (U.S. EPA 1985b).

Use of criteria for developing water quality-based permit limits and for designing waste treatment facilities requires the 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 should rely on a steady-state model (U.S. EPA 1986).

IMPLEMENTATION

Water quality standards for ammonia developed from these criteria should specify use of environmental monitoring methods which are comparable to the analytical methods employed to generate the toxicity data base. Total ammonia may be measured using an automated idophenol blue method, such as described by Technicon Industrial Systems (1973) or U.S. EPA (1979) method 350.1. Un-ionized ammonia concentrations should be calculated using the dissociation model of Whitfield (1974) as programmed by Hampson (1977). This program was used to calculate most of the un-ionized values for saltwater organisms listed in Table 1 and 2 of this document. Accurate measurement of sample pH is crucial in the calculation of the un-ionized ammonia fraction. The following equipment and procedures were used by EPA in the ammonia toxicity studies to enhance the precision of pH measurements in salt water. The pH meter reported two decimal places. A Ross electrode with ceramic junction was used due to its rapid response time; an automatic temperature compensation probe provided temperature correction. Note that the responsiveness of a new electrode may be enhanced by holding it in sea water for several days prior to use. Two National Bureau of Standards buffer solutions for calibration preferred for their stability were (1) potassium

hydrogen phthalate (pH 4.00) and (2) disodium hydrogen phosphate (pH 7.4). For overnight or weekend storage, the electrode was held in salt water, leaving the fill hole open. For daily use, the outer half-cell was filled with electrolyte to the fill hole and the electrode checked for stability. The electrode pair was calibrated once daily prior to measuring pH of samples; it was never recalibrated during a series of measurements. Following calibration, the electrode was soaked in sea water, of salinity similar to the sample, for at least 15 minutes to achieve chemical equilibrium and a steady state junction potential. When measuring pH, the sample was initially gently agitated or stirred to assure good mixing at the electrode tip, but without entraining air bubbles in the sample. Stirring was stopped to read the meter. The electrode was allowed to equilibrate so the change in meter reading was less than 0.02 pH unit/minute before recording. Following each measurement, the electrode was rinsed with sea water and placed in fresh sea water for the temporary storage between measurements. Additional suggestions to improve precision of saltwater pH measurements may be found in Zirno (1975), Grasshoff (1983), and Butler et al. (1985).

Text Table 2
Water quality criteria for saltwater aquatic life based on total ammonia (mg/L)
Criteria Maximum Concentrations

	Temperature (°C)							
	0	5	10	15	20	25	30	35
<u>pH</u>	Salinity = 10 g/kg							
7.0	270	191	131	92	62	44	29	21
7.2	175	121	83	58	40	27	19	13
7.4	110	77	52	35	25	17	12	8.3
7.6	69	48	33	23	16	11	7.7	5.6
7.8	44	31	21	15	10	7.1	5.0	3.5
8.0	27	19	13	9.4	6.4	4.6	3.1	2.3
8.2	18	12	8.5	5.8	4.2	2.9	2.1	1.5
8.4	11	7.9	5.4	3.7	2.7	1.9	1.4	1.0
8.6	7.3	5.0	3.5	2.5	1.8	1.3	0.98	0.75
8.8	4.6	3.3	2.3	1.7	1.2	0.92	0.71	0.56
9.0	2.9	2.1	1.5	1.1	0.85	0.67	0.52	0.44
	Salinity = 20 g/kg							
7.0	291	200	137	96	64	44	31	21
7.2	183	125	87	60	42	29	20	14
7.4	116	79	54	37	27	18	12	8.7
7.6	73	50	35	23	17	11	7.9	5.6
7.8	46	31	23	15	11	7.5	5.2	3.5
8.0	29	20	14	9.8	6.7	4.8	3.3	2.3
8.2	19	13	8.9	6.2	4.4	3.1	2.1	1.6
8.4	12	8.1	5.6	4.0	2.9	2.0	1.5	1.1
8.6	7.5	5.2	3.7	2.7	1.9	1.4	1.0	0.77
8.8	4.8	3.3	2.5	1.7	1.3	0.94	0.73	0.56
9.0	3.1	2.3	1.6	1.2	0.87	0.69	0.54	0.44
	Salinity = 30 g/kg							
7.0	312	208	148	102	71	48	33	23
7.2	196	135	94	64	44	31	21	15
7.4	125	85	58	40	27	19	13	9.4
7.6	79	54	37	25	21	12	8.5	6.0
7.8	50	33	23	16	11	7.9	5.4	3.7
8.0	31	21	15	10	7.3	5.0	3.5	2.5
8.2	20	14	9.6	6.7	4.6	3.3	2.3	1.7
8.4	12.7	8.7	6.0	4.2	2.9	2.1	1.6	1.1
8.6	8.1	5.6	4.0	2.7	2.0	1.4	1.1	0.81
8.8	5.2	3.5	2.5	1.8	1.3	1.0	0.75	0.58
9.0	3.3	2.3	1.7	1.2	0.94	0.71	0.56	0.46

Text Table 3

Water quality criteria for saltwater aquatic life based on total ammonia (mg/L)
Criteria Continuous Concentrations

	Temperature (°C)							
	0	5	10	15	20	25	30	35
<u>pH</u>	Salinity = 10 g/kg							
7.0	41	29	20	14	9.4	6.6	4.4	3.1
7.2	26	18	12	8.7	5.9	4.1	2.8	2.0
7.4	17	12	7.8	5.3	3.7	2.6	1.8	1.2
7.6	10	7.2	5.0	3.4	2.4	1.7	1.2	0.84
7.8	6.6	4.7	3.1	2.2	1.5	1.1	0.75	0.53
8.0	4.1	2.9	2.0	1.40	0.97	0.69	0.47	0.34
8.2	2.7	1.8	1.3	0.87	0.62	0.44	0.31	0.23
8.4	1.7	1.2	0.81	0.56	0.41	0.29	0.21	0.16
8.6	1.1	0.75	0.53	0.37	0.27	0.20	0.15	0.11
8.8	0.69	0.50	0.34	0.25	0.18	0.14	0.11	0.08
9.0	0.44	0.31	0.23	0.17	0.13	0.10	0.08	0.07
	Salinity = 20 g/kg							
7.0	44	30	21	14	9.7	6.6	4.7	3.1
7.2	27	19	13	9.0	6.2	4.4	3.0	2.1
7.4	18	12	8.1	5.6	4.1	2.7	1.9	1.3
7.6	11	7.5	5.3	3.4	2.5	1.7	1.2	0.84
7.8	6.9	4.7	3.4	2.3	1.6	1.1	0.78	0.53
8.0	4.4	3.0	2.1	1.5	1.0	0.72	0.50	0.34
8.2	2.8	1.9	1.3	0.94	0.66	0.47	0.31	0.24
8.4	1.8	1.2	0.84	0.59	0.44	0.30	0.22	0.16
8.6	1.1	0.78	0.56	0.41	0.28	0.20	0.15	0.12
8.8	0.72	0.50	0.37	0.26	0.19	0.14	0.11	0.08
9.0	0.47	0.34	0.24	0.18	0.13	0.10	0.08	0.07
	Salinity = 30 g/kg							
7.0	47	31	22	15	11	7.2	5.0	3.4
7.2	29	20	14	9.7	6.6	4.7	3.1	2.2
7.4	19	13	8.7	5.9	4.1	2.9	2.0	1.4
7.6	12	8.1	5.6	3.7	3.1	1.8	1.3	0.90
7.8	7.5	5.0	3.4	2.4	1.7	1.2	0.81	0.56
8.0	4.7	3.1	2.2	1.6	1.1	0.75	0.53	0.37
8.2	3.0	2.1	1.4	1.0	0.69	0.50	0.34	0.25
8.4	1.9	1.3	0.90	0.62	0.44	0.31	0.23	0.17
8.6	1.2	0.84	0.59	0.41	0.30	0.22	0.16	0.12
8.8	0.78	0.53	0.37	0.27	0.20	0.15	0.11	0.09
9.0	0.50	0.34	0.26	0.19	0.14	0.11	0.08	0.07

Table 1. Acute Toxicity of Ammonia to Saltwater Animals

Species	Life Stage or size	Chem.	Methods ^a	LC-50 or EC-50 (mg/L NH ₃)	pH	Temp (°C)	Sal (g/kg)	Reference
Brackish water clam, <u>Rangia cuneata</u>	adult	NH ₄ Cl	S,M	3.08 ^b	7.95	20.2	9.2	EA Eng.1986
Eastern oyster, <u>Crassostrea virginica</u>	42-62 mm	NH ₄ Cl	S,M	24-43 ^c	7.70- 7.96	20	27	Epifanio & Srna 1975
Eastern oyster, <u>Crassostrea virginica</u>	13-17 mm	NH ₄ Cl	S,M	8.6-15 ^c	7.70- 7.96	20	27	Epifanio & Srna 1975
Quahog clam, <u>Mercenaria mercenaria</u>	28-32 mm	NH ₄ Cl	S,M	3.3-5.8 ^c	7.70- 8.23	20	27	Epifanio & Srna 1975
Quahog clam, <u>Mercenaria mercenaria</u>	4.7-5.2 mm	NH ₄ Cl	S,M	4.9-8.8 ^c	7.70- 8.23	20	27	Epifanio & Srna 1975
Copepod, <u>Eucalanus pileatus</u>	adult	NH ₄ Cl	S,M	0.79 ^c	8.2	20.5	34	Venkataramiah et al.1982
Copepod, <u>Eucalanus elongatus</u>	adult	NH ₄ Cl	S,M	0.867 ^c	8.0	20.3	34	Venkataramiah et al.1982
Sargassum shrimp, <u>Latreutes fucorum</u>	.045 g	NH ₄ Cl	S,M	0.936	8.07	23.4	28	Venkataramiah et al.1981
Sargassum shrimp, <u>Latreutes fucorum</u>	.054 g	NH ₄ Cl	S,M	0.638 ^c	8.07	23.4	28	Venkataramiah et al.1981
Grass shrimp, <u>Palaemonetes pugio</u>	larva	NH ₄ Cl	S,M	1.06 ^b	7.92	20.4	10	EA Eng.1986
Grass shrimp, <u>Palaemonetes pugio</u>	16-30 mm	NH ₄ Cl	S,M	2.57	8.1	19.3	28.4	Fava et al.1984
Mysid, <u>Mysidopsis bahia</u>	juvenile 3-5 days old	NH ₄ Cl	S,M	0.27 ^b	7.06	21.2	16.0	EA Eng.1986
Mysid, <u>Mysidopsis bahia</u>	juvenile 3-5 days old	NH ₄ Cl	S,M	0.40 ^b	7.54	19.8	14.6	EA Eng.1986

Species	Life Stage or size	Chem.	Methods	LC-50 or EC-50 (mg/L NH-3)	pH	Temp (c)	Sal (g/kg)	Reference
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 3-5 days old	NH4Cl	S,M	0.92 ^b	7.92	19.6	16.7	EA Eng.1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 3-5 days old	NH4Cl	S,M	1.00 ^b	7.92	19.8	17.6	EA Eng.1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 3-5 days old	NH4Cl	S,M	0.76 ^b	7.99	19.6	14.5	EA Eng.1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 3-5 days old	NH4Cl	S,M	1.51 ^b	8.46	21.2	16.0	EA Eng.1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 3-5 days old	NH4Cl	S,M	1.68 ^b	8.92	20.6	15.6	EA Eng.1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 4 days old	NH4Cl	FT,M	0.23	6.84- 7.12	24	11	Cardin 1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 1 day old	NH4Cl	FT,M	0.50	6.9- 7.0 ^{e,f}	25	31	Cardin 1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 1 day old	NH4Cl	S,M	0.54	6.8- 7.2 ^e	25	31	Cardin 1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 3 days old	NH4Cl	S,M	1.18	7.7	25	10	Cardin 1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 2 days old	NH4Cl	FT,M	1.04	7.8- 8.1 ^{e,f}	24	11	Cardin 1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 1 day old	NH4Cl	FT,M	1.70	7.9- 8.0 ^{e,f}	26.5	30.5	Cardin 1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 3 days old	NH4Cl	S,M	3.19	7.8- 8.2	25	10	Cardin 1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 2 days old	NH4Cl	S,M	2.87	7.9- 8.1	25	20	Cardin 1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 2 days old	NH4Cl	S,M	2.82	7.9- 8.1	25	20	Cardin 1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 1 day old	NH4Cl	S,M	1.47	7.7- 8.0	25	31	Cardin 1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 1 day old	NH4Cl	S,M	2.49	7.8- 8.1	25	31	Cardin 1986
<u>Mysid,</u> <u>Mysidopsis bahia</u>	juvenile 1 day old	NH4Cl	S,M	2.98	7.8- 8.2	25	31	Cardin 1986

Species	Life Stage or size	Chem.	Methods	LC-50 or EC-50 (mg/L NH-3)	pH	Temp (c)	Sal (g/kg)	Reference
					e, f			
Mysid, <u>Mysidopsis bahia</u>	juvenile 1 day old	NH4Cl	S,M	3.41	7.9- 8.2	25	30	Cardin 1986
Mysid, <u>Mysidopsis bahia</u>	juvenile 2 days old	NH4Cl	FT,M	2.02	e, f 9.0- 9.2	24	11.5	Cardin 1986
Mysid, <u>Mysidopsis bahia</u>	juvenile 1 day old	NH4Cl	S,M	0.77	e 8.7- 9.0	25	31	Cardin 1986
Mysid, <u>Mysidopsis bahia</u>	juvenile 1 day old	NH4Cl	FT,M	2.76	e, f 8.8- 9.0	25	30	Cardin 1986
Mysid, <u>Mysidopsis bahia</u>	juvenile 1 day old	NH4Cl	S,M	0.86 ^c	8.2	19.3	30.1	Fava et al.1984
Mysid, <u>Mysidopsis bahia</u>	juvenile < 2 day old	NH4Cl	S,M	0.86 ^d	8.0- 8.2	20.0	25	Buikema et al.1981
Prawn, <u>Macrobrachium rosenbergii</u>	larvae 3-8 days old	NH4Cl	R,M	0.38 ^g	6.83	28	12	Armstrong et al.1978
Prawn, <u>Macrobrachium rosenbergii</u>	larvae 3-8 days old	NH4Cl	R,M	0.95 ^g	7.60	28	12	Armstrong et al.1978
Prawn, <u>Macrobrachium rosenbergii</u>	larvae 3-8 days old	NH4Cl	R,M	1.3 ^g	8.34	28	12	Armstrong et al.1978
American lobster, <u>Homarus americanus</u>	larva 76 mm	NH4Cl	S,M	2.21 ^c	8.1	21.9	33.4	Delistraty et al.1977
Three spined stickleback, <u>Gasterosteus aculeatus</u>	32-60 mm.	NH4Cl	S,M	2.09 ^c	7.58- 7.75	23	~11	Hazel et al.1971
Three spined stickleback, <u>Gasterosteus aculeatus</u>	32-60 mm.	NH4Cl	S,M	1.68 ^c	7.95- 7.98	23	~34	Hazel et al.1971
Three spined stickleback, <u>Gasterosteus aculeatus</u>	32-60 mm.	NH4Cl	S,M	2.7 ^c	7.93- 7.94	23	~34	Hazel et al.1971
Three spined stickleback, <u>Gasterosteus aculeatus</u>	32-60 mm.	NH4Cl	S,M	2.75 ^c	7.85- 7.97	15	~11	Hazel et al.1971
Three spined stickleback, <u>Gasterosteus aculeatus</u>	32-60 mm.	NH4Cl	S,M	5.60 ^c	8.06- 8.13	15	~34	Hazel et al.1971
Three spined stickleback, <u>Gasterosteus aculeatus</u>	32-60 mm.	NH4Cl	S,M	4.35 ^c	8.18- 8.24	15	~34	Hazel et al.1971
Striped mullet, <u>Mugil cephalus</u>	0.4 g	NH4Cl	S,M	1.23	8.08	21.0	10	Venkataramiah et al.1981
Striped mullet, <u>Mugil cephalus</u>	0.7 g	NH4Cl	S,M	1.19	8.14	22.0	10	Venkataramiah et al.1981

Species	Life Stage or size	Chem.	Methods	LC-50 or EC-50 (mg/L NH-3)	pH	Temp (°C)	Sal (g/kg)	Reference
<u>Striped mullet,</u> <u>Mugil cephalus</u>	1.8 g	NH ₄ Cl	S,M	1.63	7.99	21.0	10	Venkataramiah et al.1981
<u>Striped mullet,</u> <u>Mugil cephalus</u>	10.0 g	NH ₄ Cl	S,M	2.38	8.00	23.3	10	Venkataramiah et al.1981
<u>Planehead filefish,</u> <u>Monocanthus hispidus</u>	0.7 g	NH ₄ Cl	S,M	0.69	8.07	23.4	28	Venkataramiah et al.1981
<u>Planehead filefish,</u> <u>Monocanthus hispidus</u>	0.4 g	NH ₄ Cl	S,M	0.988	8.07	23.4	28	Venkataramiah et al.1981
<u>Red drum,</u> <u>Sciaenops ocellatus</u>	embryo-larva	(NH ₄) ₂ SO ₄	S,M	0.545 ^c	8.0- 8.2	25-26	28-30	Holt & Arnold 1983
<u>Atlantic silverside,</u> <u>Menidia menidia</u>	juvenile	NH ₄ Cl	S,M	0.14 ^b	7.96	10.8	8.5	EA Eng.1986
<u>Atlantic silverside,</u> <u>Menidia menidia</u>	juvenile	NH ₄ Cl	S,M	0.97 ^b	7.03	20.6	10.6	EA Eng.1986
<u>Atlantic silverside,</u> <u>Menidia menidia</u>	juvenile	NH ₄ Cl	S,M	1.32 ^b	7.50	20.1	10.1	EA Eng.1986
<u>Atlantic silverside,</u> <u>Menidia menidia</u>	juvenile	NH ₄ Cl	S,M	1.07 ^b	7.96	20.0	9.0	EA Eng.1986
<u>Atlantic silverside,</u> <u>Menidia menidia</u>	juvenile	NH ₄ Cl	S,M	1.10 ^b	7.96	20.1	9.2	EA Eng.1986
<u>Atlantic silverside,</u> <u>Menidia menidia</u>	juvenile	NH ₄ Cl	S,M	0.97 ^b	8.00	24.8	9.7	EA Eng.1986
<u>Atlantic silverside,</u> <u>Menidia menidia</u>	juvenile	NH ₄ Cl	S,M	1.24 ^b	8.00	20.2	10.2	EA Eng.1986
<u>Atlantic silverside,</u> <u>Menidia menidia</u>	juvenile	NH ₄ Cl	FT,M	1.05 ^b	7.92	24.8	9.9	EA Eng.1986
<u>Atlantic silverside,</u> <u>Menidia menidia</u>	juvenile	NH ₄ Cl	S,M	1.47 ^b	8.5	21.1	10.2	EA Eng.1986
<u>Atlantic silverside,</u> <u>Menidia menidia</u>	juvenile	NH ₄ Cl	S,M	1.21 ^b	8.98	21.3	10.3	EA Eng.1986
<u>Atlantic silverside,</u> <u>Menidia menidia</u>	33.5 mm	NH ₄ Cl	S,M	0.98	8.2	19.2	29.8	Fava et al.1984
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH ₄ Cl	FT,M	1.64	6.9- 7.1 ^{e,f}	25.0	11	Poucher 1986

Species	Life Stage or size	Chem.	Methods	LC-50 or EC-50 (mg/L NH-3)	pH	Temp (c)	Sal (g/kg)	Reference
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH4Cl	FT,M	0.97	6.9- 7.1	25.5	29.5	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH4Cl	FT,M	0.93	6.9- 7.1 ^{e, f}	25.5	30	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH4Cl	S,M	1.06	7.0- 7.2 ^e	26.5	31.5	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH4Cl	S,M	1.40	7.5- 7.6 ^e	25.0	31	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH4Cl	FT,M	0.88	7.8- 8.1 ^{e, f}	24	11	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 2 weeks old	NH4Cl	FT,M	0.98	7.9- 8.1 ^{e, f}	18	30.5	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH4Cl	FT,M	1.94	7.8- 8.0 ^{e, f}	26	19	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 10 days old	NH4Cl	FT,M	1.77	7.9- 8.1 ^{e, f}	25.5	30.5	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH4Cl	S,M	1.75	7.9- 8.1 ^e	24.5	32	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH4Cl	FT,M	1.70	7.9- 8.1 ^{e, f}	32.5	30	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH4Cl	S,M	1.08	8.4- 8.6 ^e	25	33	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH4Cl	FT,M	1.16	8.9- 9.1 ^{e, f}	24	11.0	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH4Cl	FT,M	0.75	8.9- 9.0 ^{e, f}	26	30	Poucher 1986
<u>Inland silverside,</u> <u>Menidia beryllina</u>	larva 1 week old	NH4Cl	S,M	0.49	9.0- 9.1 ^e	26.5	31.5	Poucher 1986
<u>Sheepshead minnow,</u> <u>Cyprinodon variegatus</u>	adult	NH4Cl	S,M	2.72 ^b	7.97	10.3	9.8	EA Eng.1986
<u>Sheepshead minnow,</u> <u>Cyprinodon variegatus</u>	adult	NH4Cl	S,M	2.36 ^b	7.92	20.6	10	EA Eng.1986
<u>Sheepshead minnow,</u> <u>Cyprinodon variegatus</u>	adult	NH4Cl	S,M	2.91 ^b	7.96	20.6	10.4	EA Eng.1986
<u>Sheepshead minnow,</u> <u>Cyprinodon variegatus</u>	adult	NH4Cl	S,M	3.37 ^b	7.98	24.8	10.8	EA Eng.1986

Species	Life Stage or size	Chem.	Methods	LC-50 or EC-50 (mg/L NH-3)	pH	Temp (°C)	Sal (g/kg)	Reference
<u>Sheepshead minnow,</u> <u>Cyprinodon variegatus</u>	larva 12.5-14.5 mm.	NH4Cl	FT,M	2.79	^{e,f} 7.6- 7.9	25	30	Poucher 1986
<u>Sheepshead minnow,</u> <u>Cyprinidon variegatus</u>	larva 12.5-15.5 mm.	NH4Cl	FT,M	3.5	^{e,f} 7.6- 7.9	32.5	32	Poucher 1986
<u>Sheepshead minnow,</u> <u>Cyprinidon variegatus</u>	larva 13.5-14.5 mm.	NH4Cl	FT,M	2.10	^{e,f} 8.0- 8.1	13	32.5	Poucher 1986
<u>Striped bass,</u> <u>Morone saxatilis</u>	20-93 mm.	NH4Cl	S,M	1.68 ^c	7.56- 7.62	15	~11	Hazel et al.1971
<u>Striped bass,</u> <u>Morone saxatilis</u>	20-93 mm.	NH4Cl	S,M	1.25 ^c	7.59- 7.72	23	~11	Hazel et al.1971
<u>Striped bass,</u> <u>Morone saxatilis</u>	20-93 mm.	NH4Cl	S,M	1.65 ^c	7.60- 7.73	23	~11	Hazel et al.1971
<u>Striped bass,</u> <u>Morone saxatilis</u>	20-93 mm.	NH4Cl	S,M	1.0 ^c	8.06- 8.12	15	~11	Hazel et al.1971
<u>Striped bass,</u> <u>Morone saxatilis</u>	20-93 mm.	NH4Cl	S,M	0.75 ^c	8.06- 8.12	15	~34	Hazel et al.1971
<u>Striped bass,</u> <u>Morone saxatilis</u>	20-93 mm.	NH4Cl	S,M	1.4 ^c	8.04- 8.18	23	~34	Hazel et al.1971
<u>Striped bass,</u> <u>Morone saxatilis</u>	larva 10 days old	NH4Cl	FT,M	0.33	^{e,f} 7.10- 7.33	21.5	5	Poucher 1986
<u>Striped bass,</u> <u>Morone saxatilis</u>	larva 1 day old	NH4Cl	S,M	1.09	^e 7.4- 7.7	18	5	Poucher 1986
<u>Striped bass,</u> <u>Morone saxatilis</u>	larva 2-3 days old	NH4Cl	FT,M	0.70	^{e,f} 7.2- 7.6	20.5	5	Poucher 1986
<u>Striped bass,</u> <u>Morone saxatilis</u>	larva 9 days old	NH4Cl	S,M	0.58	^e 7.25- 7.45	18	5	Poucher 1986
<u>Striped bass,</u> <u>Morone saxatilis</u>	juvenile	NH4Cl	S,M	0.91 ^b	7.97	20	10.2	EA Eng.1986
<u>White perch,</u> <u>Morone americana</u>	juvenile 76 mm	NH4Cl	S,M	2.13	8.0	16	14	Stevenson 1977
<u>Spot,</u> <u>Leiostomus xanthurus</u>	juvenile	NH4Cl	S,M	1.04 ^b	7.92	20.4	9.3	EA Eng.1986

Species	Life Stage or size	Chem.	Methods	LC-50 or EC-50 (mg/L NH-3)	pH	Temp (c)	Sal (g/kg)	Reference
Winter flounder, <u>Pseudopleuronectes</u> <u>americanus</u>	larva 1 day old	NH4Cl	S,M	0.53	7.9- 8.1	7.5	31	Cardin 1986
Winter flounder, <u>Pseudopleuronectes</u> <u>americanus</u>	larva 1 day old	NH4Cl	S,M	0.51	7.9- 8.1	7.5	31	Cardin 1986
Winter flounder, <u>Pseudopleuronectes</u> <u>americanus</u>	larva 1 day old	NH4Cl	S,M	0.44	7.9- 8.1	7.5	31	Cardin 1986

a

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

b

Recalculated using measured pH values rather than authors' adjusted pH values.

c

Transformed and/or recalculated using ammonia concentrations (total, NH3-N, NH-N or mM/L), salinity, temperature, and pH reported by the author(s).

d

calculated as in footnote c using salinity, temperature and pH conditions supplied to ERL-N by the author(s)

e

NaOH or HCl added to control pH.

f

3-5% NH4OH added to control pH.

g

96-h or EC-50 from authors' graph.

Table 2. Chronic Toxicity of Ammonia To Aquatic Animals

Species	Method ^a	pH	Temperature (C)	Salinity (g/kg)	Limits (mg/L NH ₃)	Chronic Value ^b (mg/L NH ₃)	Reference
<u>FRESHWATER SPECIES</u>							
Cladoceran, <u>Ceriodaphnia acanthina</u>	LC	7.0- 7.5	24.0- 25.0	-	0.199-0.0463	0.304	Mount 1982
Cladoceran, <u>Daphnia magna</u>	LC	8.09	22.1	-	0.378-0.735	0.527	Russo et al.1985
Cladoceran, <u>Daphnia magna</u>	LC	7.6	20.2	-	0.53-0.76	0.63	Russo et al.1985
Cladoceran, <u>Daphnia magna</u>	LC	7.63- 8.16	17.8- 20.8	-	0.96-1.6	1.2	Reinbold & Pescitelli 1982
Pink salmon, <u>Oncorhynchus gorbuscha</u>	ELS	6.3- 6.5	4	-	0.0024-0.004	0.0031	Rice & Bailey 1980
Pink salmon, <u>Oncorhynchus gorbuscha</u>	ELS	6.3- 6.5	4	-	0.0012-0.0024	0.0017	Rice & Bailey 1980
Rainbow trout, <u>Salmo gairdneri</u>	ELS	7.4	14.5	-	0.010-0.025	0.016	Calamari et al. 1977
Rainbow trout, <u>Salmo gairdneri</u>	LC	7.69- 7.72	9.3	-	0.0221-0.0439	0.0311	Thurston et al. 1984
Rainbow trout, <u>Salmo gairdneri</u>	ELS	7.4- 7.6	10- 12	-	0.06 upper limit	<0.06	Burkhalter & Kaya 1977
Rainbow trout, <u>Salmo gairdneri</u>	ELS	7.4- 7.6	10- 12	-	0.06-0.12	0.085	Burkhalter & Kaya 1977
Atlantic salmon, <u>Salmo salar</u>	ELS	6.7- 7.5	13	-	0.002-0.07	0.01	Samylin 1969
Fathead minnow, <u>Pimephales promelas</u>	LC	8.01	24.0	-	0.088-0.188	0.13	Thurston 1986
Fathead minnow, <u>Pimephales promelas</u>	LC	7.99	24.2	-	0.092-0.187	0.13	Thurston 1986
Fathead minnow, <u>Pimephales promelas</u>	ELS	7.63- 8.13	22.7- 26.3	-	0.15-0.34	0.22	Swigert & Spacie 1983

Species	^a Method	pH	Temperature (C)	Salinity (g/kg)	Limits (mg/L NH ₃)	Chronic Value (mg/L NH ₃)	Reference
Channel catfish, <u>Ictalurus punctatus</u>	ELS	7.6- 7.8	25.1-	-	0.073-0.146	0.103	Robinetto 1976
Channel catfish, <u>Ictalurus punctatus</u>	ELS	7.34- 7.95	23.5- 28.0	-	0.13-0.24	0.18	Swigert & Spacie 1983
Green sunfish, <u>Lepomis cyanellus</u>	ELS	7.9	22	-	0.22-0.49	0.33	McCormick et al. 1984
Bluegill, <u>Lepomis macrochirus</u>	ELS	7.74	22	-	0.063-0.136	0.0926	Smith et al. 1984
Smallmouth bass, <u>Micropterus dolomieu</u>	ELS	6.60	22.5	-	0.0342-0.0558	0.0437	Broderius et al. 1985
Smallmouth bass, <u>Micropterus dolomieu</u>	ELS	7.25	22.2	-	0.120-0.182	0.148	Broderius et al. 1985
Smallmouth bass, <u>Micropterus dolomieu</u>	ELS	7.83	22.3	-	0.472-0.760	0.599	Broderius et al. 1985
Smallmouth bass, <u>Micropterus dolomieu</u>	ELS	8.68	22.2	-	0.433-0.865	0.612	Broderius et al. 1985

SALTWATER SPECIES

Mysid, <u>Mysidopsis bahia</u>	LC	7.7- 8.0	25-27	30	0.163-0.331	0.232	Cardin 1986
Inland silverside, <u>Menidia beryllina</u>	ELS	7.9- 8.0	23.5- 25.0	30- 31.5	0.050-0.074	0.061	Poucher 1986

Acute-Chronic Ratio

<u>Species</u>	<u>Acute Value</u> (mg/L NH ₃)	<u>Chronic Value</u> (mg/L NH ₃)	<u>Ratio</u>
<u>Freshwater Species</u>			
Cladoceran, <u>Ceriodaphnia acanthina</u>	1.05	0.304	3.5
Cladoceran, <u>Daphnia magna</u>	2.68	0.527	5.1
Cladoceran, <u>Daphnia magna</u>	0.87	0.63	1.4

<u>Species</u>	<u>Acute Value</u> <u>(mg/L NH3)</u>	<u>Chronic Value</u> <u>(mg/L NH3)</u>	<u>Ratio</u>
Cladoceran, <u>Daphnia magna</u>	4.6	1.2	3.9
Pink salmon, <u>Oncorhynchus gorbuscha</u>	0.090	0.0017	53
Pink salmon, <u>Oncorhynchus gorbuscha</u>	0.090	0.0031	29
Rainbow trout, <u>Salmo gairdneri</u>	0.422	0.0311	14
Rainbow trout, <u>Salmo gairdneri</u>	0.35	0.016	22
Fathead minnow, <u>Pimephales promelas</u>	2.54	0.13	20
Fathead minnow, <u>Pimephales promelas</u>	2.56	0.13	20
Fathead minnow, <u>Pimephales promelas</u>	1.75	0.22	8.0
Channel catfish, <u>Ictalurus punctatus</u>	2.42	0.103	15
Channel catfish, <u>Ictalurus punctatus</u>	1.95	<0.25	8-34
Channel catfish, <u>Ictalurus punctatus</u>	2.12	0.283	7.5
Channel catfish, <u>Ictalurus punctatus</u>	1.58	0.18	8.8
Green sunfish, <u>Lepomis cyanellus</u>	2.05	0.33	6.3
Bluegill, <u>Lepomis macrochirus</u>	1.08	0.0926	12
Smallmouth bass, <u>Micropterus dolomieu</u>	0.81	0.0437	19
Smallmouth bass, <u>Micropterus dolomieu</u>	1.14	0.148	7.7

<u>Species</u>	<u>Acute Value</u> <u>(mg/L NH3)</u>	<u>Chronic Value</u> <u>(mg/L NH3)</u>	<u>Ratio</u>
Smallmouth bass, <u>Micropterus dolomieu</u>	1.30	0.599	2.2
Smallmouth bass, <u>Micropterus dolomieu</u>	1.77	0.612	2.9
<u>Saltwater species</u>			
Mysid, <u>Mysidopsis bahia</u>	1.70	0.232	7.2
Inland silverside, <u>Menidia beryllina</u>	1.30	0.061	21.3

Geometric mean of acute-chronic ratios for channel catfish = 10.0
 for bluegill = 12
 for rainbow trout = 14 (18 if ELS study included)
 for fathead minnow = 20 (15 if ELS study included)
 for mysid = 7.3
 for inland silverside = 21.3

^a LC = life cycle, ELS = early life stage,

^b For details concerning derivation of specific freshwater values see U.S. EPA 1985a Ambient Water Quality Criteria for Ammonia:1984. PB85 2227114 National Technical Information Service, Springfield, VA.

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

Rank ^a	Genus Mean Acute Value (mg/L NH ₃)	Species	Species Mean Acute Value (mg/L NH ₃)	Species Mean Acute-Chronic Ratio
<u>SALTWATER SPECIES</u>				
18	19.102	Eastern oyster, <u>Crassostrea virginica</u>	19.102	-
17	5.360	Quahog clam, <u>Merconaria mercenaria</u>	5.360	-
16	3.08	Brackish water clam, <u>Rangia cuneata</u>	3.08	-
15	2.932	Three-spined stickleback, <u>Gasterosteus aculeatus</u>	2.932	-
14	2.737	Sheepshead minnow, <u>Cyprinodon variegatus</u>	2.737	-
13	2.21	Lobster, <u>Homarus americanus</u>	2.21	-
12	1.651	Grass shrimp, <u>Palaemonetes pugio</u>	1.651	-
11	1.544	Striped mullet, <u>Mugil cephalus</u>	1.544	-
10	1.117	Inland silverside, <u>Menidia beryllina</u> Atlantic silverside, <u>Menidia menidia</u>	1.317 1.050	21.3 ^b -
9	1.04	Spot, <u>Leiostomus xanthurus</u>	1.04	-
8	1.021	Mysid, <u>Mysidopsis bahia</u>	1.021	7.2 ^c
7	1.012	Striped bass, <u>Morone saxatilis</u> White perch, <u>Morone americana</u>	0.481 2.13	- -
6	0.829	Copepod, <u>Eucalanus elongatus</u> Copepod, <u>Eucalanus pileatus</u>	0.867 0.793	- -

Rank ^a	Genus Mean Acute Value (mg/L NH3)	Species	Species Mean Acute Value (mg/L NH3)	Species Mean Acute-Chronic Ratio
5	0.826	Planehead filefish, <u>Monocanthus hispidus</u>	0.826	-
4	0.777	Prawn, <u>Macrobrachium rosenbergii</u>	0.777	-
3	0.773	Sargassum shrimp, <u>Latreutes fucorum</u>	0.773	-
2	0.545	Red drum, <u>Sciaenops ocellatus</u>	0.545	-
1	0.492	Winter flounder, <u>Pseudopleuronectes americanus</u>	0.492	-

^a Ranked from least sensitive to most sensitive based on Genus Mean Acute Values

^b Acute-Chronic Ratio calculated from tests with similar exposure parameters (salinity, temperature) and using the geometric mean of LC50 values for pH 7 and 8.

^c Acute-Chronic Ratio calculated from tests with similar exposure parameters (salinity, pH, and temperature)

Saltwater Final Acute Value = 0.465 mg/L NH3

Saltwater Criterion Maximum Concentration = $0.465 \text{ mg/L} / 2 = 0.233 \text{ mg/L NH}_3$

Final Acute-Chronic Ratio = (see text)

Saltwater Final Chronic Value = $0.465 \text{ mg/L} / 13.1 = 0.035 \text{ mg/L NH}_3$

Table 4. Other Data on Effects of Ammonia on Saltwater Organisms

Species	Chemical	pH	Temperature (°C)	Salinity (g/kg)	Duration	Effect	Concentration (mg/L)	Reference
Diatom, <u>Amphiprora paludosa</u>	NH ₄ Cl	8.0	12	33.7	3-10 days	46% reduction in chlorophyll a	0.247	Admiraal 1977
Diatom, <u>Gyrosigma spencerii</u>	NH ₄ Cl	8.0	12	15.0	3-10 days	66% reduction in chlorophyll a	0.247	Admiraal 1977
Diatom, <u>Navicula arenaria</u>	NH ₄ Cl	8.0	12	33.7	3-10 days	25% reduction in chlorophyll a	0.247	Admiraal 1977
Diatom, <u>Navicula cryptocephala</u>	NH ₄ Cl	8.0	12	15.0	3-10 days	63% reduction in chlorophyll a	1.018	Admiraal 1977
Diatom, <u>Navicula salinarum</u>	NH ₄ Cl	8.0	12	15.0	3-10 days	34% reduction in chlorophyll a	1.234	Admiraal 1977
Diatom, <u>Nitzschia closterium</u>	NH ₄ Cl	8.0	12	33.7	3-10 days	77% reduction in chlorophyll a	1.234	Admiraal 1977
Diatom, <u>Nitzschia dissipata</u>	NH ₄ Cl	8.0	12	33.7	3-10 days	62% reduction in chlorophyll a	0.247	Admiraal 1977
Diatom, <u>Nitzschia dubiformis</u>	NH ₄ Cl	8.0	12	33.7	3-10 days	73% reduction in chlorophyll a	0.247	Admiraal 1977
Diatom, <u>Nitzschia sigma</u>	NH ₄ Cl	8.0	12	15.0	3-10 days	66% reduction in chlorophyll a	0.247	Admiraal 1977
Diatom, <u>Stauroneis constricta</u>	NH ₄ Cl	8.0	12	33.7	3-10 days	33% reduction in chlorophyll a	0.247	Admiraal 1977
Red algae, gametophyte, <u>Champia parvula</u>	NH ₄ Cl	7.8-7.9	22-24	30	48 hours	reduced reproduction; no effect at 0.005	0.039	Thursby 1986
Red algae, tetrasporophyte, <u>Champia parvula</u>	NH ₄ Cl	7.8-7.9	22-24	30	14 days	reduced reproduction & stimulated growth no effect at 0.003	0.005- 0.026	Thursby 1986
Rotifer, <u>Brachionus plicatilis</u>	NH ₄ Cl		23	22.8	24 hours	LC50	20.9 ^a	Yu and Hirayama, 1986
Rotifer, <u>Brachionus plicatilis</u>	NH ₄ Cl	8.5	23	22.8	-	50% reduction in population growth	16.2 ^a	Yu and Hirayama, 1986
Rotifer, <u>Brachionus plicatilis</u>	NH ₄ Cl	8.3	23	22.8	-	50% reduction in net production rate	9.6 ^a	Yu and Hirayama, 1986
Nemertine worm, <u>Cerebratulus fuscus</u>	NH ₄ NO ₃	7.9	15	34	106 mins	LT50	2.3	Brown 1974

Species	Chemical	pH	Temperature (C)	Salinity (g/kg)	Duration	Effect	Concentration (mg/L)	Reference
<u>Blue mussel,</u> <u>Mytilus edulis</u>	NH4Cl	7.5	18	34	<1 hour	50% reduction in ciliary rate	0.097	Anderson et al. 1978
<u>Blue mussel,</u> <u>Mytilus edulis</u>	NH4Cl	7.5	18	34	<1 hour	90% reduction in ciliary rate	0.11	Anderson et al. 1978
<u>Blue mussel,</u> <u>Mytilus edulis</u>	NH4Cl	7.5	18	34	<1 hour	complete inhibition of cilia	0.11-0.12	Anderson et al. 1978
<u>Copepod,</u> <u>Eucalanus elongatus</u>	NH4Cl	8.0	20.3	30	7 days	LC50	0.666	Venkataramiah et al.1982
<u>Copepod,</u> <u>Eucalanus pileatus</u>	NH4Cl	8.2	20.5	34	7 days	38% mortality	0.706	Venkataramiah et al.1982
<u>Mysid,</u> <u>Mysidopsis bahia</u>	NH4Cl	7.0	29.2	3	1700 mins	LT50	1.7	Buikema et al. 1981
<u>White shrimp,</u> <u>Penaeus setiferus</u>	NH4Cl	-	28.0	30-34	3 weeks	EC50	0.72 ^a	Wickens 1976
<u>Prawn,</u> <u>Macrobrachium rosenbergii</u>	NH4Cl	7.0	29.2	3	1700 mins	LT50	1.7 ^a	Wickens 1976
<u>Prawn,</u> <u>Macrobrachium rosenbergii</u>	NH4Cl	7.0	29.2	3	1400 mins	LT50	2.7 ^a	Wickens 1976
<u>Prawn,</u> <u>Macrobrachium rosenbergii</u>	NH4Cl	7.0	29.2	3	560 mins	LT50	3.4 ^a	Wickens 1976
<u>Prawn,</u> <u>Macrobrachium rosenbergii</u>	NH4Cl	-	28.0	.5-4	6 weeks	30%-40% growth reduction	0.12 ^a	Wickens 1976
<u>Prawn,</u> <u>Macrobrachium rosenbergii</u>	NH4Cl	6.83	28.0	12	24 hours	LC50	0.66	Armstrong et al. 1978
<u>Prawn,</u> <u>Macrobrachium rosenbergii</u>	NH4Cl	6.83	28.0	12	144 hours	LC50	0.26	Armstrong et al. 1978
<u>Prawn,</u> <u>Macrobrachium rosenbergii</u>	NH4Cl	7.60	28.0	12	24 hours	LC50	2.10	Armstrong et al. 1978
<u>Prawn,</u> <u>Macrobrachium rosenbergii</u>	NH4Cl	7.60	28.0	12	144 hours	LC50	0.80	Armstrong et al. 1978
<u>Prawn,</u> <u>Macrobrachium rosenbergii</u>	NH4Cl	8.34	28.0	12	24 hours	LC50	3.58	Armstrong et al. 1978
<u>Prawn,</u> <u>Macrobrachium rosenbergii</u>	NH4Cl	8.34	28.0	12	144 hours	LC50	1.35	Armstrong et al. 1978

Species	Chemical	pH	Temperature (C)	Salinity (g/kg)	Duration	Effect	Concentration (mg/L)	Reference
Prawn, <u>Macrobrachium rosenbergii</u>	NH ₄ Cl	6.83	28.0	12	7 days	reduction in growth rate	0.11	Armstrong et al. 1978
Prawn, <u>Macrobrachium rosenbergii</u>	NH ₄ Cl	7.60	28.0	12	7 days	reduction in growth rate	0.63	Armstrong et al. 1978
Grass shrimp, <u>Palaemonetes pugio</u>	NH ₄ Cl	8.0-8.2	20.0		48 hours	LC50	0.34-0.53	Hall et al. 1978
Sargassum shrimp, <u>Latreutes fucorum</u>	NH ₄ Cl	8.15	22.3	28	21 days	LC0	0.44	Venkataramiah et al. 1982
American lobster, <u>Homarus americanus</u>	NH ₄ Cl	8.1	21.9	33.4	8 days	LC50	1.79 ^b	Delistraty et al. 1977
Coho salmon, <u>Oncorhynchus kisutch</u>	NH ₄ Cl	7.49-7.52	15.0	25	24 hours	LC50	0.50	Katz and Pierro 1967
Chinook salmon, <u>Oncorhynchus tshawytscha</u>	NH ₄ Cl	7.59	11.7	0	24 hours	LC50	0.36	Harader and Allen 1983
Chinook salmon, <u>Oncorhynchus tshawytscha</u>	NH ₄ Cl	6.99-7.26	12.7	5.2	24 hours	LC50	0.87	Harader and Allen 1983
Chinook salmon, <u>Oncorhynchus tshawytscha</u>	NH ₄ Cl	8.4-8.7	11.7	9.6	24 hours	LC50	2.19	Harader and Allen 1983
Chinook Salmon, <u>Oncorhynchus tshawytscha</u>	NH ₄ Cl	7.3-8.6	13.0	16.9	24 hours	LC50	1.38	Harader and Allen 1983
Chinook Salmon, <u>Oncorhynchus tshawytscha</u>	NH ₄ Cl	8.29-8.55	12.0	27.6	24 hours	LC50	1.15	Harader and Allen 1983
Atlantic salmon, <u>Salmo salar</u>	NH ₄ Cl	7.95	2.3	10.2	24 hours	LC50	0.28 ^c	Alabaster et al. 1979
Atlantic salmon, <u>Salmo salar</u>	NH ₄ Cl	7.92	12.0	10.2	24 hours	LC50	0.115 ^d	Alabaster et al. 1979
Atlantic silverside, <u>Menidia menidia</u>	NH ₄ Cl	-	25.0	10	28 days	significant increase in mortality	0.31	EA Eng. 1986
Striped mullet, <u>Mugil cephalus</u>	NH ₄ Cl	8.2	22.3		21 days	LC50	0.951 ^e	Venkataramiah et al. 1981

^a Transformed and/or recalculated using ammonia concentrations (total, NH₄-N, mM/L, NH₃-N).

^b Calculated using salinity, temperature and pH conditions supplied to ERL-N by the authors.

^c high d.o. = 9.5 mg/L.

^d low d.o. = 3.1 mg/L.

^e Recalculated omitting treatment with highly variable measured concentration

REFERENCES

- Admiraal, W. 1977. Tolerance of estuarine benthic diatoms to high concentrations of ammonia, nitrite ion, nitrate ion and orthophosphate. *Mar. Biol.* 43(4):307-315.
- Alabaster, J.S., D.G. Shurben, and G. Knowles. 1979. The effect of dissolved oxygen and salinity on the toxicity of ammonia to smolts of salmon, Salmo salar L. *J. Fish Biol.* 15:705-712.
- Alabaster, J.S. and R. Lloyd. 1980. Ammonia. Pages 85-102 in: *Water Quality Criteria for Freshwater Fish*. Second Ed. J. Alabaster and R. Lloyd (Eds.), Butterworth and Co. Ltd., London.
- Alderson, R. 1979. The effect of ammonia on the growth of juvenile Dover sole, Solea solea (L.) and turbot Scophthalmus maximus (L.). *Aquaculture* 17(4):291-309.
- Anderson, K.B., R.E. Sparks, and A.A. Paparo. 1978. Rapid assessment of water quality, using the fingernail clam, Musculium transversum. WRC Res. Rep. No. 133, Water Resources Center, University of Illinois, Urbana, IL: 115 p.
- Arizzi, M. and A. Nicotra. 1980. Effects of ammonia activation in sea urchin eggs. *Ultrastructural observations*. *Ultramicroscopy* 5(3):401.
- Armstrong, D.A., D. Chippendale, A.W. Knight, and J.E. Colt. 1978. Interaction of ionized and un-ionized ammonia on short-term survival and growth of prawn larvae, Macrobrachium rosenbergii. *Biol. Bull.* 154(1):15-31.
- Armstrong, D.A. 1979. Nitrogen toxicity to crustacea and aspects of its dynamics in culture systems. Pages 329-360 in: *Proc. Second Biennial Crustacean Health Workshop*. D. Lewis and J. Leong (Eds.), Texas A & M Sea Grant, TAMU-SG-79-114.
- Bartberger, C.A. and S.K. Pierce, Jr. 1976. Relationship between ammonia excretion rates and hemolymph nitrogenous compounds of a euryhaline bivalve during low salinity acclimation. *Biol. Bull.* 150(1):1-14.
- Bates, R.G. and C.H. Culberson. 1977. Hydrogen ions and the thermodynamic state of marine systems. Pages 45-61 in: *The Fate of Fossil Fuel CO₂ in the Oceans*, N.R. Anderson and A. Malahoff (Eds.). Plenum, N.Y., N.Y.
- Bates, R.G. and G.D. Pinching. 1949. Acidic dissociation constant of ammonium ion at 0 to 50°C and the base strength of ammonia. *J. Res. Nat. Bur. Stand.*, 4:419-430.
- Becker, C.D. and T.O. Thatcher. 1973. Ammonia, amines and related compounds. Pages D.1-D.28 in: *Toxicity of Power Plant Chemicals to*

Aquatic Life. United States Atomic Energy Commission, Battelle
Pacific Northwest Laboratories, Richland, WA. WASH-1249.

- Binstock, L. and H. Lecar. 1969. Ammonium ion currents in the squid giant axon. *J. Gen. Physiol.* 53(3):342-361.
- Broderius, S.J., R.A. Drummond, J.T. Flandt, and C.L. Russom. 1985. Toxicity of ammonia to early life stages of the smallmouth bass at four pH values. *Environ. Toxicol. Chem.* 4:87-96.
- Brown, A.C. 1974. Observations on the effect of ammonium nitrate solutions on some common marine animals from Table Bay. *Trans. R. Soc. S. Afr.* 41(2):217-223.
- Brown, A.C. and A.B. Currie. 1973. Tolerance of *Bullia digitalis* (Prosobranchiata) to solutions of ammonium nitrate in natural sea water. *S. Afr. J. Sci.* 69(7):219-220.
- Brownell, C.L. 1980. Water quality requirements for first-feeding in marine fish larvae. I. Ammonia, nitrite, and nitrate. *J. Exp. Mar. Biol. Ecol.* 44:269-283.
- Buikema, A.L., Jr., B.R. Niederlehner, and J. Cairns, Jr. 1981. The effects of a simulated refinery effluent and its components on the estuarine crustacean, *Mysidopsis bahia*. *Arch. Environm. Contam. Toxicol.* 10:231-239.
- Burkhalter, D.E. and C.M. Kaya. 1977. Effects of prolonged exposure to ammonia on fertilized eggs and sac fry of rainbow trout (*Salmo gairdneri*). *Trans. Am. Fish. Soc.* 106(5):470-475.
- Byerrum, R.U. and A.A. Benson. 1975. Effect of ammonia on photosynthetic rate and photosynthate release by *Amphidinium carterae* (Dinophyceae). *J. Phycol.* 11:449-452.
- Calamari, D., R. Marchetti, and G. Vailati. 1977. Effetti di trattamenti prolungati con ammoniaca su stadi di sviluppo del *Salmo gairdneri*. (Effect of prolonged treatments with ammonia on stages of development of *Salmo gairdneri*.) *Nuovi Ann. Ig. Microbiol.* 28(5):333-345. (In Italian).
- Cameron, J.N. 1986. Responses in reversed NH₃ and NH₄⁺ gradients in a teleost (*Ictalurus punctatus*), an elasmobranch (*Raja erinacea*), and a crustacean (*Callinectes sapidus*): Evidence for NH₄⁺/H⁺ exchange in the teleost and the elasmobranch. *J. Exp. Biol.* 239:183-195.
- Cardin, J.A. 1986. Memorandum to David Hansen. U.S. EPA, Narragansett, Rhode Island.
- Chin, P. 1976. Nitrogen and phosphorus excretion in *Neomysis awatschensis*.
1. Effects of temperature and salinity. Pusan Susan Taehak Haeyang

Kwahak Yonguso Yongu Pogo 9:1-6. (In Korean). [Chem. Abstr. 87(15):114956t (1977)].

Chipman, W.A., Jr. 1934. The role of pH in determining the toxicity of ammonium compounds. Ph.D. Thesis, University of Missouri, Columbia, MO:153 p.

Colt, J.E. and D.A. Armstrong. 1981. Nitrogen toxicity to crustaceans, fish, and molluscs. Pages 34-47 in: Bio-Engineering Symposium for Fish Culture. Fish Culture Section Publ. 1, American Fisheries Society.

Currie, A.B., A.C. Brown, and G.R. Bennett. 1974. The effect of ammonium nitrate solutions on some aspects of the biology of the black mussel, Choromytilus meridionalis. Trans. R. Soc. S. Afr. 41(2):209-215.

Curtis, M.W., T.L. Copeland, and C.H. Ward. 1979. Acute toxicity of 12 industrial chemicals to freshwater and saltwater organisms. Water Res. 13(2):137-141.

Delistraty, D.A., J.M. Carlberg, J.C. Van Olst, and R.F. Ford. 1977. Ammonia toxicity in cultured larvae of the American lobster (Homarus americanus). Pages 647-672 in: Proc. World Mariculture Society, 8th Ann. Meet., San Jose, Costa Rica.

EA Eng. (EA Engineering, Science, and Technology, Inc.). 1986. Proposed modified effluent limitations for ammonia. E.A. Report BET54E. Prepared for Bethlehem Steel Corporation, Sparrows Point, MD 21219.

Epel, D., R. Steinhardt, T. Humphreys, and D. Mazia. 1974. An analysis of the partial metabolic derepression of sea urchin eggs by ammonia; the existence of independent pathways. Dev. Biol. 40:245-255.

Epler, P. 1971. Oddziaływanie zanieczyszczenia wód na ich ichtiofaunę, Część II. Toksyczność amoniaku, fenoli i cyjanków. (Effect of water pollution on ichthyofauna. II. Toxicity of ammonia, phenols, and cyanides.) Postępy Nauk Roln. 71(4):67-90. (In English translation).

Epifano, E.C. and R.F. Srna. 1975. Toxicity of ammonia, nitrite ion, nitrate ion, and orthophosphate to Mercenaria mercenaria and Crassostrea virginica. Mar. Biol. 33(3):241-246.

Erickson, R.J. 1985. An evaluation of mathematical models for the effects of pH and temperature on ammonia toxicity to aquatic organisms. Water Res. 19(8):1047-1058.

European Inland Fisheries Advisory Commission. 1970. Water quality criteria for European freshwater fish. Report on ammonia and inland fisheries. EIFAC Tech. Paper No. 11: 12 p. (also in Water Res. 7(7):1011-1022 (1973).)

- Fava, J.A., J.J. Gift, A.F. Maciorowski, W.L. McCulloch, and H.J. Reisinger II. 1984. Comparative toxicity of whole and liquid phase sewage sludges to marine organisms. Pages 229-252 in: Aquatic Toxicology and Hazard Assessment: Seventh Symposium, R. Cardwell, R. Purdy and R. Banner (Eds.). ASTM STP 854, ASTM, Philadelphia, PA.
- Girard, J.P. and P. Payan. 1980. Ion exchanges through respiratory and chloride cells in freshwater- and seawater-adapted teleosts. Am. J. Physiol. 238:R260-R268.
- Goldstein, L. and R.P. Forster. 1961. Source of ammonia excreted by the gills of the marine teleost, Myoxocephalus scorpius. Am J. Physiol. 200(5):1116-1118.
- Goldstein, L., R.P. Forster, and G.M. Fanelli, Jr. 1964. Gill blood flow and ammonia excretion in the marine teleost, Myoxocephalus scorpius. Comp. Biochem. Physiol. 12(4):489-499.
- Grasshoff, K. 1983. Determination of pH. Pages 85-97 in: Methods of Seawater Analysis, Second Edition. K. Grasshoff, M. Ehrhardt, and K. Kremling (Eds.) Verlag Chemie, Deerfield Beach, FL.
- Greenwood, P.J. and A.C. Brown. 1974. Effect of ammonium nitrate solutions on fertilization and development of the sea urchin, Parechinus angulosus. Zool. Afr. 9(2):205-209.
- Grollman, A. 1929. The urine of the goosfish (Lophius piscatorius): its nitrogenous constituents with special reference to the presence in it of trimethylamine oxide. J. Biol. Chem. 81(2):267-278.
- Hall, L.W., Jr., A.L. Buikema, Jr., and J. Cairns, Jr. 1978. The effects of a simulated refinery effluent on the grass shrimp, Palaemonetes pugio. Arch. Environ. Contam. Toxicol. 7(1):23-35.
- Hampson, B.L. 1976. Ammonia concentration in relation to ammonia toxicity during a rainbow trout rearing experiment in a closed freshwater-seawater system. Aquaculture 9(1):61-70.
- Hampson, B.L. 1977. Relationship between total ammonia and free ammonia in terrestrial and ocean waters. J. Cons. int. Explor. Mer 37(2):117-122.
- Hansen, D.J. 1984. Utility of toxicity tests to measure effects of substances on marine organisms. Pages 33-56 in: Concepts in Marine Pollution Measurements. H. White (Ed.), Maryland Sea Grant College, Univ. MD., College Park, MD.
- Harader, Jr. R.R. and G.H. Allen. 1983. Ammonia toxicity to chinook salmon parr: reduction in saline water. Trans. Am. Fish. Soc. 112:834-837.
- Hays, R.M. S.D. Levine, J.D. Myers, H.O. Heinemann, M.A. Kaplan, N. Franki,

- and H. Berliner. 1977. Urea transport in the dogfish kidney. J. Exp. Zool. 199(3):309-315.
- Hazel, C.R., W. Thomsen, and S.J. Meith. 1971. Sensitivity of striped bass and stickleback to ammonia in relation to temperature and salinity. Calif. Fish and Game. 57(3): 154-161.
- Holt, G.J. and C.R. Arnold. 1983. Effects of ammonia and nitrite on growth and survival of red drum eggs and larvae. Trans. Am. Fish. Soc. 112:314-318.
- Inamura, S. 1951. Effect of various sorts of ion on the sensoria of the labyrinth of eel (Anguilla japonica). The Tohoku J. Exp. Med. 54(2):145-150.
- Johnson, J.D., D. Epel, and M. Paul. 1976. Intracellular pH and activation of sea urchin eggs after fertilization. Nature 262(5570):661-664.
- Katz, M. and R.A. Pierro. 1967. Estimates of the acute toxicity of ammonia-urea plant wastes to coho salmon, Oncorhynchus kisutch. Final report, Fisheries Research Institute, College of Fisheries, University of Washington, Seattle, WA: 15 p.
- Khoo, K.H., C.H. Culberson, and R.G. Bates. 1977. Thermodynamics of the dissociation of ammonium ion in sea water from 5 to 40°C. J. Solution Chem. 6:281-290.
- Kinne, O. 1976. End products of nitrogen metabolism. Pages 80-100 in: Marine Ecology. A Comprehensive, Integrated Treatise on Life in Oceans and Coastal Waters, Vol. 3, Part 1: Cultivation, O. Kinne (Ed.), John Wiley and Sons, London.
- Krystal, G.W. and D. Poccia. 1979. Control of chromosome condensation in the sea urchin egg. Exp. Cell Res. 123(2):207-219.
- Liebmann, H. 1960. Toxikologie des Abwassers. Sauerstoffmangel und anorganische Gifte. Gasformige Gifte. Ammoniak und Ammonium (NH_3 , NH_4). (Toxicology of waste waters. Lack of oxygen and inorganic poisons. Gaseous poisons. Ammonia and ammonium (NH_3 , NH_4). Pages 720-724 in: Handbuch der Frischwasser und Abwasser Biologie. Vol II. R. Oldebourg (Publishers), Munchen. (In English translation).
- Linden, E., B-E. Bengtsson, O. Svanberg, and G. Sundstrom. 1979. The acute toxicity of 78 chemicals and pesticide formulations against two brackish water organisms, the bleak (Alburnus alburnus) and the harpacticoid Nitocra spinipes. Chemosphere 11/12:843-851.
- Lloyd, R. 1961. The toxicity of ammonia to rainbow trout (Salmo gairdnerii Richardson). Water Waste Treat. J. 8:278-279.
- Lloyd, R. and D.W.M. Herbert. 1962. The effect of the environment on the toxicity of poisons to fish. Inst. Public Health Eng. J. 61:132-143.

- Lloyd, R. and D.J. Swift. 1976. Some physiological responses by fresh water fish to low dissolved oxygen, high carbon dioxide, ammonia and phenol with particular reference to water balance. Pages 47-69 in: Society for Experimental Biology Seminar Series. Vol. 2. Effects of Pollutants on Aquatic Organisms. A.P.M. Lockwood (Ed.). Cambridge University Press, Cambridge, MA.
- Mangum, C.P., S.U. Silverthorn, J.L. Harris, D.W. Towle, and A.R. Krall. 1976. The relationship between blood pH, ammonia excretion and adaptation to low salinity in the blue crab Callinectes sapidus. J. Exp. Zool. 195(1):129-136.
- Mangum, C.P., J.A. Dykens, R.P. Henry, and G. Polites. 1978. The excretion of NH₄⁺ and its ouabain sensitivity in aquatic annelids and molluscs. J. Exp. Zool. 203:151-157.
- McBean, R.L., M.J. Neppel, and L. Goldstein. 1966. Glutamate dehydrogenase and ammonia production in the eel (Anguilla rostrata). Comp. Biochem. Physiol. 18(4):909-920.
- McCormick, J.H., S.J. Broderius, and J.T. Fiandt. 1984. Toxicity of ammonia to early life stages of the green sunfish Lepomis cyanellus. Environ. Pollut. Ser. A. 36:147-163. Erratum in: R.J. Erickson. 1985. Water Res. 19(8): 1047-1058.
- McKee, J.E. and H.W. Wolf. (Eds). 1963. Ammonia. Pages 132-137 in: Water Quality Criteria. Second Ed., Publ. No. 3-A, State Water Quality Control Board, Sacramento, CA.
- Mihnea, P.-E. 1978. Influence de certaines eaux residuelles a teneur en ammoniacale, uree et methanol, sur les algues unicellulaires marines. (Influence of certain waste waters containing ammonia, urea and methanol on unicellular marine algae). Pages 465-469 in: Workshop on Pollution of the Mediterranean. Antalya, Nov. 24-27, 1978. International Commission for the Scientific Exploration of the Mediterranean Sea, Monaco: United Nations Environment Programme, Nairobi (Kenya). Ives J. Etud. Pollutions, Publ. by C.I.E.S.M.; Monaco (Monaco). [Aquat. Sci. and Fish. Abstr. 10(6): 7692-1Q10 (1980)].
- Millero, F.J. 1986. The pH of estuarine waters. Limnol. Oceanogr. 31(4):839-847.
- Ministry of Technology, U.K. 1963. Effects of pollution on fish: Toxicity of mixtures of zinc sulphate and ammonium chloride; Toxicity of sewage effluents; The toxicity of poisons under estuarine conditions. Pages 76-83 in: Water Pollution Research 1962, H.M. Stationery Office, London, U.K.
- Mount, D.I. 1982. Memorandum to R.C. Russo, 6 August 1982.

- Natarajan, K.V. 1970. Toxicity of ammonia to marine diatoms. J. Water Pollut. Control Fed. 42(5, Part 2):R184-R190.
- National Academy of Sciences, National Academy of Engineering. 1974. Ammonia; Nitrate-Nitrite. Pages 55 and 73 in: Water Quality Criteria 1972. EPA Ecol. Res. Ser. EPA-R3-73-033, 1973, U.S. Environmental Protection Agency, Washington, D.C.
- National Research Council. 1979. Ammonia. Subcommittee on Ammonia, Committee on Medical and Biologic Effects of Environmental Pollutants, National Research Council. University Park Press, Baltimore, MD: 384 p.
- Nelson, S.G., A.W. Knight, and H.W. Li. 1977. The metabolic cost of food utilization and ammonia production by juvenile Macrobrachium rosenbergii (Crustacea:Palaemonidae). Comp. Biochem. Physiol. 57A(1):67-72.
- Nicotra, A. and M. Arizzi. 1980. Studio ultrastrutturale degli effetti di NH₄OH sulla fecondazione di uova di riccio di mare. (An ultrastructural study on the effects of NH₄OH on the fertilization of sea urchin eggs.) Riv. Biol. 73(2):221-234. (In Italian with English translation).
- Nishioka, D.J. 1976. The initiation of cell cycle events in ammonia-treated eggs and merogons of the sea urchin. Ph.D. Thesis, University of California, Berkeley, CA:107 p.
- Okaichi, T. and S. Nishio. 1976. Identification of ammonia as the toxic principle of red tide of Noctiluca miliaris. Bull. Plankton Soc. Jpn. 23(2):25-30. (In Japanese).
- Oshima, S. 1931. On the toxic action of dissolved salts and their electrolytes upon young eels (Anquilla japonica). J. Imp. Fish. Exp. Station (Tokyo) 2:139-193. (In Japanese).
- Paul, M., J.D. Johnson, and D. Epel. 1976. Fertilization acid of sea urchin eggs is not a consequence of cortical granule exocytosis. J. Exp. Zool. 197(1):127-133.
- Paul, M. and R.N. Johnston. 1978. Absence of a Ca response following ammonia activation of sea urchin eggs. Dev. Biol. 67(2):330-335.
- Pinter, I.J. and L. Provasoli. 1963. Nutritional characteristics of some chryomonads. Pages 114-121 in: Symposium on Marine Microbiology. C.M. Oppenheimer (Ed.), Thomas Publishers, Springfield, MA.
- Poucher, S. 1986. Memorandum to David Hansen. U.S. EPA, Narragansett, Rhode Island.
- Provasoli, L. and J.J.A. McLaughlin. 1963. Limited heterotrophy of some photosynthetic dinoflagellates. Pages 105-113 in: Symposium on Marine Microbiology. C.M. Oppenheimer (Ed.), Thomas Publishers, Springfield, MA.

- Raguse-Degener, G., M. Pietschmann, F. Walvig, and H. Stolte. 1980. Excretory systems in the hagfish Myxine glutinosa. Contrib. Nephrol. 19:1-8.
- Read, L.J. 1971. The presence of high ornithine-urea cycle enzyme activity in the teleost Opsanus tau. Comp. Biochem. Physiol. 39B(2):409-413.
- Reddy, N.A. and N.R. Menon. 1979. Effects of ammonia and ammonium on tolerance and byssogenesis in Perna viridis. Mar. Ecol. Prog. Ser. 1(4):315-321.
- Reinbold, K.A. and S.M. Pescitelli. 1982. Effects of exposure to ammonia on sensitive life stages of aquatic organisms. Project Report, Contract No. 68-01-5832, Illinois Natural History Survey, Champaign, IL. (Draft).
- Rice, S.D. and J.E. Bailey. 1980. Survival, size, and emergence of pink salmon, Oncorhynchus gorbuscha, alevins after short- and long-term exposures to ammonia. Fish. Bull. 78(3):641-648.
- Richards, F.A. and M.L. Healey. 1984. The determination of ammonia aqueous solution. Tech. Rept. 84-3, Fisheries Bioassay Laboratory, Montana State University, Bozeman, MT.
- Robinette, H.R. 1976. Effect of selected sublethal levels of ammonia on the growth of channel catfish (Ictalurus punctatus). Prog. Fish. Cult. 38(1):26-29.
- Rosenberg, D.H., D.C. Burrell, K.V. Natarajan, and D.W. Hood. 1967. Oceanography of Cook Inlet with special reference to the effluent from the Collier Carbon and Chemical Plant. Pages 60-75 in: IMS - 67-3, Institute of Marine Science, University of Alaska, College, AK.
- Russo, R.C., A. Pilli, and E.L. Meyn. 1985. Memorandum to N.A. Jaworski, 4 March 1985.
- Sadler, K. 1981. The toxicity of ammonia to the European eel (Anguilla anguilla L.). Aquaculture 26(1,2):173-181.
- Samylin, A.F. 1969. Effect of ammonium carbonate on early stages of development of salmon. Uchen. Zap. Leningr. Gos. Pedagog. Inst. Im. A. I. Gertsena 422:47-62. (In English translation).
- Schimmel, S.C. 1986. Memorandum to David J. Hansen. U.S. EPA, Narragansett, Rhode Island.
- Schooler, J.M., L. Goldstein, S.C. Hartman, and R.P. Forster. 1966. Pathways of urea synthesis in the elasmobranch, Squalus acanthias. Comp. Biochem. Physiol. 18(2):271-281.
- Shen, S.S. and R.A. Steinhardt. 1978. Direct measurement of intracellular

pH during metabolic derepression of the sea urchin egg. *Nature* 272(5650):253-254.

Shilo, M. and M. Shilo. 1953. Conditions which determine the efficiency of ammonium sulphate in the control of Prymnesium parvum in fish breeding ponds. *Appl. Microbiol.* 1: 330-333.

Shilo, M. and M. Shilo. 1955. Control of the phytoflagellate Prymnesium parvum. *Verh. Int. Ver. Limnol.* 12:233-240.

Sigel, M.M., G. Ortiz-Muniz, and R.B. Shouger. 1972. Toxic effect of ammonia dissolved in sea water. *Comp. Biochem. Physiol.* 42A(1): 261-262.

Smith, W.E., T.H. Roush, and J.T. Fiandt. 1984. Toxicity of ammonia to early life stages of bluegill (Lepomis macrochirus). Internal Report, EPA-600/X-84-175, U.S. Environmental Protection Agency, Duluth, MN:11 p.

Sousa, R.J., T.L. Meade, and G.T. Felbeck, Jr. 1977. The exposure of ammonia to the photodissociated hemoglobin of the marine bloodworm, Glycera dibranchiata. *Comp. Biochem. Physiol.* 58A:19-22.

Sousa, R.J., T.L. Meade, and R.E. Wolke. 1974. Reduction of ammonia toxicity by salinity and pH manipulation. Pages 343-354 in: *Proceedings of the Fifth Annual Meeting World Mariculture Society*. J. Avault Jr. (Ed.).

Steffens, W. 1976. Zur NH₃-Empfindlichkeit der Regenbogenforelle (Salmo gairdneri). (On the sensitivity of rainbow trout (Salmo gairdneri) to NH₃.) *Z. Binnenfisch.* DDR, 23(10):315-319. (In English translation).

Steinhardt, R.A. and D. Mazia. 1973. Development of K⁺ conductance and membrane potentials in unfertilized sea urchin eggs after exposure to NH₄OH. *Nature* 241(5389):400-401.

Stephan, C.E., D.I. Mount, D.J. Hansen, J.H. Gentile, G.A. Chapman, and W.A. Brungs. 1985. Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses. NTIS #PB85-227049. National Technical Information Service, Springfield, VA.

Stevenson, T.J. 1977. The effects of ammonia, pH and salinity on the white perch, Morone americana. Ph.D. Thesis, University of Rhode Island, Kingston, RI:154 p.

Sullivan, B.K. and P.J. Ritacco. 1985. Ammonia toxicity to larval copepods in eutrophic marine ecosystems: a comparison of results from bioassays and enclosed experimental ecosystems. *Aq. Toxicol.* 7:205-217.

Swigert, J.P. and A. Spacie. 1983. Survival and growth of warm-water fishes exposed to ammonia under low flow conditions. NTIS PB83-257535. National Technical Information Service, Springfield, VA.

- Tabata, K. 1962. Suisan dobutsu ni oyobosu amonia no dokusei to pH, tansan to no kankei. (Toxicity of ammonia to aquatic animals with reference to the effect of pH and carbon dioxide.) Tokai-ku Suisan Kenkyusho Kenkyu Hokoku 34:67-74. (In English translation).
- Technicon Industrial Systems. 1973. Ammonia in water and seawater. Industrial Method No. 154-71W/Tentative. Technicon International Science Center, Tarrytown, NY.
- Thomas, W.H., J. Hastings, and M. Fujita. 1980. Ammonium input to the sea via large sewage outfalls - Part 2: Effects of ammonium on growth and photosynthesis of southern California phytoplankton cultures. Marine Environmental Research. 3(4):291-296.
- Thursby, G.B. 1986. Memorandum to David J. Hansen, U.S. EPA, Narragansett, Rhode Island.
- Thurston, R.V., R.C. Russo, and G.A. Vinogradov. 1981. Ammonia toxicity to fishes: effect of pH on the toxicity of the un-ionized ammonia species. Environ. Sci. Technol. 15(7):837-840.
- Thurston, R.V., R.C. Russo, R.J. Luedtke, C.E. Smith, E.L. Meyn, C. Chakoumakos, K.C. Wang, and C.J.D. Brown. 1984. Chronic toxicity of ammonia to rainbow trout. Trans. Am. Fish. Soc. 113(1):56-73.
- Thurston, R.V., R.C. Russo, E.L. Meyn, R.K. Zajdel, and C.E. Smith. 1986. Chronic toxicity of ammonia to fathead minnows. Trans. Am. Fish. Soc. 115:196-207.
- Tsai, C. 1975. Ammonia. Pages 63-104 in: Effects of Sewage Treatment Plant Effluents on Fish: A Review of Literature. Contribution No. 637, Center for Environmental and Estuarine Studies, University of Maryland; CRC Publ. No. 36, Chesapeake Research Consortium, Inc.
- U.S. Environmental Protection Agency. 1976. Ammonia. Pages 16-24 in: Quality Criteria for Water. EPA-440/9-9-76-023. U.S. EPA, Washington, D.C.
- U.S. Environmental Protection Agency. 1979. Methods for Chemical Analysis of Water and Wastes. EPA-600 4-79-020. U.S. EPA, Cincinnati, Ohio.
- U.S. Environmental Protection Agency. 1980. Toxic pollutant list; proposal to add ammonia. Fed. Regis. 45(2):803-806.
- U.S. Environmental Protection Agency. 1983a. Water Quality Standards Regulation. Fed. Regis. 48(217):51400-51413.
- U.S. Environmental Protection Agency. 1983b. Water Quality Standards Handbook. Office of Water Regulations and Standards, U.S. EPA, Washington, D.C.

- U.S. Environmental Protection Agency. 1985a. Ambient water quality criteria for ammonia-1984. NTIS # PB85-227114. National Technical Information Service, Springfield, VA 22161. 217 p.
- U.S. Environmental Protection Agency. 1985b. Technical Support Document for Water Quality-Based Toxics Control. Office of Water, U.S. EPA, Washington, D.C.
- U.S. Environmental Protection Agency. 1985c. Appendix B - Response to Public Comments on "Guidelines for Deriving Numerical National Water Quality Criteria for the Protection of Aquatic Organisms and Their Uses." Federal Regist. 50:30793-30796. July 29.
- U.S. Environmental Protection Agency. 1986. Chapter 1 - Stream Design Flow for Steady-State Modeling. in: Book VI - Design Conditions. Technical Guidance Manual for Performing Waste Load Allocations. Office of Water, U.S. EPA, Washington, D.C.
- U.S. Federal Water Pollution Control Administration. 1968. Water quality criteria. Report of the National Technical Advisory Committee, U.S. Dept. Interior, Washington, D.C. 234 p.
- Venkataramiah, A., G.J. Lakshmi, C. Best, G. Gunter, E. Hartwig, and P. Wilde. 1981. Studies on toxicity of OTEC plant components on marine animals from the Gulf of Mexico. NTIS# DE81030167. National Technical Information Service, Springfield, VA.
- Venkataramiah, A., G.J. Lakshmi, C. Best, G. Gunter, E. Hartwig, and P. Wilde. 1982. Studies on toxicity of OTEC plant components on Eucalanus sp. from the Gulf of Mexico. Ocean Sci. and Eng. 7(3):353-401. (Also reported in 1981 NTIS # DE82012327, National Technical Information Service, Springfield, VA.)
- Visek, W.J. 1968. Some aspects of ammonia toxicity in animal cells. J. Dairy Sci. 51(2):286-295.
- Ward, G.S., G.C. Cramm, P.R. Parrish, and S.R. Petrocelli. 1982. Effect of ammonium jarosite on early life stages of a saltwater fish, Cyprinodon variegatus. Marine Pollut. Bull. 13(6):191-195.
- Warren, K.S. 1962. Ammonia toxicity and pH. Nature 195(4836):47-49.
- Whitfield, M. 1974. The hydrolysis of ammonium ions in sea water - a theoretical study. J. Mar. Biol. Assoc. U.K. 54:565-580.
- Whitfield, M., R.A. Butler, and A.K. Covington. 1985. The determination of pH in estuarine waters. I. Definition of pH scales and the selection of buffers. Oceanol. Acta 8(4):423-432.
- Wickins, J.F. 1976. The tolerance of warm-water prawns to recirculated water. Aquaculture 9(1):19-37.

- Willingham, T. 1976. Ammonia toxicity. EPA-908/3-76-001, Control Technology Branch, Water Division, U.S. Environmental Protection Agency, Region VIII, Denver CO:103 p.
- Willingham, W.T., J.E. Colt, J.A. Fava, B.A. Hillaby, C.L. Ho, M. Katz, R.C. Russo, D.L. Swanson, and R.V. Thurston. 1979. Ammonia. Pages 6-18 in: A Review of the EPA Red Book: Quality Criteria for Water. R.V. Thurston, R.C. Russo, C.M. Fetterolf, Jr., T.A. Edsall, and Y.M. Barber, Jr. (Eds.), Water Quality Section, American Fisheries Society, Bethesda, MD.
- Winkler, M.M. and J.L. Grainger. 1978. Mechanism of action of NH_4Cl and other weak bases in the activation of sea urchin eggs. *Nature* 273(5663):536-538.
- Wilt, F.H. and D. Mazia. 1974. The stimulation of cytoplasmic polyadenylation in sea urchin eggs by ammonia. *Dev. Biol.* 37:422-424.
- Wood, J.D. 1858. Nitrogen excretion in some marine teleosts. *Can. J. Biochem. Physiol.* 36(12):1237-1242.
- Wuhrmann, K., F. Zehender, and H. Woker. 1947. Über die fischereibiologische Bedeutung des Ammonium- und Ammoniakgehaltes fliessender Gewässer. (Biological significance for fisheries of ammonium-ion and ammonia content of flowing bodies of water.) *Vierteljahrsschr. Naturforsch. Ges. Zurich* 92:198-204. (In English translation).
- Wuhrmann, K. and H. Woker. 1948. Beiträge zur Toxikologie der Fische. II. Experimentelle Untersuchungen über die Ammoniak- und Blausäurevergiftung. (Contributions to the toxicology of fishes. II. Experimental investigations on ammonia and hydrocyanic acid poisoning.) *Schweiz. Z. Hydrol.* 11:210-244. (In English translation).
- Yamagata, Y. and M. Niwa. 1982. Acute and chronic toxicity of ammonia to eel Anguilla japonica. *Nippon Suisan Gakkaishi* 48(2):171-176.
- Yu, J-P. and K. Hirayama. 1986. The effect of un-ionized ammonia on the population growth of the rotifer in mass culture. *Bull. Japanese Soc. Sci. Fisheries* 52(9):1509-1513.
- Zirino, A. 1975. Measurement of the apparent pH of seawater with a combination microelectrode. *Limnol. Oceanogr.* 20:654-657.
- Zgurovskaya, L.N. and N.G. Kustenکو. 1968. The effect of ammonia nitrogen on cell division, photosynthesis and pigment accumulation in Sceleronema costatum (Grev) Cl., Chaetoceros sp. and Prorocentrum micans Ehr. *Okeanologiya* 8(1):90-98.10