

## THE USE OF BIOACCUMULATION CRITERIA FOR HAZARD IDENTIFICATION OF METALS

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Bioaccumulation (B) is used, along with persistence (P) and acute toxicity (T; cumulatively referred to as PBT) to identify aquatic environmental hazard and to determine the potential for adverse effects to biota. Bioaccumulation also can be a component of the regulatory “toolbox” and is used in many jurisdictions for prioritization, hazard classification and risk assessment. For example, the Organisation for Economic Co-operation and Development (OECD) has developed an internationally harmonized system for hazard classification of chemical substances, based on the PBT hazard identification criteria (OECD 2001).

### *Terminology*

**Anthropogenic:** caused by human activity

**Bioaccumulation:** the process by which organisms absorb chemicals or elements directly from their environment

**Biomagnification:** the process by which a substance’s tissue concentrations increase as it is passed up the food web through two or more trophic levels

**Biota:** plants and animals

**Ligand:** a group of atoms comprising a molecule that binds to a metal

**Lipophilic:** having an affinity for lipid (fats) and an aversion for water

**Metallothionein:** a protective protein that binds heavy metals

**Trophic level:** level of an organism on the food web or food chain

### *Evaluation Criteria*

In hazard classification, acute toxicity is used to identify the potential for hazard in the short term while persistence and bioaccumulation are used as surrogates for chronic hazard potential. Bioaccumulation also is used to categorize substances (e.g. Canadian Environmental Protection Act 1999), in life cycle impact assessment models and screening level risk assessment evaluations. The only criteria used to evaluate bioaccumulation in these (and other) contexts are the bioconcentration factor (BCF) and the bioaccumulation factor (BAF). The BCF and BAF criteria are applied as cutoff or threshold values above which a substance is deemed bioaccumulative. Bioaccumulative substances, if also acutely toxic and/or persistent, are deemed to possess a potential for long-term environmental impact. BCF and BAF threshold values typically range between 500 and 5000, depending on the jurisdiction. BCF and BAF are applied to all substances, including metals and metal compounds.

### *Identifying Environmental Hazard: Anthropogenic vs. Natural Sources*

Bioaccumulation of substances, including metals, is widely accepted as one of the key factors in understanding and identifying potential environmental hazard because accumulation within or on biota must occur in order to produce adverse effects. The use of bioaccumulation in hazard identification originates from concerns related to highly toxic synthetic organic substances, including pesticides such as DDT, which not only

bioaccumulate but also biomagnify, resulting in impacts at higher trophic levels, for example in predatory birds. In these cases, the bioaccumulative nature of purely anthropogenic substances may provide useful information on the potential for long-term chronic impacts, particularly when data on chronic toxicity are lacking.

However, for naturally occurring substances such as metals, bioaccumulation is complex and many processes are available to modulate both accumulation and potential toxic impact. These mechanisms are evidenced by adaptation (evolutionary response to local conditions) and acclimation (short-term physiological response to challenges) to elevated levels of metals in the environment, both of which are known to occur in aquatic animals. All biota will naturally accumulate metals at least to some degree without deleterious effect. Furthermore, a number of metals are essential for life and in these cases, bioaccumulation in itself does not indicate the potential for adverse effects.

### *Mechanisms and Control of Bioaccumulation*

The fact that BCF and BAF were originally developed and validated for a fairly limited number of neutral, lipophilic, synthetic and toxic organics (Barron 1992; Feijtel et al. 1997) is directly related to the inherent properties of these substances. Neutral non-ionic organic substances bioaccumulate because they are intrinsically lipophilic and able to diffuse across biological surfaces (e.g. the fish gill or digestive tract epithelium). When diffusion is the primary mechanism of uptake, the degree of bioaccumulation is directly proportional to exposure concentration. Under these conditions, BCF and BAF are constant over the range of exposure concentrations and can be considered as intrinsic properties. Therefore, BCF and BAF are measures that can be suitable as criteria for bioaccumulation, but only for neutral organics with diffusion as the primary method of uptake.

BCF and BAF are calculated as the ratio, at equilibrium, of internal to external concentration.

$$\text{BCF or BAF} = \frac{\text{(whole body concentration of X)}}{\text{(exposure media concentration of X)}}$$

BAF and BCF are calculated in the same way, but for BCF, accumulation arises from water only while for BAF, it arises from both water and dietary sources.

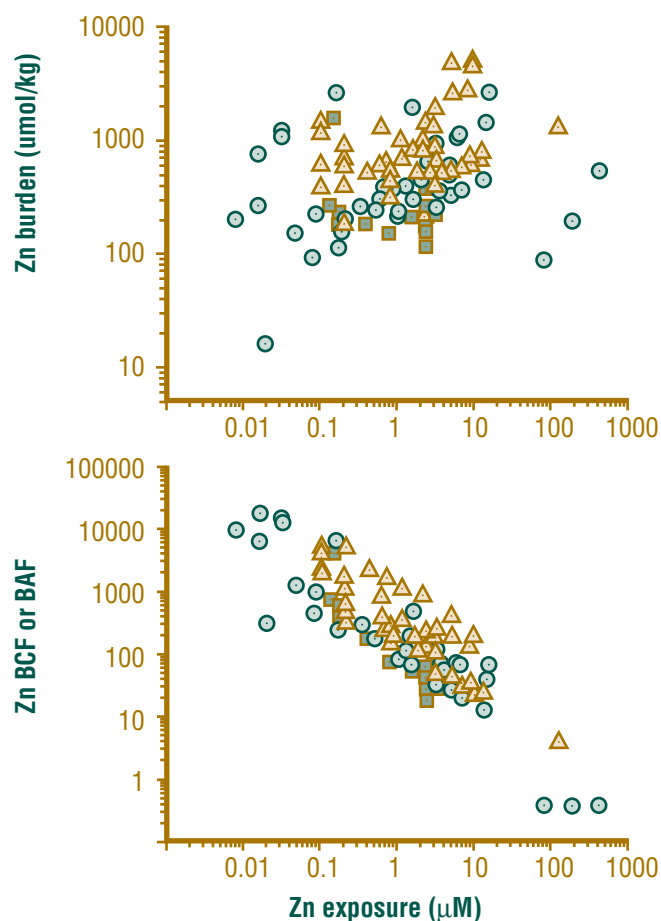
The units are generally  $\text{kg}_{\text{ww}} \cdot \text{L}^{-1}$  and equilibrium conditions are usually assumed based on the length of exposure (see standard methodologies, OECD 1996; US EPA 1996).

While diffusional uptake of neutral inorganic metal complexes can occur (e.g. Fortin and Campbell 2001), uptake of aqueous metal ions via processes that show saturable kinetics (rapid accumulation to a plateau burden as exposure concentration increases) is more common and toxicologically relevant (McDonald and Wood 1993; Wood 2000). Similarly, physiological processes control the elimination of bioaccumulated metal, usually via the kidney, liver or gills. As a result of physiological control, biota have an ability to actively regulate the bioaccumulation of many metals and maintain homeostatic control (Hamilton and Mehrle 1986; Chapman et al. 1996) over a range of exposures.

### *Inherent Limitations on the Use of Bioaccumulation in Environmental Hazard Identification of Metals*

Control over bioaccumulation is especially evident for nutritionally essential metals such as zinc (Zn) (Figure 1 top panel). Even though Zn exposure concentrations range over 6 or more orders of magnitude, Zn whole body burdens are controlled very tightly (Figure 1 top panel). Compared with essential minerals such as Zn, physiological control over accumulation is not as evident for nonessential metals such as cadmium (Cd) (Figure 2 top panel) but there still is evidence of an ability to control bioaccumulation. As a result of this ability to control or modulate metal uptake and accumulation, BCF and BAF are inversely related to exposure (Figures 1 and 2, bottom panels).

For both Cd and Zn, as well as the other metals such as nickel (Ni) and all of the others we have studied, BCF and BAF values are not only inversely related to concentration but also are highly variable. On the basis of the inverse correlation alone, BCF and BAF cannot be considered an intrinsic property of inorganic metals and metal substances. Furthermore, BCF and BAF values are highest (indicating hazard) at the lowest exposure concentrations (where no adverse effects occur) and lowest (indicating no hazard) at high exposure levels (where impacts are likely). Therefore, BCF and BAF are inappropriate as criteria for hazard identification and classification.

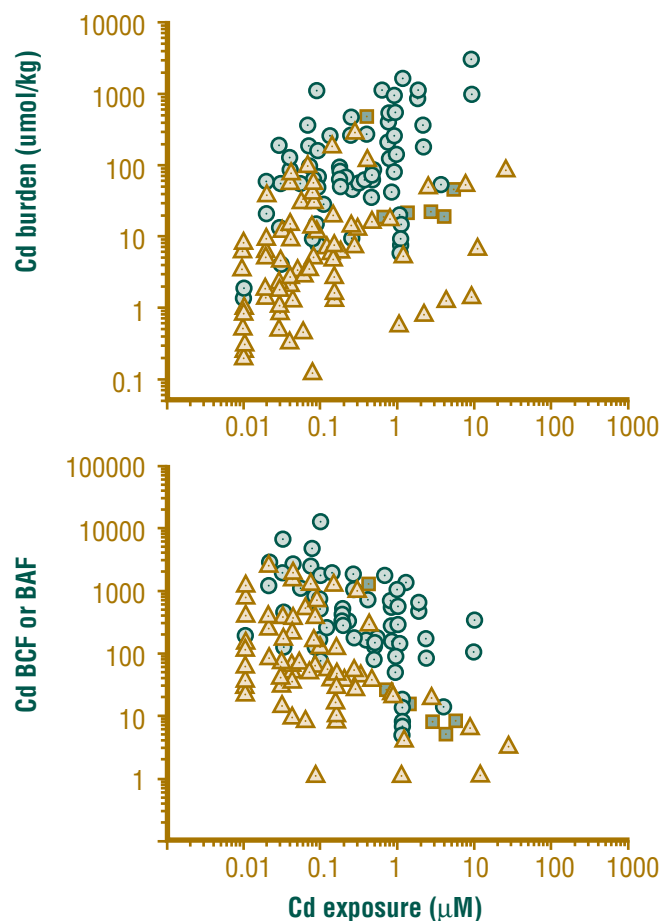


**Figure 1**

Relationships between chronic Zn exposure concentration and Zn tissue burden (top panel) and associated BCF (bottom panel). Circles and triangles show whole body data from invertebrates and fish respectively and squares are from studies with algae.

Further complicating the application of BCF and BAF to metals is the fact that many aquatic organisms store metals in detoxified forms, such as in inorganic granules or bound to metallothionein-like proteins (Mason and Jenkins 1995). The use of granules as a storage mechanism is of particular note in the context of BCFs because extremely high body burdens often are associated with this storage mechanism, but there is a lack of adverse effects. In other words, the elevated BCF values would be calculated but would be meaningless in terms of predicting undesirable environmental consequences.

Overall, the use of BCF and BAF-based criteria for the hazard classification of metals is not useful. In terms of hazard identification, the declining BCF and BAF values at elevated exposures lead to the prediction of reducing impacts as concentration increases,



**Figure 2**

Relationships between chronic Cd exposure concentration and Cd tissue burden (top panel) as well as the associated BCF (bottom panel). Circles and triangles show whole body data from invertebrates and fish respectively and squares are from studies with algae.

a conclusion that is contrary to all of the toxicological data. Using BCF and BAF for metals and inorganic metal compounds ignores fundamental physicochemical and toxicological properties associated with these substances. Compared with diffusional uptake of neutral organics, metal uptake is complex and includes a diversity of mechanisms, accumulation of both essential and non-essential elements from natural background, homeostatic control of accumulation, as well as internal detoxification, storage and elimination.

However, none of these complicating issues diminishes the importance of bioaccumulation as a factor in assessing the environmental hazard associated with metals. To correctly assess potential hazards, it is necessary to distinguish between low-level bioaccumulation of naturally occurring concentrations of metals,

nutritionally essential bioaccumulation of minerals, benign bioaccumulation (sequestration and storage) and bioaccumulation that causes adverse effects. Obviously, this is not a simple task and clearly the BCF and BAF approach is not sufficient to accomplish all these goals.

### *International Consensus*

Due to a realization that problems have arisen with the applicability of the P and B criteria to inorganic metal compounds, a workshop was held under the auspices of the Canada/European Union Metals and Minerals Working Group (MMWG) to provide a forum for international discussion of this issue and to develop recommendations for future work (Canada/EU). The Canada/EU MMWG arrived at consensus that, in contrast to organic chemicals, BCFs and BAFs have little predictive ability in hazard identification for metals and inorganic metal compounds.

Moreover, the OECD has recognized that BCF and BAF might not apply to metals. The internationally harmonized system for hazard classification of chemical substances, based on hazard identification, has recently been finalized within the framework of the OECD and provides specific guidance on the unique nature of metals and metal compounds as compared with organics (OECD 2001). Given the state of the science, as assessed by an expert working group, guidance on bioaccumulation in the context of hazard identification for the aquatic environment was limited to the fact that BCF and BAF might not be useful and that data should be reviewed on a case-by-case basis. In other words, the OECD guidance clearly recognizes the problem related to the use of BCF and BAF for metals but does not provide solutions. Therefore, there is a discontinuity or gap in the provision of science towards policy.

Within the harmonized hazard classification scheme developed through the OECD, there are both acute and chronic hazard categories. Acute hazard classification is based on the relative acute toxicity of substances and it is only the chronic hazard classification scheme that depends on assessments of the bioaccumulative nature of substances (along with persistence). This is consistent with other jurisdictions where persistence and bioaccumulation are used as surrogates for chronic toxicity. As such, the science “gap” is related specifically to criteria for the chronic

hazard classification of inorganic forms of metals. The issue, therefore, becomes how one develops science-based hazard criteria for potential chronic impacts of inorganic metal substances.

### *The Path Forward*

Given that BCF and BAF are not appropriate and that the goal, therefore, is to develop criteria for the chronic hazard classification of metals, one of the initial questions relates to whether alternative approaches can (or should) be based on, or include, measures of bioaccumulation. In other words, if BCF and BAF are to be replaced, should they be replaced with another measure of bioaccumulation or something completely different? For example, a criterion for the chronic hazard classification of metals could include an assessment of chronic toxicity endpoints, as there is a reasonable database for many metals. In this scenario, acute toxicity would continue to be the basis for acute hazard classification and chronic toxicity would be used for chronic hazard evaluations. Therefore, the two chronic toxicity surrogates—persistence and bioaccumulation—would not be required, so that the P and B of PBT would become redundant.

In spite of the clear inconsistencies between bioaccumulation and chronic hazard identification and classification, the option of developing an alternate bioaccumulation measure for metals that would replace BCF and BAF is deemed a high priority because in a number of jurisdictions, bioaccumulation as a criterion for hazard-based assessments is already written into the regulatory framework and guidance (e.g. PBT). If a bioaccumulation measure can be found to replace BCF and BAF, then the PBT framework can continue to be applied and the B part of the criteria would be redefined. In this context, the regulatory approach has moved in contrast to the scientific understanding. In doing so, it has dramatically limited the manner in which the science can be applied. A chronic hazard classification criterion that does not include bioaccumulation would be difficult to apply in regulatory frameworks where it is already required.

The challenge for the science, therefore, is to develop a bioaccumulation-based criterion for the chronic hazard of metals that can replace BCF and BAF. Recent developments such as the biotic ligand model (BLM) may provide some direction towards

beginning to understand how this challenge might be met. The BLM is a mechanistically based methodology that uses aquatic geochemistry and toxicology principles to define the fraction of the available metal that produces toxicity and then to link the bioaccumulation of that fraction to toxic impact (Playle 1998; McGeer et al. 2000; Di Toro et al. 2001; also see Fact Sheet No. 7). The principles and methodology associated with the BLM are scientifically rigorous and defensible but attempts to extend that approach to predict long-term impacts have shown that the development of a chronic BLM is a complex task.

Encouragingly, studies have shown that the degree of uptake and the chronic bioaccumulation of metals in aquatic biota are strongly influenced by processes such as aquatic speciation, ligand binding and receptor site competitive interactions (e.g. Alsop et al. 1999; Hollis et al. 2000). Conceptually, mechanistic approaches such as the BLM may be applicable in the context of chronic bioaccumulation. However, a much better understanding is required of essential mineral nutrition, acclimation and adaptation, internal handling and elimination of metals, as well as factors influencing dietary metal toxicity (see Fact Sheet No. 6).

While not specifically designed to provide information for hazard-based assessments, some of the parameters within the BLM characterize metal accumulation at the site of toxicity and these may be applicable in the context of hazard identification and classification. Alternatively, a model that predicts chronic effects for combined waterborne and dietary exposures may be useful for direct application in cases where actual chronic toxicity is used in place of surrogate measures.

### Summary

BCF and BAF applied as the bioaccumulation-based criteria for the hazard classification of metals is not supported by science. Even though BCF and BAF are not useful, chronic hazard criteria still are needed. One solution is to use chronic toxicity data (either actual data or via chronic prediction models). An alternative is to develop a new measure of bioaccumulation. This would not involve finding a better way to calculate BCF but would be a new, scientifically based measure of bioaccumulation that is specifically related to the chronic toxicity of metals.

### References

- Alsop, D. H., McGeer, J. C., McDonald, D. G. and Wood, C. M. 1999. Assessing the costs and consequences of chronic waterborne zinc exposure to juvenile rainbow trout in hard and soft water. *Environmental Toxicology and Chemistry*, 18, 1014-1025.
- Barron, M. G. 1992. Bioconcentration. *Environmental Science and Technology*, 1612-1618.
- Canada/EU. 1996. Technical Workshop on Biodegradation/Persistence and Bioaccumulation/Biomagnification of Metals and Metal Compounds. Held under the auspices of the Canada/European Union Metals and Minerals Working Group, Brussels, Dec. 11-13, 1995. Natural Resources Canada, Ottawa, Canada.
- Di Toro, D. M., Allen, H. E., Bergman, H. L., Meyer, J. S., Paquin, P. R. and Santore, R. S. 2000. Biotic ligand model of the acute toxicity of metals. 1. Technical basis: *Environmental Toxicology and Chemistry*, 20, 2383-2396.
- Feijtel, T., Kloepper-Sams, P., den Haan, K., van Egmond, R., Comber, M., Heusel, R., Wierich, P., Ten Berge, W., Gard, A., de Wolf, W. and Niessen, H. 1997. Integration of bioaccumulation in an environment of risk assessment. *Chemosphere*, 34, 2337-2350.
- Fortin, C. and Campbell, P. G. C. 2001. Thiosulfate enhances silver uptake by a green alga: role of anion transporters in metal uptake. *Environmental Science and Technology*, 35, 2214-2218.
- Hollis, L., McGeer, J. C., McDonald, D. G. and Wood, C. M. 2000. Effects of long term sublethal Cd exposure in rainbow trout during soft water exposure: implications for biotic ligand modeling. *Aquatic Toxicology*, 51, 93-105.
- McDonald, D. G. and Wood, C. M. 1993. Branchial mechanisms of acclimation to metals in freshwater fish. pgs 297-321. In: *Fish Ecophysiology*. Rankin, J. C. and F. B. Jensen, eds., Chapman & Hall, London.
- McGeer, J. C., Playle, R. C., Wood, C. M. and Galvez, F. 2000. A physiologically based acute toxicity model for predicting the effects of waterborne silver on rainbow trout in fresh waters. *Environmental Science and Technology*, 34, 4199-4207.

OECD 2001. Harmonized Integrated Hazard Classification System for Human Health and Environmental Hazards of Chemical Substances and Mixtures. Annex 2, Guidance Document on the Use of the Harmonized System for the Classification of Chemicals Which Are Hazardous for the Aquatic Environment. OECD Series on Testing and Assessment. ENV/JM/MONO(2001)6 OECD, 75775 Paris Cedex 16. (<http://www1.oecd.org/ehs/Class/harmonisedintegrated.pdf>).

OECD 1996. Bioaccumulation: test for the degree of bioconcentration in fish. OECD Guideline for testing of chemicals 305C.

Playle, R. C. 1998. Modelling metal interactions at fish gills. *Science of the Total Environment*, 219, 147-163.

US EPA 1996. Fish BCF. Ecological Effects Test Guidelines, OPPTS 850.1730.

Wood, C. M. 2000. Toxic responses of the gill. in press In: *Target Organ Toxicity in Marine and Freshwater Teleosts*, Benson, W. H. and D. W. Schlenck, eds., Taylor and Francis, Washington, D.C.

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## Fact Sheet on Environmental Risk Assessment

This is the eighth in an occasional series of *Fact Sheets* to be produced by ICMM on metal-specific issues in environmental risk assessment. Authorship selection and editorial review are coordinated by Dr. Anne Fairbrother of Parametrix, Inc. Each *Fact Sheet* is reviewed for technical merit by Dr. Erik Smolders of Katholieke Universiteit (Catholic University) Leuven, Belgium, and by a panel of experts in metal-related regulatory issues. While the *Fact Sheets* reflect the views of the authors, they are intended to provide an objective review of each topic. ICMM hopes these publications provide insights into complex issues in regulatory science, and welcomes questions and comments.

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