UNITED STATES DEPARTMENT OF THE INTERIOR

NATIONAL IRRIGATION WATER QUALITY PROGRAM
INFORMATION REPORT NO. 3

Guidelines for Interpretation of the Biological Effects of Selected Constituents in Biota, Water, and Sediment

Molybdenum

Participating Agencies:

Bureau of Reclamation
U.S. Fish and Wildlife Service
U.S. Geological Survey
Bureau of Indian Affairs

November 1998

Molybdenum

Description

Molybdenum (Mo) is a silver-white metallic element of the second transition series; its atomic number is 42, and its atomic weight is 95.94 (Pais and Jones 1997). It has chemical properties similar to those of chromium. It is commonly used in steel alloys because it imparts hardness, strength, heat resistance (melting point 2,617°C), and corrosion resistance to these alloys. Molybdenum is present in all plant and animal tissues and is considered an essential micronutrient for most life forms (Schroeder et al. 1970; Underwood 1971; Chappell and Peterson 1976; Chappell et al. 1979; Goyer 1986; Eisler 1989).

Occurrence

Molybdenum does not occur free in nature and is only found in combination with sulfur, oxygen, tungsten, lead, uranium, iron, magnesium, cobalt, vanadium, bismuth, or calcium. Its principal ore is molybdenite (MoS_2), "a lead-gray hexagonal mineral . . . [which] resembles graphite in appearance and to the touch, but has a bluer color" (Bates and Jackson 1987). Less important sources include wulfenite ($PbMoO_4$), powellite ($CaMoO_4$), and molybdophyllite ($PbMoSiO_4$). Molybdenum is widely disseminated in the environment: its abundance in the Earth's crust is estimated at 1–1.5 mg/kg (Budaveri 1996); and back-ground concentrations in the United States are 1.2–4.1 µg/L for rivers, <1 µg/L for ground-water, 5–57 mg/kg dw for river sediments, and 1.2 (0.1–40) mg/kg dw for soils (Friberg et al. 1975; Chappell et al. 1979). Molybdenum concentrations in animal tissues are generally highest in liver, followed by kidney, spleen, lung, brain, and muscle (Berman 1980). Total body molybdenum is present to the largest degree in skeletal tissue (Underwood 1977).

Molybdenum is used primarily in the manufacture of steel alloys for aircraft and weapons. It is also used as an electrode material and as a catalyst in petroleum refining. Most of the recent global production of about 100,000 tons annually comes from the United States. Three mines in Colorado account for nearly 70 percent of domestic pro-duction. Human activities that contribute to molybdenum contamination include the combustion of fossil fuels, and smelting, mining, and milling operations for steel, copper, and uranium.

Summary of Effects

Table 26 summarizes the predicted effects of environmental exposures to molybdenum, based on the limited information currently available.

Study Approaches

The majority of papers reviewed for this report were laboratory studies dealing with molybdenum effects on mammals and poultry. Mammalian literature consisted of studies done on domestic animals, primarily rats, and was published from the late 1940's to early 1960's. Avian literature consisted exclusively of poultry studies published in the late 1950's to early 1960's. For aquatic species, the literature was composed primarily of freshwater laboratory studies and offered little information about fish, invertebrates, amphi-bians, or reptiles. The review adequately addressed the formally published scientific

Table 26.—Predicted molybdenum effect levels

Media	No effect	Level of concern	Toxicity threshold	Explanation
Water (mg/L)	0.02	0.02–0.12	0.12	For fish. 0.02, upper limit of natural background (Eisler 1989); 0.12, LC10 for larval trout (Birge et al. 1980)
	0.02	0.02–0.96	0.96	For amphibians. 0.02, upper limit of natural background (Eisler 1989); 0.96, LC50 for larval toads (Birge 1978)
	- - -	- - -	>50	For plants. Reduced growth of green algae; 96-h exposure
Domestic chickens (mg/kg in feed)	- - -	>500	>6,000	Adverse effects on reproduction and on survival, respectively
Bird eggs (mg/kg dw)	23	23–33	<33	Lepore and Miller (1965)
Mammals (Cu:Mo ratio in feed)	6:1–10:1	<2:1 *or* >10:1	- - -	Ratios found to lead to either Cu deficiency or Cu toxicosis

literature, but not the scientific "gray literature," which includes government reports and unpublished studies.

Abiotic Factors Affecting Bioavailability

Water

Natural molybdenum concentrations in ground and surface waters rarely exceed 20 µg/L; higher concentrations probably indicate industrial contamination (Eisler 1989). Concentrations in surface waters range from 0.4 µg/L in uncontaminated North American rivers to as much as 100,000 µg/L in mining wastewater. In the United States, ground-water molybdenum concentrations are usually <1 µg/L but have been reported as high as 50,000 µg/L near uranium mills in Colorado (Eisler 1989). Molybdenum concentrations in saline water appear to be directly related to salinity (Prange and Kremling 1985; Sloot et al. 1985).

Aquatic organisms are relatively resistant to molybdenum and generally show no adverse effects on growth or survival at water concentrations lower than 50 mg/L (Eisler 1989); however, there are large differences between species in their ability to bioconcentrate molybdenum. Blue-green algae (*Anabaena oscillaroides*) had a bioconcentration factor (BCF) of 3,300 after 1 hour of exposure at a concentration of 0.005 µg Mo/L (Steeg et al. 1986). The freshwater alga *Nitella flexilis* and some lake periphyton had BCFs of 628 and 3,570, respectively, in 25 days when placed in a 0.014-µg Mo/L concentration (Short et al. 1971). In a 3.3-mg Mo/L con-centration, crayfish (*Pacifastacus leniusculus*) had BCFs of 5.7 in muscle and 9.8 in the carapace. High bioconcentration of molyb-denum by certain species of aquatic algae and invertebrates has been recorded without apparent harm to the organism; however, the hazard potential to organisms that feed on the bioconcentrators is not clear (Eisler 1989).

Soil

Soils average 1–2 mg/kg molybdenum, although they range from trace concentrations to 40 mg/kg or greater. In the United States, molybdenum concentrations in soils generally increase from east to west (Adriano 1986; Kubota 1977).

The largest concentrations of molybdenum are found in the 30 cm of soil nearest the surface. Its uptake into certain legumes and other plants may correlate with the soluble molybdenum concentrations in the soil, but this relationship does not occur with all types of plants. Molybdenum uptake by plants can vary dramatically even between different varieties of the same species (Barshad 1948).

Biota

Plants

Molybdenum is considered essential for aquatic plant growth, but the concentrations required are not known. Aquatic plants are relatively resistant to molybdenum toxicity. Concentrations observed to cause adverse effects in sensitive species were 50 mg/L for growth and 108 mg/L for development (table 27).

The molybdenum content of some plants has been shown to vary by stage of development, as evidenced by a twofold to threefold increase from spring to fall in leaf and stem concentrations of alfalfa and some grasses. Although older plants may contain more molybdenum, younger plants appear to cause more molybdenosis in animals. This dif-ference may arise because animals consume different parts of young, succulent plants.

Fish

Acute toxicity values for molybdenum in the literature (table 27) indicate that it is relatively nontoxic to fish. The one exception was newly fertilized eggs of rainbow trout exposed for 28 days through 4 days posthatch; these had an LC50 of 0.79 mg/L and an LC10 of 0.12 mg/L. In general, molybdenum was more toxic to younger fish than to older fish, although a study by Hamilton and Buhl (1990) found that the 96-hr LC50 values for all Chinook and coho salmon exceeded 1,000 mg/L regardless of the quality of the dilution water (soft, fresh, or brackish) or the life stage tested (eyed egg, alevin, or fry). Moreover, the addition of molybdenum to test mixtures of boron, selenite, and selenate seemed to increase the acute toxicity of these mixtures to Chinook and coho salmon (Hamilton and Buhl 1990).

Few studies have compared the molybdenum concentrations in fish tissues to ambient concentrations, and the toxicological effects of molybdenum in fish tissues are unknown (Eisler 1989; Saiki et al. 1993). As shown in table 27, Ward (1973) found that, in nature, tissue molybdenum concentrations in rainbow trout increased only slightly with increasing water concentrations. Saiki et al. (1992) confirmed Ward's observations in controlled experiments. An eightfold range of waterborne molybdenum caused very little variation in the concentration of molybdenum in tissues of juvenile Chinook salmon or striped bass.

Birds

There are no data showing molybdenum's effects on wild birds. In domestic birds, adverse effects have been reported for growth at dietary molybdenum levels >200 mg/kg, for reproduction at 500 mg/kg, and for survival at 6,000 mg/kg (Eisler 1989). Poor growth was the only symptom of molyb-denum toxicity noted by Miller and Denton (1959) even at 2,250 mg Mo/kg added to the diet. In all groups in which the level of added molybdenum inhibited growth, inorganic sulfate alleviated part of the growth inhibition. The addition of inorganic sulfate caused a considerable decrease in the molybdenum content of liver tissues. Liver molybdenum

Table 27.—Effects of molybdenum on living organisms as reported in published studies

Species	Mo concentration (mg/L *or* mg/kg)	Where measured	Effects	Reference
Plants				
Euglena gracilis	108	Water	Abnormal development	Colmano 1973
	>960		No growth	
Green algae, *Chlorella vulgaris*	50	Water	Reduced growth after 96 h	Sakaguchi et al. 1981
Invertebrates				
Amphipod, *Crangonyx pseudogracilis*	2,650	Soft water	96-h LC50	Martin and Holdich 1986
	3,618		48-h LC50	
Hermit crab, *Eupagurua bernhardus*	222	Water	48-h LC50	Abbott 1977
Fish				
Chinook and coho salmon (eyed eggs, alevins, and fry)	>1,000	Fresh, brackish and soft water	96-h LC50	Hamilton and Buhl 1990
Fathead minnow, *Pimephales promelas*	70	Soft water	96-h LC50	McConnell 1977
	360	Hard water		
Rainbow trout, *Oncorhynchus mykiss*	Trace	Water	Mo in tissue 5–118 µg/kg ww	Ward 1973
	6		Mo in tissue 10–146 µg/kg ww	
	300		Mo in tissue 13–332 µg/kg ww	
	800		96-h LC50 (20-mm size class)	McConnell 1977
	1,320		96-h LC50 (55-mm size class)	
Rainbow trout (fertilization through 4 days post-hatch)	0.12	Moderately hard water	28-d LC10	Birge et al. 1980
	0.79		28-d LC50	
Sheepshead minnow, *Cyprindon variegatus*	3,057	Water	96-h LC50	Knothe and Van Riper 1988
Amphibians				
Frogs	2,000	Water	Zone of toxic action	Venchikov and Kaprielov 1976

Table 27.—Effects of molybdenum on living organisms as reported in published studies—Continued

Species	Mo concentration (mg/L *or* mg/kg)	Where measured	Effects	Reference
Birds				
Chicken	2,250 Mo	Dietary; basal diet 0.25% sulfur, 3.3 ppm Mo, and 13 ppm Cu	Body weight 37% that of control chicks	Miller and Denton 1959
	2,250 Mo + 13,200 sulfate		Body weight 72% that of control chicks	
	750 Mo + 2,200 sulfate		Decrease in Mo content in liver tissues of chicks	
Chicken (chicks)	200 (sodium molybdate)	Diet	Reduced growth after 56 d	Arthur et al. 1958
	300 (sodium molybdate dihydrate)	Diet	25% reduced growth after 24 d	Kratzer 1952
	500 (sodium molybdate dihydrate)	High-sulfate purified diet	Minimum toxic dose after 28 d; lowest concentration depressing growth	Davies et al. 1960
Turkey (poults)	300 (sodium molybdate dihydrate)	Diet	25% reduced growth after 24 d	Kratzer 1952
Mammals				
Cattle, *Bos* spp.	60	Diet	Low Cu in liver; intestinal disturbances; brittle bones prone to fracture	Penumarthy and Oehme 1978
Cattle (lactating cows)	40 Mo, 6 Cu	Diet	30% reduction in milk yield after 63 d; rapid decline in plasma copper; milk Mo levels 1.6 ppm; growth reduction in nursing calves	Wittenberg and Devlin 1987
Mouse (*Mus* sp.)	10	Drinking water	Decrease in survival of 2d and 3d generations	Earl and Vish 1979
Mule deer	2,500 (sodium molybdate)	Diet	Weight loss after 27 d	Ward and Nagy 1976
	5,000 (sodium molybdate)		Reduced feeding after 14 d	
Rat	80	Cu-deficient diet	Inhibited growth and reduced survival	Underwood 1971, 1979
	5000	Diet	Lethal in 2 weeks	Chappell et al. 1979; Friberg et al. 1975

Table 27.—Effects of molybdenum on living organisms as reported in published studies—Continued

Species	Mo concentration (mg/L *or* mg/kg)	Where measured	Effects	Reference
Mammals—Continued				
Rabbit (*Oryctolagus* sp.)	100	Diet	Reduced growth, hair loss, dermatosis, anemia, skeletal and joint deformities (lifetime exposure)	Chappell et al. 1979
	1000	Diet	Weight and hair loss, leg deformities, dermatosis, anemia, death (28 d)	Arrington and Davis 1953
	2,000–4,000	Diet	Many deaths of weanlings in 37 d, adults in 53 d; survivors were anorexic, diarrhetic, anemic, and had front leg abnormalities	Friberg et al. 1975; Arrington and Davis 1953
Sheep, *Ovis* spp.	~5.5–12.5	Grazing pastures treated with 420 g Mo/ha at start, week 45, and week 72	Lameness, connective tissue lesions in most sheep; Mo concentrations (mg/kg fw): plasma 1.7, liver 6.0–6.4; kidney 6.9–8.1	Pitt et al. 1980
Sheep (lambs)	Cu:Mo < 0.4	Soil	15–39% swayback	Friberg and Lener 1986

concentrations of 22-36 mg/kg dw (6–10 mg/kg ww) have been correlated with toxic effects in domestic birds (Puls 1988). When copper was added to the diet, in addition to molybdenum and inorganic sulfate, a further reduction in molybdenum liver tissue concentrations was observed. These studies show that the amount of molybdenum stored by the liver tissues is dependent upon the amount in the diet and upon the ratios of molybdenum, copper, and sulfate in the diet. Increasing the molybdenum content of the diet increased the copper storage of the liver.

Avian eggs normally contain <1 mg Mo/kg (dry weight basis), averaging about 0.25 mg Mo/kg (Romanoff and Romanoff 1949). Lepore and Miller (1965) studied the effects of maternally deposited molybdenum content on the viability (i.e., hatchability) of eggs laid by White Rock chickens. They observed normal egg viability up to about 23 mg Mo/kg in the egg (dry weight basis). At 33 mg/kg, about 50 percent of the eggs were inviable (i.e., the approximate EC50). Thus, the threshold for avian embryotoxicity occurs between 23 and 33 mg Mo/kg egg (dry weight basis). The EC100 concentration was approximately 60 mg/kg. Based on transfer rates of molybdenum from the maternal diet to the eggs, as documented by Lepore and Miller (1965) and Motzok et al. (1957), the dietary threshold for reproductive impairment lies somewhere between 100 and 500 mg Mo/kg (dry feed basis). This suggests that, in the absence of significant interaction effects, molybdenum-induced avian embryotoxicity in the field may be very rare. Lynch et al. (1988) reported that even downstream from spills of molybdenum mill tailings in the Red River of New Mexico, benthic invertebrates averaged only 29 mg Mo/kg (dry weight basis). Evaporation ponds for subsurface agricultural drainage water in California's Tulare Lake Basin were found to contain as much as 40,000 µg Mo/L in the water (Westcot et al. 1988), yet the maximum concentration of molybdenum in aquatic invertebrates was about 80 mg/kg (dry weight basis; Moore et al. 1989), and the maximum level in avian eggs was 16 mg/kg (Ohlendorf et al. 1993). Presumably, cases of environmental contamination with molybdenum more severe than these examples would be extremely rare.

Mammals

Currently available data for molybdenum's effects on wild mammals are inadequate (table 27). The toxicological properties of molybdenum in mammals are governed by its interaction with copper and sulfur; residues of molybdenum alone are not sufficient to diagnose molybdenum poisoning (Eisler 1989). The optimum dietary copper: molybdenum ratio (Cu:Mo) is between 6:1 and 10:1 (assuming that concentrations of both elements are above minimum requirements). A Cu:Mo ratio less than 2:1 will result in a copper deficiency, whereas a Cu:Mo above 10:1 increases the risk of developing copper toxicosis, particularly in sheep (Osweiler et al. 1985).

Molybdenosis is a copper-deficiency disease that is caused by the depressing effect of molybdenum on the physiological availability of copper (Clawson et al. 1972; Dollahite et al. 1972; Alloway 1973; Erdman et al. 1978; and others cited in Eisler 1989). Because of the unique environment of the rumen, cattle and other ruminants are far more susceptible to the toxic effects of molybdenum than other species. Toxicity generally occurs when cattle graze pastures where the forage contains 20–100 mg Mo/kg dw (Underwood 1979). Younger animals and lactating cows appear more susceptible. Molybdenosis can be controlled by oral or intravenous administration of copper sulfate.

Where ruminant diets contained copper at 8–11 mg/kg dw, cattle were poisoned at molybdenum levels of 5–6 mg/kg and sheep at 10–12 mg/kg. Where dietary copper was low (<8 mg/kg) or the sulfate-ion level was high, molybdenum at 1–2 mg/kg ration was toxic to some cattle (Buck 1978).

Generally in monogastric animals, sulfate protects against molybdenum toxicity, whereas in ruminants it enhances the toxicity. Sulfate alleviated molybdenum-induced symptoms in rats, chicks, and rabbits. In ruminants, molybdenum toxicosis was induced by feeding diets supplemented with both molybdenum and sulfate to sheep and cattle. Sulfate greatly increased the severity of molybdenum toxicosis in cattle. Sulfate intensified molybdenum toxicity in copper-deficient rats but prevented molybdenum toxicity in copper-sufficient rats. Where sulfate was used to alleviate molybdenum toxicity in monogastric animals, the dietary level of sulfate was in the range 1,500– 8,000 mg/kg. In sheep, molybdenum toxicosis was produced by feeding diets containing molybdenum at levels of 2–50 mg/ kg and sulfate at 4,000–10,000 mg/kg (Pitt 1976).

Some animals may be able to adapt to excess molybdenum over successive generations. When compared to rats on a control diet, second- and third-generation rats exposed to excess dietary molybdenum did not show physiological alterations like those seen in first-generation rats (such as reduced stress response) (Winston et al. 1976).

Interactions

Molybdenum toxicological properties are governed to a large extent by interactions with copper and sulfur, but interactions with other metals and compounds may confound this interrelation. For molybdenum, interactions are so dominant that a particular level of intake in an animal's diet can lead to either molybdenum deficiency or toxicity, depending on the relative intakes of copper and inorganic sulfur (Schroeder et al. 1970; Underwood 1971, 1979; Clawson et al. 1972; Suttle 1973, 1983; Friberg et al. 1975; Buck 1978; Friberg and Lener 1986; Goyer 1986; Kincaid et al. 1986; and others cited in Eisler 1989). A low copper-to-molybdenum ratio (<2), rather than the absolute dietary concen-tration of molybdenum, is the primary determinant of an organism's susceptibility to molybdenum poisoning. The first indications of the interaction between copper and molybdenum came from England more than 40 years ago, when cattle grazing on herbage rich in molybdenum developed molybdenosis. Molybdenosis is not expected to occur in animals when the copper-to-molybdenum ratio is near 5 (Buck 1978; Ward 1978; Mills and Bremner 1980).

On the other hand, studies of molybdenum metabolism are of limited value unless the status of inorganic sulfate in the diet is known (Underwood 1971, 1979); inorganic sulfate alleviates molybdenum toxicity by increasing molybdenum excretion. Molybdenum levels in animal tissues give little indication of the dietary molybdenum status and are of little value for diagnosing molybdenum toxicity unless the sulfate, protein, and copper status of the diet are also known (Eisler 1989).

Regulatory Standards

U.S. Environmental Protection Agency standards and criteria [See Appendix II for explanation of terms. Source: EPA 1995]		
Status	Listed for regulation; carcinogenicity unknown.	
Drinking water MCL	None established	
Drinking-water health advisories for 70-kg adult	Reference dose: Long-term HA: Lifetime HA: DWEL:	5 µg/kg/day 50 µg/L 40 µg/L 200 µg/L

No regulatory standards currently exist for the protection of fish and wildlife from dietary exposure to molybdenum. Molybdenum is not an EPA priority pollutant, and no national water-quality criteria for the protection of freshwater aquatic life have been developed. For standards and criteria set by State agencies, contact those agencies directly. See Appendix I for a listing of water-quality officials in the 17 Western States.

References

Abbott, O.J. 1977. The toxicity of ammonium molybdate to marine invertebrates. *Mar. Pollut. Bull.* 8:204–205.

Adriano, D.C. 1986. *Trace elements in the terrestrial environment.* Springer-Verlag, New York. 533 p.

Alloway, B.J. 1973. Copper and molybdenum in swayback pastures. *J. Agricult. Sci. (Camb.)* 80:521–524.

Arrington, L.R., and G.K. Davis. 1953. Molybdenum toxicity in the rabbit. *J. Nutr.* 51:295–304.

Arthur, D., I. Motzok, and H.D. Branion. 1958. Interaction of dietary copper and molybdenum in rations fed to poultry. *Poult Sci.* 37:1181.

Barshad, I. 1948. Molybdenum content of pasture plants in relation to toxicity to cattle. *Soil Sci.* 66:187–195.

Bates, R.L., and J.A. Jackson. 1987. *Glossary of Geology*, 3d ed. American Geological Institute, Alexandria, Virginia.

Berman, E. 1980. Molybdenum. In: *Toxic metals and their analysis.* Heyden Press, London. p. 161–169.

Birge, W.J. 1978. Aquatic toxicology of trace elements of coal and fly ash. In: J.H. Thorp and J.W. Gibbons, eds., *Energy and environmental stress in aquatic systems.* U.S. Department of Energy Symposium Series, No. 48. National Technical Information Service, Springfield, Virginia, Rept. CONF–771114, p. 219–240.

Birge, W.J., J.A. Black, A.G. Westerman, and J.E. Hudson. 1980. Aquatic toxicity tests on inorganic elements occurring in oil shale. In: C. Gale, ed., *Oil shale symposium: sampling, analysis and quality assurance.*, U.S. Environ. Protect. Agcy. Rept. 600/9–80–022, p. 519–534.

Buck, W.B. 1978. Copper/molybdenum toxicity in animals. In: F.W. Oehme, ed., *Toxicity of heavy metals in the environment.* Marcel Dekker, New York. Pt. 1, p. 491–515.

Budaveri, S. 1996. *The Merck index: An encyclopedia of chemicals, drugs, and biologicals*, 12th ed. Merck & Co., Whitehouse Station, New Jersey.

CH2M Hill, H.T. Harvey and Associates, and G.L. Horner. 1993. Cumulative impacts of agriculture evaporation basins on wildlife. Technical Report.

Chappell, W.R., and K.K. Peterson, eds. 1976. *Molybdenum in the environment. Vol. 1, The biology of molybdenum.* Marcel Dekker, New York. 315 p.

Chappell, W.R., R.R. Meglen, R. Moure-Eraso, C.C. Solomons, T.A. Tsongas, P.A. Walravens, and P.W. Winston. 1979. *Human health effects of molybdenum in drinking water.* U.S. Environ. Protect. Agcy. Rept. 600/1–79–006. 101 p.

Clawson, W.J., A.L. Lesperance, V.R. Bohman, and D.C. Layhee. 1972. Interrelationship of dietary molybdenum and copper on growth and tissue composition of cattle. *J. Anim. Sci.* 34:516–520.

Colmano, G. 1973. Molybdenum toxicity: abnormal cellular division of teratogenic appearance in *Euglena gracilis*. *Bull. Environ. Contam. Toxicol.* 9:361–364.

Davies, R.E., B.L. Reid, A. Kurnick, and J.R. Couch. 1960. The effect of sulfate on molybdenum toxicity in the chick. *J. Nutr.* 70:193–198.

Dollahite, J.W., L.D. Rowe, L.M. Cook, D. Hightower, E.M. Bailey, and J.R. Kyzar. 1972. Copper deficiency and molybdenosis intoxication associated with grazing near a uranium mine. *Southwest. Vet.* 26:47–50.

Earl, F.L., and T.J. Vish. 1979. Teratogenicity of heavy metals. In: F.W. Oehme, ed., *Toxicity of heavy metals in the environment.* Marcel Dekker, New York. Pt. 2, p. 617–639.

Eisler, R. 1989. *Molybdenum hazards to fish, wildlife, and invertebrates: a synoptic review.* U.S. Fish Wildl. Serv. Biol. Rep. 85(1.19). 61 p.

EPA (Environmental Protection Agency). 1995. Drinking water regulations and health advisories. U.S. Environmental Protection Agency, Office of Water, Washington. 11 p.

Erdman, J.A., R.J. Ebens, and A.A. Case. 1978. Molybdenosis: a potential problem in ruminants grazing on coal mine spoils. *J. Range Manage.* 31:34–36.

Friberg, L., and J. Lener. 1986. Molybdenum. In: L. Friberg, G.F. Nordberg, and V.B. Vouk, eds., *Handbook of the toxicology of metals, vol. II: Specific metals.* Elsevier Science Publ., New York, p. 446–461.

Friberg, L., P. Boston, G. Nordberg, M. Piscator, and K.H. Robert. 1975. *Molybdenum—a toxicological appraisal.* U.S. Environ. Protect. Agcy. Rept. 600/1–75–004. 142 p.

Gilani, S.H., and Y. Alibhai. 1990. Teratogenicity of metals to chick embryos. *J. Toxicol. Environ. Health.* 30:23–31.

Goyer, R.A. 1986. Toxic effects of metals. In: C.D. Klassen, M.O. Amdur, and J. Doull, eds. *Casarett and Doull's toxicology*, 3d ed. Macmillan Publ., New York, p. 582–635.

Gray, L.F., and L.J. Daniel. 1954. Some effects of excess molybdenum on the nutrition of the rat. *J. Nutr.* 53:43–51.

Gray, L.F., and G.H. Ellis. 1950. Some inter-relationships of copper, molybdenum, zinc, and lead in the nutrition of the rat. *J. Nutr.* 40:441–452.

Hamilton, S.J., and K.J. Buhl. 1990. Acute toxicity of boron, molybdenum, and selenium to fry of Chinook salmon and coho salmon. *Arch. Environ. Contam. Toxicol.* 19:366–373.

Hamilton, S.J., and R.H. Wiedmeyer. 1990. Concentrations of boron, molybdenum, and selenium in Chinook salmon. *Trans. Am. Fish. Soc.* 119:500–510.

Ingersoll, C.G., F.J. Dwyer, S.A. Burch, M.K. Nelson, D.R. Buckler, and J.B. Hunn. 1992. The use of freshwater and saltwater animals to distinguish between the toxic effects of salinity and contaminants in irrigation drain water. *Environ. Toxicol. Chem.* 11:503–511.

Ivan, M., and D.M. Veira. 1985. Effects of copper sulfate supplement on growth, tissue concentration, and ruminal solubilities of molybdenum and copper in sheep fed low and high molybdenum diets. *J. Dairy Sci.* 68:891–896.

Jeter, M.A., and G. K. Davis. 1953. The effect of dietary molybdenum upon growth, hemo-globin, reproduction, and lactation of rats. *J. Nutr.* 54:215–220.

Johnson, H.L., and R.F. Miller. 1963. Possible mechanisms for dietary molybdenum toxicity in the rat. *J. Nutr.* 81:271–278.

Kincaid, R.L., R.M. Blauwiekel, and J.D. Cronrath. 1986. Supplementation of copper as copper sulfate or copper proteinate for growing calves fed forages containing molybdenum. *J. Dairy Sci.* 69:160–163.

Knothe, D.W., and G.G. Van Riper. 1988. Acute toxicity of sodium molybdate dihydrate (Molhibit 100) to selected saltwater organisms. *Bull. Environ. Contam. Toxicol.* 40:785–790.

Kratzer, F.H. 1952. Effect of dietary molybdenum upon chicks and poults. *Proc. Soc. Exp. Biol. Med.* 80:483–486.

Kubota, J. 1977. Molybdenum status of United States soils and plants. In: W.R. Chappell and K.K. Petersen, eds. *Molybdenum in the environment. Vol. 2, The biochemistry, cycling, and industrial uses of molybdenum.* Marcel Dekker, Inc., New York. p. 731–737.

Lee, C.W., C.-H. Pak, J.-M. Choi, and J.R. Self. 1992. Induced micronutrient toxicity in *Petunia hybrida*. *J. Plant Nutr.* 15(3):327–339.

Lemly, A.D., coordinator. 1990. *Agricultural irrigation studies in support of the San Joaquin Valley Drainage Program, Final Report.* U.S. Fish and Wildlife Service, National Fisheries Contaminant Research Center, Columbia, Missouri.

Lepore, P.D., and R.F. Miller. 1965. Embryonic viability as influenced by excess molybdenum in chicken breeder diets. *Proc. Soc. Exp. Biol. Med.* 118:155–157.

Lepore, P.D., R.F. Miller, and H.S. Siegel. 1961. Molybdenum toxicity in the developing chick embryo. *Poult. Sci.* 41:1047–1049.

Lynch, T.R., C.J. Popp, and G.Z. Jacobi. 1988. Aquatic insects as environmental monitors of trace metal contamination: Red River, New Mexico. *Water Air Soil Pollut.* 42:19–31.

Martin, T.R., and D.M. Holdich. 1986. The acute lethal toxicity of heavy metals to peracarid crustaceans (with particular reference to fresh-water asellids and gammarids). *Water Res.* 20(9):1137–1147.

McConnell, R.P. 1977. Toxicity of molybdenum to rainbow trout under laboratory conditions. In: W.R. Chappell and K.K. Peterson, eds. *Molybdenum in the environment. Vol. 2, The geochemistry, cycling, and industrial uses of molybdenum.* Marcel Dekker, New York, p. 725–730.

Mehring, A.L., Jr., J.H. Brumbaugh, A.J. Sutherland, and H.W. Titus. 1959. The tolerance of growing chickens for dietary copper. *Poult. Sci.* 39:713–719.

Miller, E.C., and C.A. Denton. 1959. Molybdenum-sulfate interrelationship in the growing chicks. *Poult. Sci.* 38: 910–916.

Mills, C.F., and I. Bremner. 1980. Nutritional aspects of molybdenum in animals. In: M.P. Coughlan, ed. *Molybdenum and molybdenum-containing enzymes.* Pergamon Press, Elmsford, New York, p. 517–542.

Mills, C.F., K.J. Monty, A. Ichihara, and P.B. Pearson. 1957. Metabolic effects of molybdenum on the toxicity of the rat. *J. Nutr.* 65: 129–142.

Moore, P.A., Jr., and W.H. Patrick, Jr. 1991. Aluminum, boron, and molybdenum availability and uptake by rice in acid sulfate soils. *Plant and Soil.* 136:171–181.

Moore, S.B., S.J. Detwiler, J. Winckel, and M.D. Weegar. 1989. *Biological residue data for evaporation ponds in the San Joaquin Valley, California*. San Joaquin Valley Drainage Program, Sacramento, California.

Morgan, J.D., D.G. Mitchell, and P.M. Chapman. 1986. Individual and combined toxicity of manganese and molybdenum to mussel, *Mytilus edulis*, larvae. *Bull. Environ. Contam. Toxicol.* 37:303–307.

Motzok, I., D. Arthur, and H.D. Branion. 1957. Feeding of molybdenum to poultry. *Poultry Sci.* 36:1144.

Ohlendorf, H.M., J.P. Skorupa, M.K. Saiki, and D.A. Barnum. 1993. Food-chain transfer of trace elements to wildlife. In: *Management of irrigation and drainage systems: Integrated perspectives.* R.G. Allen and C.M.U. Neale, eds. Proceedings of the 1993 National Conference on Irrigation and Drainage Engineering. Park City, Utah; July 21–23, 1993. American Society of Civil Engineers, New York. p. 596–603.

Osweiler G.D., T.L. Carson, and W.B. Buck, eds. 1985. *Clinical and diagnostic veterinary toxicology*, 3rd ed. Kendall/Hunt Publishing Co., Dubuque, Iowa.

Pais, I., and J.B. Jones, Jr., eds. 1997. *The handbook of trace elements.* St. Lucie Press, Boca Raton, Florida.

Penumarthy, L., and F.W. Oehme. 1978. Molybdenum toxicosis in cattle. *Vet. Human Toxicol.* 20:11–12.

Phillippo, M., W.R. Humphries, I. Bremner, T. Atkinson, and G. Henderson. Molybdenum-induced infertility in cattle. In: *Trace elements in man and animals—TEMA 5*, C.F. Mills, I. Bremner, and J.K. Chesters, eds. Proceedings of the Fifth International Symposium on Trace Elements in Man and Animals.

Pitt, M.A. 1976. Molybdenum toxicity: interactions between copper, molybdenum, and sulphate. *Agents Actions* 6:758–769.

Pitt, M., J. Fraser, and D.C. Thurley. 1980. Molybdenum toxicity in sheep: epiphysiolysis, exotoses and biochemical changes. *J. Comp. Pathol.* 90:567–576.

Prange, A., and K. Kremling. 1985. Distribution of dissolved molybdenum, uranium and vanadium in Baltic Sea waters. *Marine Chem.* 16:259–274.

Puls, R. 1988. *Mineral levels in animal health—Diagnostic data.* Sherpa International, Clearbrook, BC, Canada.

Romanoff, A.L., and A.J. Romanoff. 1949. *The avian egg.* John Wiley and Sons, New York.

Saiki, M.K. 1990. Elemental concentrations in fishes from the Salton Sea, California. *Water, Air, Soil Pollut.* 52:41–56.

Saiki, M.K., M.R. Jennings, and R.H. Wiedmeyer. 1992. Toxicity of agricultural subsurface drainwater from the San Joaquin Valley, California, to juvenile chinook salmon and striped bass. *Trans. Am. Fisheries Soc.* 121:78–93.

Saiki, M.K., M.R. Jennings, and W.G. Brumbaugh. 1993. Boron, molybdenum, and selenium in aquatic food chains from the lower San Joaquin and its tributaries, California. *Arch. Environ. Contam. Toxicol.* 24:307–319.

Sakaguchi, T., A. Nakajima, and T. Horikoshi. 1981. Studies on the accumulation of heavy metal elements in biological systems. XVIII, Accumulation of molybdenum by green microalgae. *Eur. J. Appl. Microbiol. Biotechnol.* 12:84–89.

Schroeder, H.A., J.J. Balassa, and I.H. Tipton. 1970. Essential trace metals in man: molybdenum. *J. Chron. Dis.* 23:481–499.

Shirley, R.L., R.L.D. Owens, and G.K. Davis. 1951. Alimentary excretion of phosphorus-32 in rats on high molybdenum and copper diets. *J. Nutr.* 44: 595–601.

Short, Z.F., P.R. Olson, R.F. Palumbo, J.R. Donaldson, and F.G. Lowman. 1971. Uptake of molybdenum, marked with ^{99}Mo, by the biota of Fern Lake, Washington, in a laboratory and a field experiment. In: D.J. Nelson, ed. *Radionuclides in ecosystems.* Proceedings of the Third National Symposium on Radioecology, Oak Ridge, Tennessee, May 10–12, 1971, v. 1, p. 474–485.

SJVDP (San Joaquin Valley Drainage Program). 1990. *Fish and wildlife resources and agricultural drainage in the San Joaquin Valley, California.* Sacramento, California, San Joaquin Valley Drainage Program. Vol. 1, sec. 3.

Sloot, H.A. van der, D. Hoede, J. Wijkstra, J.C. Duinker, and R.F. Nolting. 1985. Anionic species of V, As, Se, Mo, Sb, Te, and W in the Scheldt and Rhine estuaries and the Southern Bight (North Sea). *Estuar. Coastal Shelf Sci.* 21:633–651.

State Water Resources Control Board. 1988. Regulation of agricultural drainage to the San Joaquin River. California State Water Resources Control Board, Sacramento, Technical Committee Report, Order No. W.Q. 85–1.

Steeg, P.F. ter, P.J. Hanson, and H.W. Paerl. 1986. Growth-limiting quantities and accumulation of molybdenum in *Anabaena oscillarioides* (Cyanobacteria). *Hydrobiologia* 140:143–147.

Suttle, N.F. 1973. The nutritional significance of the Cu:Mo interrelationship to ruminants and non-ruminants. In: D.D. Hemphill, ed., *Trace substances in environmental health—VII.* Univ. Missouri, Columbia, Missouri, p. 245–249.

Suttle, N.F. 1983. A role for thiomolybdates in the Cu × Mo × S interaction in ruminant nutrition. In: P. Brattner and P. Schramel, eds., *Trace-element analytical chemistry in medicine and biology.* Water de Gruyter, New York. Vol. 2, p. 599–610.

Teekell, R.A., and W.A. Lyke. 1960. Protein binding of molybdenum-99 in plasma, liver, and kidney of chicks. *Poult. Sci.* 40:1277–1281.

Teekell, R.A., and A.B. Watts. 1959. Molybdenum supplementation of chick diets. *Poult. Sci.* 38:1127–1132.

Tong, S.S.C., W.D. Youngs, W.H. Gutenmann, and D.J. Lisk. 1974. Trace metals in Lake Cayuga lake trout (*Salvelinus namaycush*) in relation to age. *J. Fish. Res. Board Canada.* 31(2):238–239.

Underwood, E.J. 1971. Molybdenum. Chap. 4 of: *Trace elements in human and animal nutrition.* Academic Press, New York, p. 116–140.

Underwood, E.J. 1977. *Trace elements in human and animal nutrition.* Academic Press, New York. 545 p.

Underwood, E.J. 1979. Interactions of trace elements. In: F.W. Oehme, ed., *Toxicity of heavy metals in the environment.* Marcel Dekker, New York. Pt. 2, p. 641–668.

Venchikov, A.I., and G.M. Kaprielov. 1976. Reaction of the frog organism to changes in the molybdenum content of the environment. In: W.R. Chappell and K.K. Peterson, eds. *Molybdenum in the environment. Vol. 1, The biology of molybdenum.* Marcel Dekker, New York, p. 177–183.

Vohra, P., and F.H. Kratzer. 1957. The effect of dietary copper and molybdenum on turkey poults. *Poult. Sci.* 36:1096–1098.

Ward, G.M. 1978. Molybdenum toxicity and hypocuprosis in ruminants: a review. *J. Anim. Sci.* 46:1078–1085.

Ward, G.M., and J.G. Nagy. 1976. Molybdenum and copper in Colorado forages, molybdenum toxicity in deer, and copper supplementation in cattle. In: W.R. Chappell and K.K. Peterson, eds., *Molybdenum in the environment. Vol. 1, The biology of molybdenum.* Marcel Dekker, New York, p. 97–113.

Ward, J.V. 1973. Molybdenum concentrations in tissues of rainbow trout (*Salmo gairdneri*) and kokanee salmon (*Oncorhynchus nerka*) from waters differing widely in molybdenum content. *J. Fish. Res. Board Can.* 30:841–842.

Westcot, D., S. Rosenbaum, B. Grewell, and K. Belden. 1988. Water and sediment quality in evaporation basins used for the disposal of agricultural subsurface drainage water in the San Joaquin Valley, California. California Regional Water Quality Control Board, Central Valley Region. Sacramento, California.

Whiteside, C.H., T.M. Ferguson, B.L. Reid, and J.R. Couch. 1960. Molybdenum, zinc, and unidentified factor sources in the diet of caged layers. *Poult. Sci.* 40: 313–318.

Wide, M. 1984. Effect of short-term exposure to five industrial metals on the embryonic and fetal development of the mouse. *Environ. Res.* 33: 47–53.

Winston, P.W., M.S. Heppe, L. Hoffman, L.J. Kosarek, and R.S. Spangler. 1976. Physiological adaptations to excess molybdenum ingested over several generations. In: W.R. Chappell and K.K. Peterson, eds., *Molybdenum in the environment. Vol. 1, The biology of molybdenum.* Marcel Dekker, New York, p. 185–200.

Wittenberg, K.M., and T.J. Devlin. 1987. Effects of dietary molybdenum on productivity and metabolic parameters of lactating beef cows and their offspring. *Can. J. Anim. Sci.* 67:1055–1066.