5. METALS RESEARCH NEEDS

The field of metals risk assessment has been advancing rapidly for more than 5 years, as reflected in the large amount of information described in this document. However, significant uncertainties and gaps remain that require additional research if accurate assessments are to be conducted. This chapter briefly reviews major, ongoing research programs within and outside EPA and provides a list of recommendations for future research endeavors. This chapter is not intended to outline a research strategy for metals risk assessment. Rather, it discusses the current direction of metals-related research conducted by EPA, external institutions, and academia as it relates to uncertainties and gaps in metals risk science.

5.1. U.S. EPA RESEARCH

EPA has devoted significant resources to researching metals-related topics, and a variety of metals-related endeavors are planned and under way in an ongoing effort to better understand the behavior and effects of metals in humans and the environment and to advance the field of metals risk assessment. Specific summaries of metals-related research at EPA are available for viewing on the Agency's Science Inventory, a searchable catalog of EPA research available at http://cfpub.epa.gov/si. In addition, EPA's Office of Research and Development (ORD) has a multiyear planning effort to guide the direction of its research program. The purpose of the multiyear plans (MYPs) is to provide a framework that integrates research across ORD's laboratories and centers. The MYP for contaminated sediments describes a number of projects planned and under way that involve current topics and research needs. The most recently available MYPs are available for review at http://www.epa.gov/osp/myp.htm. Examples of planned and ongoing Agency research and assessment projects involving metals topics include the following:

- Ecological effects of selenium on soil invertebrates to support the development of soil-screening limits for selenium (fiscal year [FY] 2004).
- Ecological assessment of the risks associated with ground water contamination and exposures (FY 2005).
- Characterization and assessment of the impact of metals speciation on ecological receptors (FY 2006).
- Evaluation of stabilization of metals in sediments (FY 2007).

- Evaluation of perturbation on metals speciation and ecological receptors (FY 2008).

5.2. EXTERNAL RESEARCH

The Metals in the Environment Research Network (MITE-RN) is a network of collaborating institutions with participants from academia, government, and industry, formed in 1998 with the aim of developing a better understanding of sources of metals in the environment, how metals move and transform within the environment, and how they can affect ecosystems and human health (www.mite-rn.org). MITE-RN has been funded at approximately $7 million for the period 1999–2004 and has been refunded for the next 5 years (2005–2010). Funding consists of contributions from the Mining Association of Canada; National Sciences and Engineering Research Canada; the Ontario Power Generation Inc.; “in-kind” contributions from Environment Canada, Fisheries and Oceans Canada, and Natural Resources Canada; and funding support from the International Lead Zinc Research Organization, International Copper Association, and Nickel Producer’s Environmental Research Organization. MITE-RN has published many research articles covering all of the topics discussed in the framework (www.mite-rn.org/files/mite-rn_pubs.pdf). The most recent compilation of papers may be found in Human and Ecological Risk Assessment, vol. 9 (4).

Several universities have established multidisciplinary research centers for metals. For example, under a grant from the National Institutes of Environmental Health Sciences (NIEHS), Harvard University has established the Metals Research Core, which promotes innovative research among investigators who are studying the environmental fate and health effects of exposure to metals and related fields with emphasis on potential gene-metal, metal nutrient, and metal-metal interactions (www.hsph.harvard.edu/niehs/metals.html). The Agency funds a multi-institutional Center for Study of Metals in the Environment, coordinated out of the University of Delaware and including Colorado School of Mines, Manhattan College, McMaster University, Ohio State University, Oklahoma State University, University of Wyoming, and University of Missouri at Rolla (www.ce.udel.edu/CSME/Index.html). The Center for Air Toxic Metals® (CATM®) at the University of North Dakota Energy and Environmental Research Center (EERC), established in 1992 by the U.S. EPA’s Office of Environmental Engineering and Technology, develops information on trace elements that can be used to develop pollution prevention strategies (www.eerc.und.nodak.edu/catm/). Dartmouth’s Toxic Metals Research Center is an interdisciplinary group that studies how arsenic and other metals affect human health and the environment (http://www.dartmouth.edu/~toxmetal/). The Agency also funds the

Hazardous Substance Research Centers (HSRCs), which address metals-linked topics, such as mining, contaminated sediments, and ground water contamination. Web sites for HSRCs may be accessed at:

http://www.engr.colostate.edu/hsrc/new.html
http://www.hsrc.org/hsrc/html/ssw/newsletter/sswnews.html
http://wrhsrc.oregonstate.edu/publications/index.htm

The metals industry also sponsors research conducted at both public and private institutions worldwide. Sponsors include the International Lead Zinc Research Organization (www.ilzro.org), the International Copper Association (www.ica.org), the Nickel Producer's Environmental Research Organization (www.nipera.org), the International Zinc Association (www.iza.org), Eurometeaux, the International Cobalt Association, and the International Council on Mining and Metals (www.icmm.com).

5.3. SPECIFIC RECOMMENDATIONS

The information provided here is a summary of research recommendations provided in the metals issue papers (http://cfpub2.epa.gov/ncea/raf/recordisplay.cfm?deid=59052) and additional comments provided by reviewers of this framework.

5.3.1. Environmental Chemistry

In general, environmental chemistry of metals research could benefit from:

- The development of more routine chemical-species-specific analytical methods.

- The development of extraction techniques that have general utility in assessing bioavailability and/or mobility.

- The validation of geochemical and chemical-specific environmental fate and transport models.

- Additional research on metal mobility and how to apply the Diffuse Layer (DL) adsorption model to metal behavior in soils and sediments using estimated values.

- Increased understanding of metal chemistry in sediments, including the redox behavior metals.
- Research to understand the chemical and physical forms of metals in the primary media of exposure.

- Improved reliability of aging predictions.

5.3.2. Bioaccumulation and Bioavailability

5.3.2.1. *Aquatic*

- Evaluation of the bioaccumulation of metals bound to colloidal material in ambient water.

- More thorough evaluation of the efflux rates of metals from different animals, including specific tissues, following bioaccumulation from the dissolved phase and from the dietary pathway.

- Evaluation of metal bioaccumulation in aquatic bacteria, which may influence the fluxes of certain metals in aquatic systems and which may introduce metals into bacteria-based food chains.

- A more detailed knowledge base is required on the basic physiology and ecology of organisms that are used or at least have the potential to serve as bioindicator organisms. Furthermore, monitoring programs could focus on key biomarkers of exposure and effects and would be wise to develop an algorithm to calculate an integrated stress index.

- New approaches to evaluate the bioaccumulation of metals from waters in which there are numerous contaminants (such as would be found in most contaminated harbors or rivers) to assess synergistic and antagonistic effects.

- With regard to the BCF/BAF model, development of additional guidance should be directed at reducing uncertainty and consideration should be given to:
  - Articulating the limitations of the BCF/BAF approach.
  - When the BCF/BAF approach is or is not applicable.
  - How the BCF/BAF approach could be modified.
  - What alternative measures and criteria could be used to better account for metal bioaccumulation in relation to toxicity potential.

5.3.2.2. *Terrestrial Soil Organisms*

- Development and validation of empirical and mechanistic models linking soil physicochemical characteristics, metal speciation, and toxic effects and bioaccumulation in soil invertebrates (e.g., Biotic Ligand Model (BLM) for soil organisms).

- Development and validation of kinetics models describing metal bioaccumulation in soil invertebrates.

- Basic research on the physiology of metal metabolism in various groups of soil invertebrates; evaluation of the relevance of soil pore water or diet in exposure and partitioning of metals in soil invertebrates.

- Identification of the risks for predators associated with the consumption of soil invertebrates containing metals; evaluation of the risk to predators of consuming metal partitioned to different fractions in soil invertebrates (e.g., storage granules versus metallothionein).

- Development of metal-specific biomarkers capable of quantitatively detecting magnitude and species of metal exposure.

5.3.3. Exposure

Research on exposure issues is best defined with regard to the particular receptors; hence, this section is divided into discussions of exposure research for human, terrestrial, and aquatic organisms.

5.3.3.1. *Human Health Receptors*

- Research to improve sampling, measurement approaches, and exposure models.

- Data on rates of soil and surface dust ingestion, including estimates of central tendencies, both short-term and long-term, inter- and intraindividual variability (e.g., within-age and across ages), and relative contributions of surface dust and soil.

- Information about the types and frequencies of activities that place children in contact with contaminated soils, dusts, or surfaces (e.g., hand-to-mouth behavior, rates of contact with surfaces).

- Methods to predict concentrations in surface dust, a primary medium of contact, from measurements made in surface soil samples, surface dust wipe samples, and surface dust vacuum samples.

- Better estimates of dietary intakes of metals.

- Information on the contribution of locally harvested foods to metal intakes (e.g., uptake of metals from soil, intakes of home-grown or home-harvested foods).

5.3.3.2. *Aquatic Receptors*

- Define the best ways of expressing exposure concentration.

- Accommodate differences in exposure durations.

- Combining exposure concentrations when exposure involves metal mixtures.

- Assess the relative merits of different methods used to express exposure concentrations in sediments and suspended solids.

- Compare the simple extrapolation methods to richer survival or time-to-event models is essential.

5.3.3.3. *Terrestrial Receptors*

- Conduct further work to define or reduce the associated uncertainty of using generalized wildlife exposure models.

- Develop laboratory test data for soil systems that better reflect the actual forms of metals in field soil.

- Develop data for terrestrial receptors on the joint effect of metals in mixtures.

5.3.4. Human Health Effects

- Research should be conducted concerning the potential interactions between essential metals and nonessential metals and between nonessential metals (i.e., metal mixtures).

- Research should be conducted concerning the applicability of toxicokinetic and toxicodynamic models for risk assessment for metals and inorganic metal compounds. Consideration should be given to differences in models for essential and nonessential metals, for low versus high dose exposures, for multipathway exposures, and for mixtures of metals with multiple modes of action.

- Research is needed on methods to assess mixed (or multiple) exposures, including occupational exposures.

- There should be further research and development regarding the use of biomarkers, especially genomic, transcriptomic, and proteomic methodologies as endpoints and their relationship to frank effects on human health endpoints used in risk assessment.

- Speciation of metals in tissues of target organs should be determined. Research should be conducted on mechanisms of toxicity, including carcinogenicity, and on whether carcinogenicity of specific metals is a threshold or nonthreshold event.

- Research is needed to meet the needs of sensitive individuals on the basis of genetic and developmental factors.

- Research should be conducted to determine the potential essential or beneficial effects of metals and inorganic metal compounds (especially as these effects impact low-dose extrapolation).

5.3.5. Characterization of Ecological Effects

Because of significant differences in ecology, physiology, and toxicology of aquatic and terrestrial organisms, research recommendations are provided separately for each group.

5.3.5.1. *Toxicological Research Needs*

- **Test matrix.** Perform tests under conditions that are representative of environmentally relevant exposure conditions to form a basis for development of methods to extrapolate from laboratory to field conditions, and from site to site in the field in situations where the water-, sediment-, or soil-quality characteristics are quite variable.

- **Model development.** Develop descriptive statistical models that establish the boundaries for which the results are applicable. Develop predictive speciation and uptake models, such as the Free Ion Activity Model (FIAM) or Terrestrial Biotic Ligand Model (tBLM).

- **Test design.** Conducting a concerted effort to generate reasonably complete concentration-response surfaces for metals in major soils representative of larger areas of the continent would be very useful. Test designs should be based on regression models and strive to depict the range of responses from relatively low concentrations to relatively high concentrations.

- **Measurement endpoints.** Multiple endpoints should be scored over the course of the in-life portion of tests. Data on growth parameters, overall healthiness of test organisms, and behavioral and reproductive endpoints should be explored. Such data could be useful in developing descriptive statistical models, including multiple regressions and clustering analyses. In addition, such data could be used to calibrate predictive models that attempt to relate effects across exposure periods.

- **Interspecies extrapolation.** Studies designed to develop interspecies extrapolation models, especially for terrestrial organisms, are necessary.

- **Interactions among metals.** Research to understand interactive effects, for both acute and chronic exposures, is necessary. Methods for representing the joint effects of metal mixtures on the organism, in the context of the BLM, have been proposed, but these methods have not been implemented or tested to date.

5.3.5.2. *Ecological Research Needs*

- **Extrapolations from laboratory to field.** Studies documenting the correspondence or lack of correspondence between simple laboratory toxicity tests and field assessments are necessary. In situations where laboratory and field results are inconsistent, research is necessary to identify factors that contribute to these differences.

- **Indirect effects of metals and species interactions.** Studies of the effects of metals on species interactions and their ecological significance are needed.

- **Acclimation and adaptation to metals.** Additional research is necessary to understand the cost of tolerance and adaptation to metals and the potential consequences with regard to exposure to multiple stressors.

5.3.6. Unit World Model for Metals

Recognizing the continuing need to overcome limitations in understanding and, therefore, adequately predicting metal behavior in the environment, it has been proposed that use of a suite of evolving computational modeling tools could provide the basis for metals assessments, particularly for hazard ranking and screening-level risk assessments. The model would be run for a generic environment (the “Unit World”), giving output in the form of substance-specific loadings that would result in accumulations in target compartments that equal specified toxicity thresholds (e.g., LC_{50}, EC_{25}), known as the “critical load.” It is anticipated that such outputs could be used for both classification and priority ranking as well as for regional (or national) screening assessments. For screening assessments, an attempt is made to describe how the substance will behave in the environment, to which media it will partition (e.g., air, soil, or water), how long it will persist, in which media it will primarily degrade, and ultimately, what mass input will result in media that will cause a toxic effect. These assessments introduce an illustrative or hypothetical release into a hypothetical, evaluative region of interest. The model yields calculated masses, concentrations, and rates of transport and transformation that are entirely fictitious. Features that do not depend on the quantity of chemical or specific environmental characteristics, such as environmental persistence, relative importance of degradation and transport pathways, and relative concentrations among media, can be deduced. It should be noted that the decision point for whether an assessment of toxicity is required is derived through an evaluation of environmental fate processes.

This approach also could be used to conduct a risk assessment in which real emission rates are introduced into a model construct of a real environment in an attempt to calculate real masses and concentrations. These predicted environmental concentrations (PECs) can be compared with measured values to evaluate the performance of the model and with concentrations below which adverse toxicological effects are not expected to occur (e.g., PNECs). This comparison results in an assessment of the risk of an adverse effect at the predicted concentration.

A "critical load" is defined as the mass per unit time of a substance that, when introduced into the environment, results in accumulations in environmental media that reach specified toxicity thresholds. Key inputs are toxicity data (acute or chronic thresholds) for individual environmental compartments and the physical and chemical properties of the substance. Fate models may be envisioned as being run in reverse to back-calculate the loading that results in achieving the specified toxicity concentration. Processes that affect fate and potential exposure of organisms, such as intercompartmental transfer, complexation, and adsorption and precipitation reactions, are included. Since many of the fate processes that affect metal ions and organic compounds are similar, a common modeling framework may be envisioned for organic substances and metals, with processes (e.g., biodegradation) turned on or off as required, depending on the nature of the substance.

Unit World Model

The **Unit World Model** calculates the mass loading needed to achieve the critical load of metal in each environmental compartment (soil, sediment, water). A ***critical load*** is the amount of substance in the environment that results in specified toxicity thresholds.

The Unit World approach uses models derived from previous modeling efforts for metals for aquatic systems (e.g., Di Toro, 2001; Bhavsar et al., submitted). The aim is to produce a model that is similar but that includes the processes that are necessary to describe the behavior of metals in both aquatic and terrestrial environments simultaneously. The model is not intended to represent a specific location but, rather, a representative setting that is typical of the class of environments being evaluated. It also is not intended to be a complete description of metal fate and transport. Rather, it focuses on the primary processes that affect the toxicity and long-term fate of metals. It is designed to be used for evaluative purposes, not for detailed site-specific evaluation.

The model framework, presented in Figure 5-1, is composed of an aquatic and terrestrial sector. The model is formulated as a series of mass balance equations that are formulated assuming that the rates of adsorption and desorption are fast relative to the other processes (i.e., the local equilibrium assumption). By contrast, the kinetics of metal sulfide precipitation and dissolution are formulated as kinetic processes. The concentrations and characteristics of the necessary water column and particulate partitioning phases will be established to represent the "unit worlds" to be used in the evaluation.

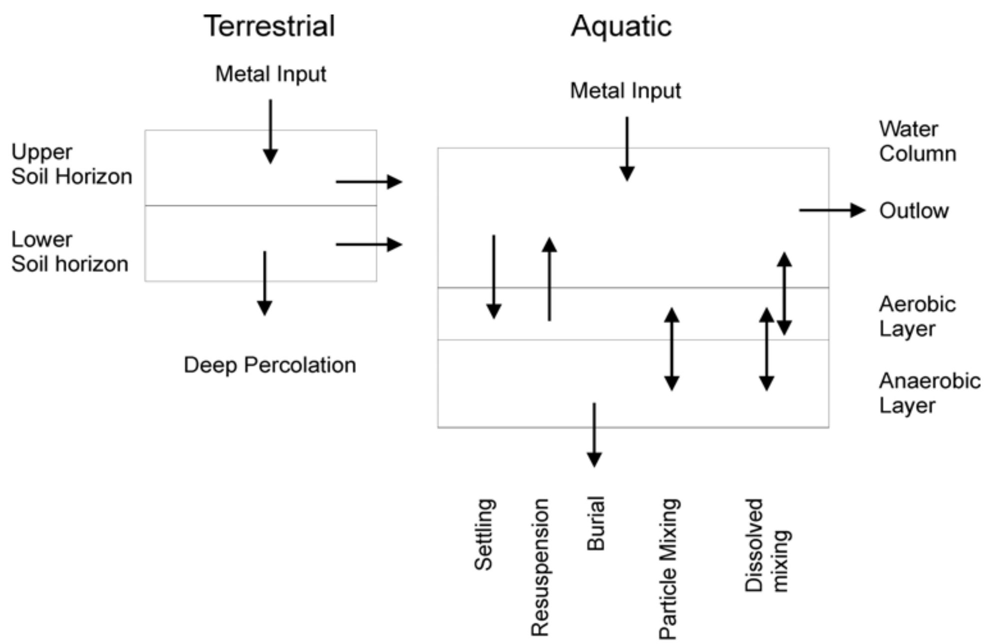

Figure 5-1. Schematic representation of the Unit World Model for Metals.

Partitioning in the water column and aerobic sediment layer is computed using WHAM6/SCAMP (Tipping, 1998; Lofts and Tipping, 1998). These models have been calibrated with laboratory data and have parameters for many of the metals that are of interest. Some field testing has also been performed with reasonable results (Bryan et al., 2002; Lofts and Tipping, 1998). The aqueous phase speciation includes dissolved organic carbon (DOC) complexation. The particulate partitioning phases are organic carbon; the oxides of Al, Si, Mn, and Fe; and a mineral cation exchanger. The concentrations of these particulate phases are specified externally as part of the input parameters. SCAMP assumes that the partitioning to these phases is additive. The importance of metal sulfide precipitation in the anaerobic layer and subsequent oxidation in the aerobic layer is well known, and models of these phenomena have been developed (e.g., Di Toro et al., 1996; Boudreau, 1991).

The soil model comprises two soil horizons, containing solids and solution. The upper horizon receives the metal of interest in soluble form. The soil solution flows from the upper horizon to the lower or directly to a surface water. Soil solution from the lower horizon flows to the surface water or is lost, together with dissolved metal and metal bound to suspended particulate matter (SPM), to deep percolation. The physical and chemical conditions are specified for each horizon; the upper horizon has a higher organic matter content than the lower. The processes governing metals in soils include solution speciation (described with WHAM6) and solid-solution partitioning (described using K_d values, characterized by multiple regression equations with pH and soil organic matter (Sauvé et al., 2000, 1998), and take into account competition for dissolved organic matter binding sites by Al and Fe(III) species (Tipping et al., 2002), particle aging (to be characterized for different metals on the basis of experimental information, taking account of soil pH), and the input flux of background metals from weathering. The value of F_{in} (moles m^{-2} a^{-1}) that is sought from the model corresponds to the Critical Load.

There are very few key processes that most significantly influence the outcome of the model (i.e., the critical load). These are the input terms of ecotoxicity and bioaccumulation, the speciation and partitioning reactions between water, sediment, and soil that determine both the fate—the compartments where the metal finally resides—and the bioavailability. Additionally, the transfer of metals into nonbioavailable forms has a significant impact on the critical load. In this model, these transfer processes are aging reactions in soils and acid-volatile sulfide (AVS)-binding of the metal. The approach assumes that the soluble metal form is introduced to the air compartment and is distributed appropriately to the soil and water compartments.

Calculation of the fraction of soluble metal relative to the parent compound, or "transfer" factor, is done separately.

The Unit World Model approach is based on well-established principles governing the environmental behavior of metals. However, at present, the proposed approach should be considered as a conceptual framework embodying components that are at different stages of development and evaluation. It will therefore be necessary to undertake a series of well-integrated activities to move forward from the conceptual stage to a fully implemented and accepted evaluative method that is capable of tracing the significant fate and transport processes of a wide range of metals and predicting both the concentration and speciation at the exposure point with a sufficient degree of accuracy to reflect the objectives of the assessment (classification, ranking, or screening-level risk assessment).