A CRITICAL REVIEW OF MEND STUDIES CONDUCTED TO 1991 ON SUBAQUEOUS DISPOSAL OF TAILINGS

MEND Project 2.11.1(d)

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A CRITICAL REVIEW OF MEND STUDIES CONDUCTED TO 1991 ON SUBAQUEOUS DISPOSAL OF TAILINGS

Final Report by

The Rawson Academy of Aquatic Science
1 Nicholas Street, Suite 404, Ottawa, K1N 7B7.

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EXECUTIVE SUMMARY

MEND (Mine Environment Neutral Drainage) studies on the subaqueous disposal of tailings material (outlined under MEND project 2.11.1) were subject to critical review by a group of experts, under the direction of the Rawson Academy of Aquatic Science, Ottawa. The review had two objectives. In summary, these were:

- To provide technical and scientific assessment of MEND studies on subaqueous disposal of tailings (presented in Part I of this report).
- To outline additional requirements necessary for the MEND studies on subaqueous disposal to maintain a credible scientific approach. (presented in Part II of this report)

The following key points were established during the review and subsequent discussions between the scientific review team (SRT) and representatives of MEND.

Technical and Scientific Assessment

Subaqueous disposal of tailings appears to offer physico-chemical advantages over terrestrial disposal, particularly with respect to sulphur oxidation and generation of acid waters.

The process of tailings disposal is potentially highly disruptive of lake ecosystems and normally it would take several decades (possibly centuries in some lakes) before natural sedimentation provided sufficient cover to insulate the lake ecosystem from the influence of the tailings (both the metals flux and substrate effects). However, remedial measures may be applied to reduce the extent of impact and accelerate recovery.

The MEND literature review of geochemical processes controlling metals release is excellent, it is well written and comprehensive (at the time of completion).

The background limnologies of the MEND case-study lakes (Anderson, Buttle and Mandy) are suitable only for gross comparisons. They do not support clear interpretation of cause and effect associated with tailings disposal.

Field studies were designed to obtain limited information, specifically to assess whether or not the reactivity of tailings disposed of underwater (in the real environment) remained low. For this

purpose the data are sufficient; however, the data are neither useful to address effects which occur during the process of disposal nor long term ecosystem adjustments to the introductions of tailings.

Limitations inherent in chemical extraction techniques may restrict the extent to which available data are used to address study objectives.

Additional Requirements

Suggestions have been made for more detailed field studies of (metals) fluxes in the case-study lakes, rates of accumulation and for measurements of whole lake ecological response, and references are provided in the report. The reviewers' comments and recommendations, and further documentation are available from the MEND secretariat.

A more extensive but selective literature review has been suggested to cover aspects of toxic effects, particle behavior in response to in-lake hydrodynamic conditions, improved field and analytical techniques and methods, and biological indices of whole lake effects.

The general view of a joint meeting between the SRT and representatives of MEND was that site-specific preferences for subaqueous disposal of tailings would include:

- infilling of a small headwater lake;
- disposal in an artificial structure; and
- in-lake disposal (in which tailings represent only a small part of the total lake volume).

It was recognized that in-lake disposal was not a usual practice and may not be acceptable. To some extent,this view could modify future development of subaqueous disposal studies under the MEND program.

RÉSUMÉ

Les études du Programme de neutralisation des eaux de drainage dans l'environnement minier (NEDEM) portant sur l'élimination subaquatique des résidus miniers (décrites dans le cadre du projet NEDEM 2.11.1) ont fait l'objet d'un examen critique par un groupe d'experts, sous la direction de l'Académie Rawson des sciences de l'eau (Ottawa). Cet examen visait deux objectifs, dont voici le résumé:

- fournir une évaluation technique et scientifique des études NEDEM sur l'élimination subaquatique des rejets miniers (présentée dans la Partie I du présent rapport);
- préciser les exigences supplémentaires nécessaires aux études NEDEM sur l'élimination subaquatique des rejets miniers, afin de maintenir une approche scientifique crédible (présentée dans la Partie II du présent rapport).

Les principaux points suivants ont été établis dans le cadre de l'examen et des discussions subséquentes entre l'équipe responsable de l'examen scientifique et les représentants du NEDEM.

Évaluation technique et scientifique

L'élimination subaquatique des résidus miniers semble offrir des avantages physico-chimiques par rapport à leur élimination terrestre, particulièrement en ce qui touche l'oxydation du soufre et la production des eaux acides.

Le processus d'élimination des résidus miniers a la capacité de troubler énormément les écosystèmes lacustres; normalement, il peut s'écouler plusieurs décennies (et possiblement quelques siècles dans certains cas) avant que la sédimentation ne puisse constituer une couche suffisamment épaisse pour isoler un écosystème lacustre de l'influence des résidus miniers (c.à.d. à la fois les effets des flux métalliques et des substrats). Quoi qu'il en soit, des mesures correctives pourraient s'appliquer afin de limiter la portée de l'impact et d'accélérer le retour à la normale.

La revue faite par les documents NEDEM des processus géochimiques contrôlant la libération des métaux s'avère excellente; les textes sont bien rédigés et complets (au moment de la fin de l'examen).

Les données limnologiques générales des lacs faisant l'objet d'une étude de cas NEDEM (Anderson, Buttle et Mandy) sont inadéquates, sauf pour des comparaisons très approximatives.

Elles ne peuvent étayer une interprétation limpide des causes et effets rattachés à l'élimination des résidus miniers.

Les études faites sur le terrain ont été conçues pour obtenir une information limitée, plus précisément pour évaluer si la réactivité des résidus éliminés dans l'eau (et dans un environnement réel) demeure faible. Les données sont suffisantes à cette fin; cependant celles-ci ne peuvent servir à préciser les effets qui se produisent dans le cadre du processus d'élimination, ni les ajustements écosystémiques à long terme nécessités par l'apport de résidus miniers.

Les limites inhérentes aux techniques d'extraction chimique peuvent limiter le degré auquel les données disponibles desservent les objectifs visés par l'étude.

Exigences supplémentaires

Des suggestions ont été faites relativement à la tenue d'études sur le terrain plus complètes des flux métalliques dans les lacs visés par l'étude de cas, des taux d'accumulation et de la mesure des réactions écologiques de lacs entiers à l'élimination subaquatique de résidus miniers. Les documents de référence sont fournis dans le rapport. Les commentaires des experts traitent largement de ces suggestions et les recommandations detaillées sout disponsible en s'adressant au secrétariat du NEDEM.

Il a été suggéré que l'on procède à une revue plus poussée mais sélective des documents afférents pour traiter certains aspects des effets toxiques, le comportement des particules en réaction aux conditions hydrauliques présentes dans les lacs, l'amélioration des techniques et méthodes utilisées pour l'analyse sur le terrain et les mesures biologiques des effets sur les lac entiers.

L'opinion générale qui s'est dégagée lors d'une réunion conjointe de l'équipe responsable de l'examen scientifique et l'équipe NEDEM est la suivante relativement au choix d'un site pour l'élimination subaquatique des résidus miniers (par ordre de préférence):

- le remplissage d'un petit lac en amont;
- l'élimination des rejets dans un réservoir artificiel; et,
- l'élimination des rejets dans le lac (ceux-ci ne représentant qu'une petite partie du volume lacustre total)

On reconnaît que l'élimination des rejets dans le lac ne constitue pas généralement une pratique acceptable. Jusqu'à un certain point, cette opinion pourrait modifier l'élaboration future des études d'élimination subaquatique des déchets dans le cadre du programme NEDEM.

INTRODUCTION

The Rawson Academy of Aquatic Science (RAAS) is pleased to submit this critical review of MEND (Mine Environment Neutral Drainage) studies conducted to 1991 on the subaqueous disposal of tailings. The objectives of the study are defined in the Terms of Reference (Attachment 1). In summary, there are two principle and related requirements.

1. To conduct a technical and scientific review of all aspects of the MEND studies on subaqueous disposal of tailings.

2. To define additional information requirements so that it will be possible to establish the scientific credibility of the approach.

It is clearly understood that tailings disposal presents a large and increasing problem for the mining industry, both in terms of environmental impact and cost, and that before application of disposal technologies such as subaqueous disposal, the approach must be proven scientifically sound. Proposals for subaqueous disposal of tailings can not be submitted for public scrutiny unless there is a scientifically sound and well justified basis for the approach. Under the MEND program, a series of reports on field investigations and background reports on subaqueous disposal of tailings have been prepared.

Assessment of work to-date by MEND, open discussions of the studies at a recent international conference (September, 1991, Montreal), and preliminary considerations of environmental scientists suggest that the subaqueous disposal of tailings might provide an effective means of resolving some of the problems associated with acid-generating tailings. At the request of MEND, the studies on subaqueous disposal have been submitted to detailed and rigorous scientific review. Following the review, recommendations are now provided to guide ongoing work including field work planned for the current season. The review has been based on the documents listed in Attachment 2. On request, additional information has been provided to members of the scientific review team (SRT). The membership of the SRT is listed in Attachment 3.

The approach used to complete the review generally followed the outline submitted as part of the Rawson Academy's original proposal to EMR (December, 1991). The guidelines for review (prepared by the project manager, December 27th, 1991) are provided as Attachment 4. The review was implemented in four stages. Stage 1 comprised a "first-cut" assessment of MEND documentation and this was circulated amongst all members of the SRT. In stage 2, an in-depth

review was prepared by each member of the review team and these were also circulated. A joint meeting of the SRT and representatives of MEND was held at the Canada Centre for Inland Waters (CCIW), Burlington, Ontario (March, 10th, 1991). This meeting completed stage 3 of the approach and it was also attended by two members of staff from the centre. Key points arising from discussions during that meeting have been incorporated into the body of this report. A list of attendees is provided as Attachment 5. In the last stage of the review, all members of the SRT have provided additional comments and suggestions for inclusion in this report (see text and Attachment 6). A number of references have been recommended by the reviewers and these are cited in this report. Some original documents have also been provided to the MEND Secretariat.

The next section of this report provides a synthesis of reviewer comments (SRT members) and it incorporates additional comments arising from the joint SRT-MEND meeting, as appropriate. Detailed and specific comments have been provided in the individual contributions of the reviewers, and these are available from the MEND Secretariat. This report follows the guidelines outlined in Attachment 2.

PART I OF SRT REVIEW:

TECHNICAL AND SCIENTIFIC REVIEW OF ALL ASPECTS OF THE MEND STUDIES ON SUBAQUEOUS DISPOSAL OF TAILINGS (ALSO DEFINED AS OBJECTIVE I)

CONCEPTUAL BASIS FOR SUBAQUEOUS DISPOSAL OF TAILINGS

Subaqueous disposal of tailings appears to offer physico-chemical advantages over terrestrial disposal, with respect to sulphur oxidation and the generation of acidic waters. Two separate mechanisms are evident in the documentation provided, these include oxide blocking and sulphide precipitation of mobile metals.

However, in real world conditions, many other concerns should be taken into account. These include processes involved during the introduction of tailings into a lake, the biological and physical reworking of tailings underwater, the burial of benthic biota and hence modification of food-web structures, and the effects of solids ingestion on metal uptake by organisms.

Conceptually, the SRT agreed that once buried under 5-10 cm or more of normal lake sediment, diffusional conditions will largely control the geochemical behavior of tailings, and they would be relatively stable over the long term (assuming additional influences such as groundwater migration are negligible). However, diffusional fluxes are only part of the total flux condition, especially during the period of tailings introduction and dispersal within a lake when particle surface effects (both as suspended particulates and as bed material) often occur under oxic conditions.

The consensus of the SRT was that apart from the difficulties and inadequacies in dealing with actual in-lake conditions, the conceptual approach of disposal of large volumes of mine tailings in most lakes was unsound; particularly, it was not reasonable to expect that it would be possible to retain productive biological use during (large volume) tailings introduction. In very large lakes the problems are localized rather than lakewide. True, negative effects could be established within a rather short time frame (probably 2 or 3 years). But to show that no significant detrimental effects occurred would be very difficult (if at all possible), it would take a long time (10 years, plus), it would be costly and, at best, uncertain.

Considerations seem to suggest the following key points.

- It would be easiest to fill-in some existing small lake or depression, and retain a shallow water or, possibly, wetland[1] cover over the surface of the tailings. This means it would be necessary to accept a major change in habitat type but, providing potential problems of

[1]The SRT did not access the use of wetlands for metal stabilization (the topic of a separate MEND program). Rather the term is used to reflect an environmental continuum from shallow ponded water to more or less continuously flooded terrestrial habitat.

contamination (groundwater, for example) are addressed, remedial work could result in beneficial use from the modified habitat.

- In most locations, and certainly those without suitable topographic closure, it may be best to create above-ground artificial structures to hold the tailings underwater. The structures would provide confined aquatic conditions without the loss of natural aquatic habitat. Since the structures and fill would be designed from the "bottom-up" a high degree of quality control should be possible and this would ensure that performance met design specifications. However, the possibility of long term structural failure (10^2 to 10^3 years) is probably greater than for in-lake disposal.

- Disposal in a deep lake may be possible but, from the point of view of environmental impact,it is clearly the least desirable option. Disposal practices would have to be designed to minimize negative impacts but they would be costly and difficult, and it would be virtually impossible to ensure no ill-effect (either during disposal or the subsequent recovery phase). Some remedial actions might be applied to lakes historically used for this purpose and experience gained could prove useful in dealing with more contemporary disposal activities. Despite many biological problems it should be noted that, over the long term, this environment may offer the most secure form of disposal.

- If the industry can demonstrate substantial examples of restoration or lake enhancement there may be a greater public willingness to accept temporary and minor environmental degradation so long as full recovery is practical and enforceable. Similarly, although not explored by the SRT, there may be a willingness to consider application of the principle of no net loss (of habitat) in some form of compensatory framework.

- The concept of sustainable development is extremely important and is broadly addressed by the MEND program. For the most part it means minimizing waste, back-filling, re-using, re-cycling, and treating it before disposal; and ensuring that disposal has the least undesirable impact, and that it has long term (indefinite) security. In particular, tailings generation, storage, treatment and disposal, need to be viewed from a holistic perspective, looking at the totality of effects rather than just the limitations of *in-situ* geochemistry.

- The application of a single "generic" approach to subaqueous tailings disposal does not seem practical; for the most part, considerations (involving a range of economic political, technical and environmental factors, etc.) should be site-specific.

LITERATURE REVIEW

There was unanimous agreement amongst the SRT that the documentation providing an overview of sediment geochemistry (relating to tailings disposal) was excellent. The review was well written and up-to-date at the time of writing, and it was well focused. The reviewers were concerned, however, about the use of inadequate experimental and analytical technologies and their reflection in the reference literature. This point is discussed further with respect to both field and laboratory studies. The SRT also felt that the literature review was inadequate in dealing with sediment/aquatic toxicities; many recent publications were not cited and little if any work on solids ingestion was cited. The SRT recognized that sediment toxicity was not the principal focus of review but felt it important to present a greater understanding of this topic.

To improve the review coverage of both metal toxicities, and experimental and analytical technologies,and to provide additional limnological and ecological background information, a number of additional references have been suggested (Attachment 8).

PROPOSAL FOR STUDIES ON THE EFFECTS OF UNDERWATER DISPOSAL OF WASTE ROCK AND TAILINGS

This refers to the background report on MEND project 2.11.1 (Subaqueous Disposal of Tailings, by J. D. Robertson) which is listed as document 1 in Attachment 2.

The following comments are applicable:

- It is difficult to consider any lake as "biologically barren", and this term needs to be defined (see p6., Attachment 1, for assumed meaning).
- The prime objective was to determine the reactivity of tailings in subaqueous environments, based on case-studies. The studies confirmed long term low level reactivities. The studies did not address a broad range of related environmental issues, nor were they intended to.
- The flux measurements which were carried out are not considered sufficiently reliable or representative to be extrapolated to the whole lake.
- The physical and chemical processes were not sufficiently studied to establish many important interactions between sediments, water and biota.

- The report provides little information about the immediate impact of tailings disposal, or the longer term "aging" of subaqueous environments modified by tailings disposal.

BACKGROUND LIMNOLOGIES OF CASE-STUDY LAKES

Limnological data, before in-lake disposal, are negligible. Overall, the background limnologies are inadequate to establish anything other than the most obvious trends in lake conditions (over the case-history period). Also, the data are insufficient to establish to the extent to which present lake conditions reflect existing interactions between tailings, water and biota. Lag effects complicate environmental assessment and a lack of both spatial and temporal information severely limit abilities to interpret what is available. The level of background information is not the same for each of the case-studies. Most information is available for Buttle Lake and least for Anderson Lake; for none of the lakes is it sufficient. Some of the more specific comments include:

- Chemically, Mandy Lake is an unusual Boreal Forest lake. It will require careful study since the ability to make comparison with other lakes, in similar ecoregions, is less than for the other two case-study lakes.

- So far, the case-studies have yielded nothing definite in terms of specific cause and effect, between subaqueous deposition of tailings and the status of indigenous communities.

- Information about regional hydrologies (including groundwater) is inadequate.

- Information is available about cause/effect impacts in a number of naturally acidic lakes and those anthropogenically acidified (acid rain effects, Sudbury smelters etc); some aspects of these existing case histories might have been used to supplement the tailings studies.

- The metal and sulphate concentrations in lake waters were variable. In some lakes, concentrations may not be specifically related to the present impact of tailings but, rather, to previous impact histories. For example, the effects of early mine effluent discharge, groundwater seepage, surface drainage in land-disposed/stored tailings, and the impacts of site construction and decommissioning.

- A related concern was the extent to which sulphur oxidation by reduced tailings could consume hypolimnetic oxygen, driving the chemistry of a system towards anoxic

conditions. Clearly, this would be of most concern under diffusion-limited conditions and after the initial phase of tailings disposal.

- At one time, Buttle Lake had a thriving population of cutthroat trout (*Oncorhynchus clarki*) but no information is presented about the status of this fishery. Linked to this, is the possibility that tailings may have covered fish spawning grounds (of this and/or other species).

- In addition to the lack of seasonal and interannual water quality and biological information, there is a lack of any discussion about episodic/catastrophic impacts which may have taken place in the receiving water bodies or may occur in the future (either natural or man-induced).

- Further discussion of wetland conditions should have been presented (particularly with respect to Mandy Lake). It was noted that root respiration might affect the oxic environment of surficial sediment.

FIELD STUDIES AND ANALYTICAL WORK

Apart from the obvious comments about the lack of adequate background limnology, the SRT expressed major concerns about trying to make too much of conclusions drawn from such limited field and laboratory data. In particular, concerns were drawn to the following points:

- Large volumes (Buttle) and variable inflow (Mandy) create natural conditions in which it is difficult to establish the response of whole-lake water chemistry to the introduction of tailings. Therefore accurate flux measurements at the sediment/water interface are particularly important in establishing cause and effect responses in the biota.

- There was a lack of replicate coring and sub-sampling.

- Also, it would have been helpful to have additional cores from other areas of the lakebed in each lake.

- There is a lack of seasonal data (core and water column).

- There is a lack of detailed water chemistry profiling (or at least sampling based on integration within thermally stratified layers).

- The flux measurements based on comparison of pore water chemistry with the "average" chemistry of the overlying water can not be considered reliable nor representative of actual fluxes across the sediment/water interface.

- Complementary means of measuring sediment/water (chemical) fluxes should have been used (for example, flux chambers and dialysis measurements). In such studies, sediment and water are sampled/measured simultaneously.

- Information about the concentrations of metals in most levels of the food-web is lacking. Metals in fish are useful but not sufficient on their own. For example, metals in periphyton (attached algae), rooted plants, zooplankton, insect larvae, clams and snails, fish, mammals, amphibians and reptiles may add significantly to the understanding of metals effects.

- The case studies did not sample suspended materials, nor report concentrations of suspended solids.

- The lake studies provided little or no information about biological community structures, fish health (for example, teratogenic effects), whole lake metabolism, surface microbial processes, nor did they address nutrient/metals relationships.

- In terms of laboratory studies, the SRT was concerned about analysis of metals in water. It was suggested that QA/QC should be documented as part of analytical reporting. Where not readily available, a lack of this information adds to difficulties in comparison of historical data series.

- Neither redox nor pH profiles were established in the cores.

- There is little information about sediment texture or particle-size. Minerals may be size-associated and particle-size is important in terms of hydrodynamic behavior (erosion, transportation and deposition).

- Sedimentation rates are important and there are many ways to establish the dating of core samples (some of the best use local marker horizons within the sediment column); these were not established. Also, it should be noted that water content and compaction are important factors influencing rates of sediment accumulation.

- Core-logs are important as confirmation of the quality of core material (lack of disturbance) and as a guide to depositional processes and depositional history. Detailed core-logs should have been prepared. In addition, non-destructive x-radiography can provide important clues about biological re-working and the relative significance of advective processes at/near the sediment/water interface.

- The chemical extraction procedures used in the recent studies on cores from the case-study lakes were designed for application under oxic rather than anoxic conditions, and for sediments with relatively low sulphide content. As a result, interpretations should be treated with caution; the fact that extractions were performed on dried samples may add further complications. The SRT felt that direct access to the laboratory data would not likely improve its ability to assess current interpretations (based on these data).

OVERVIEWS AND CONCLUSIONS

The SRT concluded, while it is appropriate to suggest geochemical evidence supports the view that subaqueous disposal of tailings results in a substantially less reactive environment than terrestrial disposal, the nature and extent of biological response in the aquatic environment is (at best) unclear. It is probable that severe physico-chemical effects occur during subaqueous disposal of tailings and although amelioration and subsequent remediation may be possible, the effectiveness of many measures is not yet predictable, with reasonable certainty. In limited circumstances, however, the No-Net-Loss of Habitat policy of the Federal Department of Fisheries and Oceans might be applicable to some aspects of in-lake tailings disposal. Although more detailed studies would be useful (Part II, following), from the perspective of science there is little to be gained from a wider (geographic) spread of the case-study lakes.

Members of the SRT also noted that the current levels of scientific understanding and case-history study data are not sufficient to encourage industry to seek approval for subaqueous disposal as a preferrer option. Also, it was noted that government regulations comprise not only requirements applied to industrial disposal of tailings but to field experimentation, as well. The scope of manipulative field research is becoming more restricted and this could influence new directions and, maybe, locations of research.

PART II OF SRT REVIEW:

DEFINE INFORMATION REQUIREMENTS SO THAT IT WILL BE POSSIBLE TO ESTABLISH THE SCIENTIFIC CREDIBILITY OF THE APPROACH (OBJECTIVE II)

SCOPE AND DETAIL OF THE LITERATURE REVIEW

The SRT recommends, for the purpose of studies on the impact of and remedial actions for subaqueous disposal of tailings, that selective and additional literature reviews would be useful on the following topics:

- Biological uptake of metals and bioaccumulation of metals.
- Toxic effects of metals and metal/nutrient interactions (this should include consideration of literature on lake acidification and dredged material disposal).
- The physical behavior of fine particles in relation to plume dispersion, bed stability, and biological and physical reworking (this includes a very substantial quantity of literature which has already been developed for the dredging industry).
- Field and analytical techniques applicable to improved measurements of the fluxes of metals and nutrients at the sediment/water interface.
- Means of showing cause and effect at the community level in biota, and health and productivity effects including whole lake metabolism.
- The role of wetlands in metal stabilization* , including macro and micro- biochemistry of vegetation and complex interactions between plants, sediment and water (literature on this topic includes discussions associated with dredged material disposal).

Members of the SRT have provided citations and reference materials (Attachment 6) which relate to many of the above topics. More could be provided but, at this point, it is perhaps most wise to decide exactly which direction the next thrust of the MEND program on subaqueous disposal should follow.

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* There is a continuum between shallow water and flooded terrestrial habitat and, therefore, some of the literature on wetland research is applicable to subaqueous disposal of tailings. The SRT is aware that MEND has a separate program on wetland studies.

RE-DEFINITION OF HYPOTHESES AND/OR NEW HYPOTHESES

This heading refers to hypotheses which would be associated with possible options for subaqueous tailings disposal. The generality of views expressed by both members of the SRT and MEND, during the March 10th meeting, was to the effect that site-specific preferences for subaqueous disposal of tailings would include:

- Disposal in and near-filling of a small headwater lake or depression having a limited catchment.
- Disposal in a man-made structure.
- Deep lake disposal.

It was felt that no new disposal in a large lake would be considered unless under extremely limited circumstances in which other forms of placement proved infeasible. Unconfined disposal in a large or deep lake would not be acceptable. Irrespective of present practices, however, remedial actions may be useful at some sites where past disposal has led to the deposition of tailings in lakes or closely adjacent to them.

It was also felt that options exist to develop a range of water depths as a surface cover over the tailings. In most situations, the hypothesis that subaqueous disposal of tailings would result in a least reactive environment was thought to remain valid. Also, but not discussed, the possibility remains that some tailings disposal could be accommodated within a lake, in some type of retaining structure. However, in this case, concern lies most particularly with the safety and stability of the containment (this also includes any form of engineered outlet). Both the SRT and MEND representatives agreed that means to avoid groundwater contamination would be a key issue with respect to the use of headwater lakes/depressions as sites for receiving tailings materials. Also, local hydrology would have to be such that it maintained a slight positive water balance at the disposal site. The options represent conditions in which there is least damage or the lowest probability of risk to the environment.

The SRT was of the opinion the hypothesis that subaqueous disposal of tailings represented long term least effect on a lake environment was neither proved nor disproved. Despite many apparent problems subaqueous disposal raises a number of important issues which should be resolved. In particular, it would be valuable to complete more detailed work on some of the MEND case-study

lakes, and to carry out a demonstration study with tailings to clearly document the nature of before and after effects, and the rates of system recovery under controlled conditions.

BACKGROUND LIMNOLOGICAL DATA

Because of a lack of good historical information on the limnology of the study lakes, it is not useful to collect large sets of data for comparative analysis of trends in water quality or biological populations. However, other forms of trend data are useful. For example, lake sediments may provide a record of both proxy and direct change in water quality and biota, in response to the discharge of tailings. Many techniques are now available in which preserved algal and microfaunal remains can be used to identify significant changes in lake chemistry, such as would be caused by the introduction of large volumes of tailings material. Sediment texture and structure may also provide evidence of the depositional mechanisms which controlled dispersal of the tailings. If the sediment data are linked with reasonable estimates of local hydrology (for example the quality and quantity of inflows, and residence time), it should be possible to define a number of changes that have occurred as a result of tailings disposal and to quantify some of the aspects of change (both chemical and biological).

Present limnological studies should focus on estimates of mass balance for selected chemicals (for example, metals and sulphates), whole lake metabolism and community structure, spatially and seasonally representative measurements of nutrient and metal fluxes in the water column and at the sediment/water interface (including chemical speciation), the health and biological response of sensitive species to available metals, and metal concentrations at selected points within the food-web. The identification of sensitive lake-specific indicator species together with measures of community structure and lake metabolism should provide a basis for interpreting future trends in lake recovery (and their link to the sediment record).

In shallow Anderson lake, where large quantities of fresh tailings are carried into the water column, there are additional opportunities to study fluxes that may be associated with the effects of near continuous interactions of particulate materials with relatively well oxygenated water.

Documentation submitted to the MEND Secretariat provides a summary of recent work associated with whole-lake cadmium additions at the Experimental Lakes Area (northwest Ontario) undertaken by the Department of Fisheries and Oceans. This work illustrates the type of demonstration project that might be developed to model the effects of tailings disposal in lakes, incorporating the lessons

already learned from case-studies and related observations (such as studies on acidified lakes and dredged material disposal). In stages, a project of this type could advance through open lake disposal to pond development and even wetland formation in a small, confined upland basin.

FIELD DATA

The collection of field data will require the use of more appropriate and better equipment for sampling and in situ measurements. As an example, the need for better estimates of fluxes at the sediment/water interface would probably require the use of flux chambers, dialysis arrays (including profiles in water and sediment), suspended sediment sampling, thermal profiling of the water column and current measurements. In addition, replicate samples would be required at a number of representative sites in each study lake, with samples taken to reflect seasonal variabilities. At least two years of data would be required. The use of mesocosm experiments and in-lake containments (limnocorrals) offers further opportunities in the design of demonstration studies.

The contributions by Leach and Herron, and Duffy, Oglesby and Reckahn (in Bush and Sly, 1992), noted in Attachment 8, also provide an extensive overview of limnological and ecological requirements which may be used in the selection of appropriate indigenous biological indicators.

LABORATORY DATA

Just as improved field work will require more sophisticated equipment, more frequent sampling and better QA/QC, the same types of improvement must be sought in laboratory analyses. Detailed core-logs and the use of non-destructive analysis (for example x-radiography) may be required to aid selection of subsamples for detailed microscopical analysis of preserved organic matter, and mineralogy and particle-size analysis. Sequential chemical extractions should be appropriate to the core mineralogies (both in terms of solid phase and pore water chemistry). Studies of particle surface textures, also, may be used to identify leaching/dissolution effects. The identification of historical marker horizons and profiles of water content (or other estimates of bulk density) will be required to derive rates of sediment accumulation. Sediment accumulation is an integrated measure of particle settlement, compaction, resuspension, organic degradation, bioturbation, de-watering, and other processes which occur at or near the sediment surface.

ATTACHMENT 1

TERMS OF REFERENCE

TERMS OF REFERENCE FOR THE PEER REVIEW

1. Objectives

There are two interdependent objectives of this review which are outlined as follows:

1. The primary objective is to perform a technical and scientific review of all aspects of the work conducted to date. This will include review of the study approach, the specific methodology used and the results obtained on each lake studied. The review document will provide an overview judgement of the work conducted and a detailed critique of the strong and weak points of this work. Recommendation will be provided for strengthening the weak areas for any similar future work which may be conducted. These recommendations will supplement similar recommendations which will be provided in fulfilling the requirements of the following "objective 2".

2. The ultimate objective of the project is to develop a sound understanding of this method of control of acid generation so that the scientific community can clearly assess under what conditions the method could be implemented. In order to achieve this, a solid and complete technical database is needed. The work conducted has provided some of the required information but additional information in such areas as the biological, limnology and water chemistry areas is needed to complete this task. Therefore, a second objective is to review the work conducted to date, and to define the additional information requirements which are needed to present the project such that support and approval can be obtained from the scientific community. This will require a detailed description of the areas for study, and the ultimate application of this information, and a general estimate of the costs for completing the database. This assessment is not intended to define the idealistic ultra scientific database which will be far too expensive to achieve but rather to define a level of database which is complete enough to serve as a decision making tool for the application of these methods of acid drainage control, compatible with ambient water quality objectives.

2. Key Questions to Focus the Review

The following questions are provided to assist in focusing the review to a satisfactory end point.

1. Has the work demonstrated that this method will or will not have unacceptable environmental effects when practiced?

   a) in biologically "barren" lakes
   b) in biologically productive lakes under rigorous operating conditions

2. If there is not enough known to make this assessment, how much more and what type of work would be required for successfully assessing each of the above scenarios.

3. Studies have only been conducted to date in western lakes. Are additional lakes, particularly in eastern Canada needed? If additional studies are needed, what additional new information from these lakes will effectively complement the existing information?

4. Limited studies have been conducted in lakes actively depositing tailings. Are more of these case histories needed?

5. Is sufficient information known to develop basic criteria or conditions where underwater disposal would be environmentally acceptable?

6. Would a demonstration project be of value in assessing the environmental effects? If so, what criteria would be important in developing such a project?

3. Information Available

The following information is available for review:

a) The original terms of reference for the initial literature review for the project. The recommendations from this report provided the general terms of reference for the subsequent studies.

b) A summary report entitled "Background Information for Project 2.11.1 Subaqueous Disposal of Tailings", by J.D. Robertson.

c) Reports prepared by the consultant, Rescan Environmental Services Ltd., on each lake studied. These are listed as follows:

Underwater Disposal of Waste Rock and Tailings - PROPOSAL;

Subaqueous Disposal of Reactive Mine Wastes: An Overview;

Geochemical Assessment of Subaqueous Tailings Disposal in Buttle Lake, British Columbia;

A Preliminary Assessment of Subaqueous Tailings Disposal in Anderson Lake, Manitoba;

Geochemical Assessment of Subaqueous Tailings Disposal in Anderson Lake, Snow Lake, Manitoba;

Geochemical Assessment of Subaqueous Tailings Disposal in Mandy Lake, Flin Flon Area, Manitoba; and

A Preliminary Assessment of Subaqueous Tailings Disposal in Mandy Lake, Manitoba.

d) Two papers presented at the Second International Conference on the Abatement of Acidic Drainage, September 1991, Montreal. They are:

Subaqueous Disposal of Reactive Mine Waste: An Overview of the Practice with Case Studies, by J. Robertson, Placer Dome; and

Diagenetic Reactivity of Mine Tailings in Mesotrophic and Oligotrophic Lakes in Manitoba and British Columbia, by T. Pedersen, University of British Columbia.

4. Contact Person from the MEND Project

Discussions will be required between the reviewers and the consultant personnel and project managers to clarify details and to provide information which is not included in the reports. The contact names and numbers from the Consultants are:

• Mr. Clem Pelletier - Rescan	Tel:	(604) 689-9460
	Fax:	(604) 687-4277
• Dr. Tom Pedersen - U.B.C. Department of Oceanography	Tel:	(604) 822-5984
	Fax:	(604) 822-6091

The managers of the overall projects and the contact numbers are:

• Mr. Jim Robertson - Placer Dome Inc.	Tel:	(604) 661-1557
	Fax:	(604) 661-3792
• Mr. Wayne Fraser - Hudson Bay Mining and Smelting	Tel:	(204) 687-2171
	Fax:	(204) 687-5793

Arrangements for the peer review contract are by CANMET and the contact name and number is:

• Mr. Gilles Tremblay	Tel:	(613) 992-0968
	Fax:	(613) 996-9673

5. Outline of Rawson Personnel

The Rawson Academy personnel, their credentials, and their area of responsibility in the review should be clearly outlined.

6. Schedule for Completion

The review contract should commence as soon as possible.

As the results of the review are critical to the planning for the future work for 1992 and additional years, there is some urgency for completing the review expediently.

The review should be completed within two and one-half months after the contract has been awarded.

A meeting may be required between the various parties to allow efficient communication of some of the needed information. If this is needed, the location and appropriate time should be proposed by Rawson in their proposal.

A panel discussion of the results of the review will be required to a small group of MEND representatives. Location and time to be proposed by Rawson.

Two camera ready copies of the final report will be required by March 31, 1992.

7. Budget

The budget for the project should specify the cost for performing the evaluation for the two objectives outlined.

BACKGROUND INFORMATION FOR MEND PROJECT 2.11.1 SUBAQUEOUS DISPOSAL OF TAILINGS

Introduction

The subaqueous study started in 1988 through a project which was funded by the B.C. Acid Mine Drainage Task Force. This initial overview report provided the basis for subsequent work which was performed during the past three years on four lakes in B.C. and Manitoba. These later studies have been registered under the appropriate MEND and B.C. AMD programs and the various reports are available through these groups.

This report summarizes the original terms of reference, the progress made to date, and outlines additional work which is required to achieve final objectives of developing criteria for applying this technology in the industry. Significant additional funding and work is required to complete the technical support for promoting this method of tailings disposal. The public and regulatory consultation program is a separate important exercise which requires extensive careful planning and is essential for the success of this project.

Terms of Reference

Political and Public Policy Issues

The concept of disposing of tailings materials in lakes is controversial and generally not acceptable as standard practice by Canadian regulatory agencies or the public. Consequently, this study was initiated with the recognition that there were several possible ultimate scenarios for its application. These are outlined as follows:

1. Not acceptable in any lakes.

2. * Limited application in biologically barren lakes.

3. Applicable to biologically productive lakes under rigorous conditions which verified the effectiveness and minimal impact of the systems on the adjacent environment.

* Undefined term but presumed implicit of lakes without evident macrofauna (particularly, fish), RAAS.

These three scenarios are still currently valid and the ultimate policy which will determine the scenario which will be applied is only partially determined by the development of solid technical evidence which supports this disposal strategy. The need for a comprehensive review program to enlist political and public support of this method was recognized in the original planning of this project. This important exercise has not been formally initiated to date.

Technical Issues

The primary objective of the studies on geochemistry was to determine the reactivity of tailings materials in a subaqueous environment. If the initial results indicated that the tailings materials were rendered unreactive, it would be concluded that this method presented a high potential for the control of reactive tailings and additional work would be warranted.

Preliminary biophysical studies were performed on each lake. The biophysical studies were included in the original plans to prepare basic information relating to the impacts of the tailings and potential leachates on the aquatic life. These studies were originally planned to provide a base for the later geochemical studies and to answer basic questions concerning the general biological community in each lake. They were not intended to fully resolve the many complex questions which will undoubtably be asked by the regulatory agencies and the public on the full impact of these tailings on the aquatic communities.

A final general objective was to develop criteria for the use of this method for general disposal of reactive tailings. Such criteria would be applicable to new projects as well as existing sites with acid drainage problems.

History of the Studies

In 1989, a work plan was developed which consisted of evaluating four lakes over two year periods for each lake. The initial year consisted of evaluating the biophysical features of the lake as a preliminary exercise in preparation for the second year of work. The second year consisted of performing detailed geochemical work on the interstitial water at two or three sites in the lake. Each phase resulted in the preparation of a separate report.

A brief summary of the work conducted is outlined in the following table:

LAKE	PHASE	YEAR OF STUDY
General Overview of Canadian Mines	Planning	1988
Buttle	Biophysical Geochemistry	pre 1989 1989
Mandy	Biophysical Geochemistry	1989 1990
Anderson	Biophysical Geochemistry	1989 1990

Project Results

The studies conducted to date have been documented in a series of reports.

The following basic conclusions have been developed from the work conducted to date.

1. The reactivity of the tailings materials is low as illustrated by the extremely low levels of dissolved metals (low parts per billion and parts per trillion) in the interstitial pore water in the tailings. The original hypothesis of reduced reactivity due to the submerged conditions has initially been verified.

2. The preliminary estimates of metal flux rates from the sediments indicate that these rates are low and should not have a significant impact on the overall metal balances within the lake.

3. The physical conditions detected in each lake have allowed estimates of the basic chemical mechanisms which may be acting to maintain low reactivity conditions in and around the tailings deposits.

4. * Biological communities exist in some of the lakes studied.

5. Initial studies indicate that the metal levels in the water and fish are variable depending on the history of the lake (active or abandoned). Some levels appear to be elevated while others are typical of the levels in regional lakes.

Additional work is required to fully demonstrate that this disposal method has extremely low impact on the water quality and biological communities in the lakes in both the short and long term time frames.

The foregoing conclusions illustrate that the basic elements of the original hypothesis have been successfully addressed as the tailings reactivity has been demonstrated to be low and the biological communities have been demonstrated to be present in the adjacent environment. In order to more fully understand these systems, and to develop comprehensive conclusive case history information which will withstand scientific, regulatory and public scrutiny, additional technical supportive work is required.

Technical Work

The additional technical work required to supplement the existing data and to more fully develop the case histories are outlined as follows:

1. A peer review is needed by an independent and credible scientific group of the methodology used and the results obtained from the evaluation of the lakes studied to date (Buttle in B.C., Mandy and Anderson in Manitoba).

   The objective is to obtain endorsement of the work conducted as well as determining deficiencies which may be corrected in the proposed additional work.

THE FOLLOWING TEXT IS FOR INFORMATION ONLY AND DOES NOT FORM PART OF THIS CONTRACT

2. Lakes are needed for study in Ontario and Québec in order to ensure a wider range of geographical and political coverage. Preliminary and detailed studies are needed for these lakes.

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* Biological communities were present in all of the lakes studied but top trophic levels which characterize upper parts of the food-web structure were absent in some lakes, RAAS.

3. Additional data are needed on operational mines which are disposing of reactive tailings in lakes in Canada. Each lake should have a completely documented case history which will withstand serious scrutiny.

4. Some international exchange of data or case history information would assist in supporting our results. Scandinavia may provide appropriate sites and information which may be accessed through discussions and jointly funded projects through international contacts.

Scientific, Regulatory and Public Review

A comprehensive and thorough strategy is needed to develop a program for the review of the results of current and future studies by the public, regulatory agencies and scientific communities. This is a significant task which, if mishandled, could result in the termination of the application of this potential control technique, and the elimination of the progress made in the work conducted to date. The basic elements of this program have not been finalized as there are many possible methods and strategies which may be appropriate to accomplish different objectives. However, the basic areas requiring attention are:

1. Scientific review of the work conducted to date.

2. Regulatory review of the existing work, the future proposed work and the final reports.

   This involves each of the provincial agencies as well as the federal regulatory agencies. This has been partially accomplished through the joint industry/government committees associated with the MEND program. All potentially affected agencies need to ultimately be involved to ensure complete review and acceptance of the final criteria and methodology.

3. Public review of the overall concept and scientific database which supports the application of this control method.

The review by the scientific and regulatory agencies and a more complete and active role in the planning of the next phases of this study may be the most effective means of achieving some consensus in the final conclusions of this project. Public involvement will be delayed until more complete case histories have been developed and a complete strategy has been developed.

ATTACHMENT 2

LIST OF DOCUMENTS PROVIDED

DOCUMENTS REVIEWED

1. A summary report entitled "Background Information for Project 2.11.1 Subaqueous Disposal of Tailings":, by J.D. Robertson.

2. Reports prepared by the consultant, Rescan Environmental Services Ltd., on each lake studied. These are listed as follows:

   a. Underwater Disposal of Waste Rock and Tailings - PROPOSAL;

   b. Subaqueous Disposal of Reactive Mine Wastes: An Overview;

   c. Geochemical Assessment of Subaqueous Tailings Disposal in Buttle Lake, British Columbia;

   d. A Preliminary Assessment of Subaqueous Tailings Disposal in Anderson Lake, Manitoba;

   e. Geochemical Assessment of Subaqueous Tailings Disposal in Anderson Lake, Snow Lake, Manitoba;

   f. Geochemical Assessment of Subaqueous Tailings Disposal in Mandy Lake, Flin Flon Area, Manitoba; and

   g. A Preliminary Assessment of Subaqueous Tailings Disposal in Mandy Lake, Manitoba.

3. Two papers presented at the Second International Conference on the Abatement of Acidic Drainage, September 1991, Montréal. They are:

   a. Subaqueous Disposal of Reactive Mine Waste: An Overview of the Practice with Case Studies, By J. Robertson, Placer Dome; and

   b. Diagenetic Reactivity of Mine Tailings in Mesotrophic and Oligotrophic Lakes in Manitoba and British Columbia, by T. Pedersen, University of British Columbia.

ATTACHMENT 3

MEMBERS OF THE SCIENTIFIC REVIEW TEAM

Members of Scientific Review Team

Dr. P. G. C. Campbell, INRS-Eau, 2700 rue Einstein, Ste. Foy, Quebec, G1V 4C7.

Dr. P. Dillon, OME Research Station, POB 39, Dorset, Ontario, P0A 1E0.

Dr. R. Hecky, Freshwater Institute, 501 University Crescent, Winnipeg, Manitoba, R3T 2N6.

Dr. R. A. Ryder, RAR and Associates, Thunder Bay, Ontario, P7B 5E4.

Dr. P. G. Sly, Director Science Program, Rawson Academy of Aquatic Science, Ottawa, Ontario, K1A 7B7.

Dr. R. L. Thomas, Director, Great Lakes Institute, University of Windsor, Ontario, N9B 3P4.

ATTACHMENT 4

GUIDELINES FOR REVIEW

GUIDELINES FOR REVIEW

We have been asked to keep our review closely relevant to the interests of MEND and the need to achieve/maintain environmentally acceptable conditions during and after subaqueous disposal. Our comments and recommendations should avoid excessive detail or curiosity-related issues unless there is a good reason to address them.

However, given the need to establish the validity of the concepts underlying subaqueous disposal of tailings, I think we may assume that a pragmatic approach will require us to present conclusions that are BEYOND REASONABLE DOUBT. Also, as a "most sensitive use" we should consider that it is intended to achieve/maintain ambient water quality suitable for a local fishery (recreational or subsistence). The fishery could be largely dependent on the natural reproduction of native species, and contaminant levels in fish tissue should not exceed guidelines for unlimited consumption (this, of course, refers to contaminants associated with the tailings).

Bear in mind the eventual need to develop predictive models of one sort or another, as the basis for constructing/manipulating ponded areas and the need to address the physical, chemical and biological aspects of various forcing functions and environmental response (largely in terms of the chemistry of open water and interstitial water, and the uptake and bioaccumulation of metals within the food-web). Therefore, processes like bed erosion, bioturbation, and benthic irrigation, for example, shouldn't be ignored.

After reading through the accompanying documents, the Terms of Reference and these guidelines, I would like each reviewer to make a rough list of the weaknesses and gaps in the material contained in the documents. I already have a similar "grab-bag" and I'll circulate copies of these rough lists to everyone so that, as far as possible, we catch all the important points to address, quickly. I suggest that each of you wait to do the detailed review until after receiving the rough lists. Doug Hyde or I will call each reviewer for their list mid-January (hopefully).

It will be my job to prepare the draft and final contract reports , the first of which will form the basis of discussions during the joint meeting between ourselves and the MEND Team. I plan to prepare an overview/synthesis of all your comments and to provide copies of each of your comments as attachments. Therefore, it will be most helpful if you would reference you detailed comments to each document (as listed in attachment 3) by page and

paragraph (number from top down). You can reach the Academy by phone/fax, mail, or E-mail (Compuserve 73220, 2304), and although we have a Mac. environment we can accept/prepare DOS in large/small disks, in ASCII, or WP 4.8-5.1; MS Word or DOS text in ASCII and on 3.5" diskette is prefered. I am also prepared to receive some specific comments written over copies of the document pages, for example on figures/graphs if they can be read, but I would prefer text.

I would like to prepare our response in two parts. Part I should address Objective 1 of the Terms of Reference (summarized as point 1 in my covering letter). This review should address each of the following six topics, separately, with reference to each of the documents as appropriate:

1) The conceptual basis for subaqueous disposal of tailings and the identification of environmental issues and concerns;

2) The literature review;

3) The proposal for studies on the effects of "Underwater Disposal of Waste Rock and Tailings";

4) Background limnologies of case-study lakes (Buttle, Anderson, and Mandy);

5) Field studies and analytical work;

6) Overviews and conclusions (those which are contained in the above documents);

Part II of the report will address objective 2 of the Terms of Reference which is summarized as point 2 in my covering letter. For this, please prepare comments and recommendations which relate to the following topics (specifically, what is needed and how to get it):

7) Scope and detail of the literature review;

8) Re-definition of hypotheses and/or addition of alternative hypotheses to be assessed;

9) Background limnological data;

10) Field data;

11) Laboratory data;

12) Other.

The Terms of Reference provide a number of very useful pointers, with respect to both general and more specific items that need to be addressed. However, at this point I do not intend to list everything else I can think of that ought to be addressed. Rather, I leave it to you to decide what points you wish to address. I expect that each reviewer will make both general and specific comments. For example, it's clear that much of the background limnological information is inadequate; I hope that in addition to such comments each of you would be reasonably specific about what essential information are required (perhaps thinking in model terms as was done for the lakeshore capacity studies, or some other approach).

If you feel I should change or add to these guidelines please say so, as soon as possible.

ATTACHMENT 5

ATTENDEES, MARCH 10TH MEETING CCIW BURLINGTON.

Attendees at joint Science Review Team - MEND-Team meeting, Canada Centre Inland Waters, Burlington, Ontario, L7R 4A6, Tuesday, March 10th, 1992.

NAME	ORGANIZATION	PHONE
Peter Sly	Rawson Academy, Ottawa	613-563-2636
Gilles Tremblay	CANMET/MEND, Ottawa	613-992-0968
George Hope	LAC Minerals, Toronto	416-777-2375
Jim Robertson	Placer Dome, Vancouver	604-661-1557
Dick Ryder	RAR and Assocs., Thunder Bay	807-983-2106
Wayne Fraser	Hudson Bay Mining, Manitoba	204-687-2171
Alena Mudroch	DOE-NWRI, Burlington	416-336-4707
Rod Allan	DOE/NWRI, Burlington	416-336-4678
Peter Campbell	INRS-Eau, Quebec	418-654-2538
Peter Dillon	Ont. MOE, Dorset	705-766-2418
Mike Sudbury	Falconbridge (MAC), Toronto	416-863-7276
Mike Filion	Teck Corp., Vancouver	604-687-1117

ATTACHMENT 6

RECOMMENDED REFERENCE MATERIALS.

This attachment lists three recent publications which provide major sources of reference material. They cover (1) the classification and structure of lake habitat and biological systems, (2) biological availability of metals in sediments, and (3) the biological monitoring of heavy metals in sediments. In addition, two short reference lists cover recent additions to the literature from Dr. Campbell and colleagues at INRS-Eau (Quebec), and staff of the National Water Research Institute (NWRI, Burlington). Original documentation (publications 1, 2 and 3, above) has been provided to the MEND Secretariat.

Documentation

(1) Busch, W.-D.N., and P. G. Sly (Eds) 1992. The development of an aquatic habitat classification system for lakes. C.R.C. Press Inc. (In press). [Specifically, see contributions: "A review of lake habitat classification" by J.H. Leach and R.C. Herron, and "Biological measures having possible application to the classification of the aquatic habitat in the Great Lakes: A review" by W.G. Duffy, R.T. Oglesby, and J.A. Reckahn].

(2) Campbell, P. G. C., A. G. Lewis, P.M. Chapman, A.R. Crowder, W.K. Fletcher, B. Imber, S.N. Luoma, P.M. Stokes, and M. Winfrey, 1988. Biologically available metals in sediments. National Research Council of Canada, Publ. No. NRCC 27694. Ottawa.

(3) E.V.S. Consultants Ltd. 1990. Literature review for biological monitoring of heavy metals in aquatic environments. Unpub. Rept. for Energy Mines and Resources Canada, and B.C. Ministry of Energy, Mines and Petroleum Resources, under the Canada/B.C. Mineral Development Agreement. E.V.S. Consultants, North Vancouver, B.C., V7P 2H4.

Recent Publications by Dr. Campbell and Colleagues Dealing, Largely With Partitioning

Belzile, N., R. DeVitre, and A. Tessier, 1989. *In situ* collection of diagenetic iron and manganese oxyhydroxides from natural sediments. Nature, 340: 376-377.

Campbell, P.C.G., and P.M. Stokes, 1985. Acidification and toxicity of metals to aquatic biota. Can. J. Fish. Aquat. Sci., 42: 2034-2049.

Campbell, P.C.G., and A. Tessier, 1987. Current status of metal speciation studies. In Patterson, J.W., and R. Passino (Eds), Metals speciation, separation and recovery. Lewis Publs. Inc., M.I., 201-224.

Campbell, P.C.G., and A. Tessier, 1987. Metal speciation in natural waters: Influence of environmental acidification. In Hites, R.A., and S.J. Eisenreich (Eds), Sources and fates of aquatic pollutants. Advances in Chemistry Series No. 216., Amer. Chem. Soc., 186-207.

Campbell, P.C.G., and A. Tessier, 1989. Biological availability of metals in sediments: analytical approaches. Proc. Internat. Conf. Heavy Metals in the Environment. Geneva, September 11-15, 1989. Vol. 1, pp 516-525.

Carigan, R., F. Rapin and A. Tessier, 1985. Sediment porewater sampling for metal analysis: A comparison of techniques. Geochem. Cosmo. Acta., 49: 2493-2497.

Hare, L., P.G.C. Campbell, A. Tessier, and N, Belzile, 1989. Gut sediments in a burrowing mayfly (*Ephemeroptera, Hexagenia limbata*): their contribution to animal trace element burdens, their removal, and the efficiency of a correction for their presence. Can. J. Fish. Aquat. Sci. 46: 451-456.

Hare, L., E. Saouter, P.G.C. Campbell, A. Tessier, F. Ribeyre, and A. Boudou, 1991. Dynamics of cadmium, lead and zinc exchange between nymphs of the burrowing mayfly *Hexagenia rigida* (*Ephemeroptera*) and the environment. Can. J. Fish. Aquat. Sci. 48: 39-47.

Hare, L.A., A. Tessier, and P.G.C. Campbell, 1991. Trace element distributions in aquatic insects: variations amoung genera, elements, and lakes. Can. J. Fish. Aquat. Sci. 48: 1481-1491.

Rapin, F., A. Tessier, P.C.G. Campbell, and R. Carigan, 1986. Potential artifacts in the determination of metal partitioning in sediments by a sequential extraction procedure. Environ. Sci. Technol., 20: 836-840.

Tessier, A., and P.G.C. Campbell, 1988. Comments on the testing of the accuracy of an extraction procedure for determining the partitioning of trace metals in sediments. Analyt. Chem. 60: 1475-1476.

Tessier, A., and P.G.C. Campbell, 1988. Partitioning of trace metals in sediments. In Kramer, J.R., and H.E. Allen (Eds), Metal speciation: Theory, analysis and application. Lewis Publs. Inc., M.I., 183-199.

Tessier, A., and P.G.C. Campbell, 1991. Comment on Pitfalls of sequential extractions. Wat. Res. 25: 115-117.

Recent Publications by Staff From the National Water Research Institute on the Impact of Mining Activities

PAST AND ONGOING RESEARCH AT THE NATIONAL WATER RESEARCH INSTITUTE INTO THE IMPACTS OF THE MINING INDUSTRY ON AQUATIC ENVIRONMENTS

NWRI Contribution 92-50

R.J. Allan, T.A. Jackson, S. Joshi, A. Mudroch,
J. Nriagu and T. Reynoldson

1. A.I.T. 1989. Metals and Metalloids in the Hydrosphere; Impact through Mining and Industry, and Prevention Technology in Tropical Environments. Pub. Asian Institute of Technology, Bangkok, 191 pp.

2. Allan, R.J. 1974. Metal contents of lake sediment cores from established mining areas: and interface of exploration and environmental geochemistry. Geol. Surv. Canada Paper 74-1B:43-49.

3. Allan, R.J. 1975. Natural versus unnatural heavy metal concentrations in lake sediments in Canada. International Conf. on Heavy Metals in the Environment, p. 785-808.

4. Allan, R.J. 1979. Heavy metals in bottom sediments of Great Slave Lake (Canada) - a reconnaissance. Environmental Geology 3: 49-58.

5. Allan, R.J. 1988. Mining activities as sources of metals and metalloids to the hydrosphere. in Metals and Metalloids in the Hydroshpere, Impact Through Mining and Industry, and Prevention Technology. Technical Documents in Hydrology, Pub. UNESCO, Paris, p. 45-67.

6. Allan, R.J. and Mudroch, A. 1989. The impact of gold mining on Canadian aquatic environments and remedial options. In Metals and Metalloids in the Hydrosphere, Impact Through Mining and Industry, and Prevention Technology in Tropical Environments. Pub. Asian Institute of Technology, Bangkok, p. 47-62.

7. Arafat, N. and Nriagu, J.O. 1986. pH-induced release of metals from polluted lake sediments Water, Air and Soil Pollut. 31:991-998.

8. Carignan, R. and Nriagu, J.O. 1985. Trace metal deposition and mobility in sediments of two lakes near Sudbury, Ontario. Geochim. Cosmochim. Acta 49:1753-1764.

9. Carignan. R. and Rosa. F. 1990. Measurements of in situ apparent diffusion coefficients at the sediment-water interface of Lake Erie sediments. CCIW report, 31 p.

10. Jackson, T.A. 1978a. The biogeochemistry of heavy metals in polluted lakes and streams at Flin Flon, Canada, and a proposed method for limiting heavy metal pollution of natural waters. Environ. Geol. 2:173-189.

11. Jackson, T.A. 1978b. A biogeochemical study of heavy metals in lakes and streams, and a proposed method for limiting heavy-metal pollution of natural waters [extended abstract]. Verhandl. Internat. Verein. Limnol. 20:1945-1946.

12. Jackson, T.A. 1979. Relationships between the properties of heavy metals and their biogeochemical behavior in lakes and river-lake systems. In Management and Control of Heavy Metals in the Environment (Proc. Internat. Conf., London, England, Sept., 1979), publ. by CEP Consultants Ltd., Edinburgh, Scotland, p. 457-460.

13. Jackson, T.A. 1984. Effects of inorganic cadmium, zinc, copper, and mercury on methyl mercury production in polluted lake sediments. In Nriagu, J.O. (ed.), Environmental Impacts of Smelters, John Wiley & Sons, p. 551-578. [Invited contribution].

14. Jackson, T.A. 1989. Ingibitory and stimulatory effects of Cu, Cd, Zn, Hg, and Se on microbial production of methyl mercury in sediments. In Vernet, J. P. (ed.), 1989 Heavy Metals in the Environment, vol. 1, p. 65-68. Publ. by CEP Consultants Ltd., Edinburgh, Scotland.

15. Jackson, T.A. and Klaverkamp, J.F. 1991. Heavy metal speciation and its biological consequences in lakes polluted by smelter fallout. Abstract, 2nd Internat. Symposium on Environmental Geochemistry (Uppsala, Sweden, 1991): In press.

16. Joshi, SR.. and Waite, D.T. and Platford, R.F. 1989. Vertical Distribution of Uranium Mine Tailings Contaminants in the Langley Bay, Lake Athabasca Sediments. Sci. Total Environ. 87/88:85-104.

17. Klaverkamp, J.F., Harrison, S.E., and Jackson, T.A. 1989. Metal accumulation in sediments and fish from lakes near a base metal smelter in Flin Flon, Manitoba. Abstract, 10th Annual Meeting of Society of Environmental Toxicology and Chemistry (Toronto, Ontario, 1989), p. 177.

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