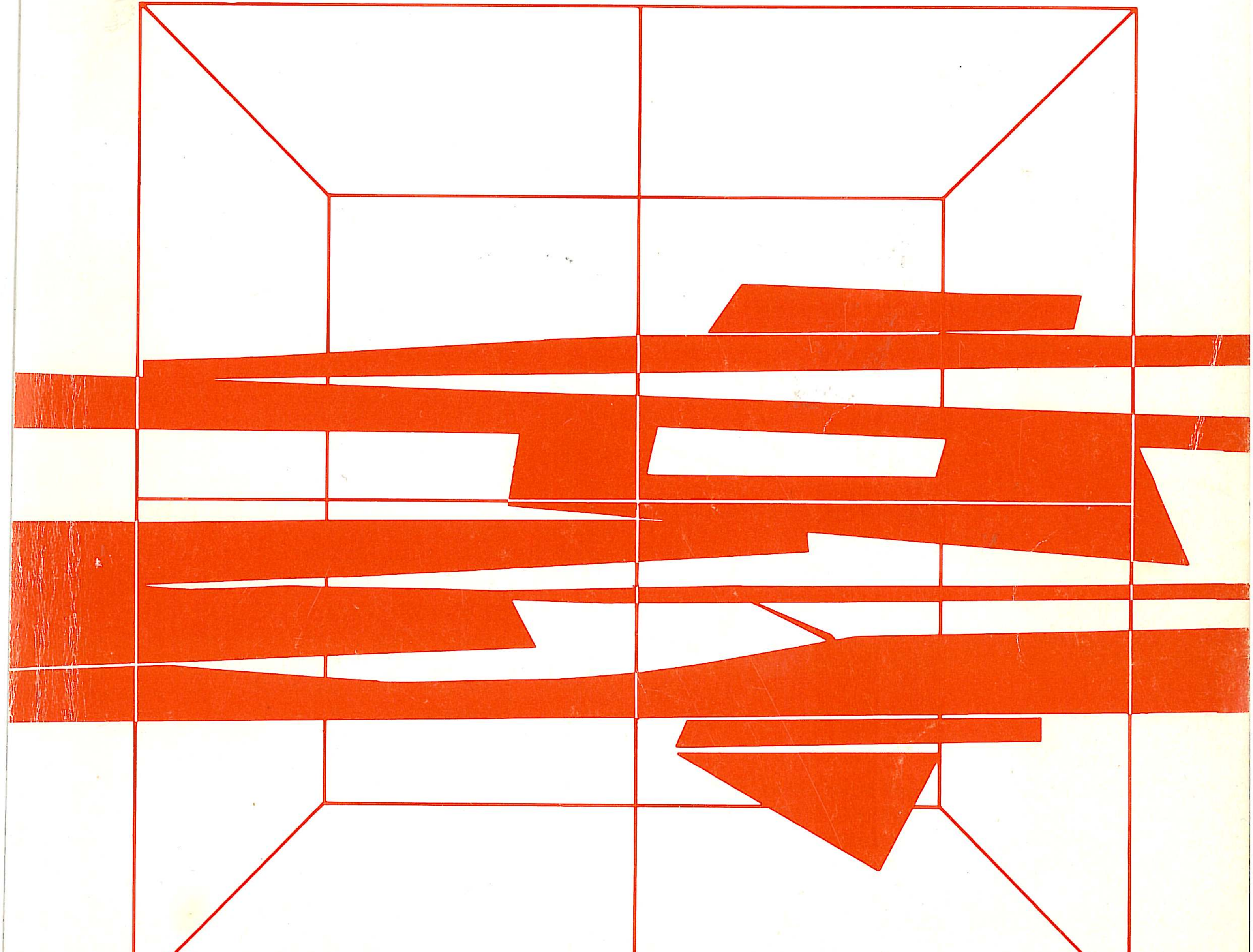
Long-term Ecological Behaviour of Abandoned Uranium Mill Tailings

3. Radionuclide Concentrations and Other Characteristics of Tailings, Surface Waters, and Vegetation

Report EPS 3/HA/4
February 1988



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LONG-TERM ECOLOGICAL BEHAVIOUR OF ABANDONED URANIUM MILL TAILINGS

3. RADIONUCLIDE CONCENTRATIONS AND OTHER CHARACTERISTICS OF TAILINGS, SURFACE WATERS, AND VEGETATION

by

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for

Environment Canada,
Atomic Energy Control Board
Energy, Mines & Resources Canada

Report EPS 3/HA/4
February 1988

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ABSTRACT

Physical and chemical characteristics of abandoned, or inactive, uranium mill tailings are compared with those of the mineralized nontailings environments. Concentrations of radionuclides and heavy metals in uranium tailings, nontailings mineral areas, vegetation, and surface waters have been measured. The differences between wetlands and terrestrial areas of the uranium tailings are described.

Concentrations of radionuclides and heavy metals in vegetation and surface waters from uranium mill tailings were generally lower. Uptake of radium-226 and lead-210 in cattail populations and trees (white birch and trembling aspen) appeared to be species-specific. Aerial deposition of tailings on the above-ground leafy matter of trees did not seem to affect their radionuclide concentration. In the wetlands on uranium tailings, radionuclide and heavy metal concentrations in cattail litter suggest that the litter acts as a sink for these elements. The concentrations of the contaminants in surface waters on uranium tailings are not much different from those in waters on control nontailing areas.

RÉSUMÉ

On étudie les caractéristiques physiques et chimiques de l'environnement à des dépôts abandonnés ou inutilisés de résidus d'extraction de l'uranium et dans des zones minéralisées non associées à de tels résidus (zones tampons). Les concentrations de radionucléides et de métaux lourds ont été mesurées aux emplacements des dépôts, dans les zones minéralisées tampons, ainsi que dans la végétation et les eaux de surface. On décrit les différences observées entre les zones humides et les zones terrestres des dépôts.

Les concentrations de radionucléides et de métaux lourds dans la végétation et les eaux de surface étaient généralement plus faibles aux emplacements des dépôts. Les caractéristiques d'incorporation du radium-226 et du plomb-210 dans les populations de quenouille et les arbres (bouleau à papier et peuplier faux-tremble) semblaient varier selon l'espèce. Les retombées de résidus sur le feuillage des arbres ne semblent pas avoir eu d'effets sur les teneurs en radionucléides de ceux-ci. Dans les zones humides des dépôts de résidus, les concentrations de radionucléides et de métaux lourds dans la litière de quenouille semblent indiquer que celle-ci agit comme un piège pour ces éléments. Les concentrations des contaminants dans les eaux à la surface des dépôts ne différaient pas de façon importante de celles qui ont été mesurées dans les eaux des zones témoins.

FOREWORD

Environmental contamination with radioactivity is a continuous public concern. Previous studies in this series related to identification of invading biota on abandoned, or inactive, uranium mill tailings (Phase I) and sustenance of the biota that were present there (Phase II). The present investigation looks at the radionuclides and heavy metals that have been taken up by the prevalent biota and their fate/pathway in the ecosystem. It is hoped that the results of this study will be useful for scientists, managers, regulators, and environmentalists alike.

The research was carried out under contract by Margarete Kalin, formerly of the University of Toronto. Funding for the project was jointly provided by the Atomic Energy Control Board, Environment Canada, and Energy, Mines and Resources Canada.

Water Quality Branch
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It was a challenging task indeed to assemble the information collected over 4 years into a data base, and I am indebted to many people who assisted over the years. My foremost thanks are due to Martin P. Smith, who with his dedication to detail, sense of organization, and programing skills produced the data base, the foundation of this report, and assisted in the data analysis. I thank Katherine Frerot for entering about 5000 data records into the computer and Margarete Chan for typing a never-ending string of tables, as well as the manuscript. Finally, I am grateful to Mary Olaveson, whose assistance was invaluable during the production of this report.

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SUMMARY

Inactive or abandoned uranium mill tailings in the two uranium producing provinces of Canada, Ontario and Saskatchewan, have been studied to obtain information on some of the parameters that will enable predictions to be made about possible pathways for long-lived radionuclides to enter the surrounding environment. Populations of the major indigenous plant species that colonize these waste sites were identified. Cattail stands on wet areas and trembling aspen and white birch colonies on dry areas were found to be typical of tailings sites.

Physical and chemical data describing the surface (0 to 25 cm depth) of the uranium tailings and the associated surface waters, i.e., waters on the tailings, as well as seepages leaving the area, were collected over a period of 4 years. Along with this information, biological data on the indigenous vegetation growing on the tailings were collected and are summarized in this report.

A comparison of physical factors (moisture content, organic matter content, pH, and electrical conductivity) and chemical factors (elemental and radionuclide concentrations) of the tailings surface from three tailings sites (Bancroft, Elliot Lake, and Uranium City) with soils from nearby control areas is presented. Similar physical and chemical characteristics were determined for surface waters and the results from these analyses are compared with those derived from leachate solutions from the root-zone depths of the tailings. Terrestrial and wetland vegetation are analyzed for radionuclide concentrations in different parts of the plants (e.g., leaves, stems, rhizomes, and roots). Composite samples of above-ground biomass and associated litter accumulations were also analyzed.

The tailings characteristics reported are from four abandoned, unreclaimed uranium tailings sites in the Bancroft area (25 ha); six inactive, revegetated sites in the Elliot Lake area (248 ha); and two abandoned sites in the Uranium City area (76 ha). All of the investigated sites are one to two decades old.

Tailings. The moisture content in the root zone in terrestrial tailings areas is slightly higher than at the surface (0 to 5 cm depth). In wetland areas of tailings, the organic matter content is higher than in the terrestrial tailings areas. Wet areas on tailings are generally neutral to alkaline, with pH differences of 0.5 to 1 unit. Dry areas exhibit a larger range of pH values, e.g., from 2.7 to 7.0 for the Elliot Lake area and from 5.2 to

9.0 for the Uranium City area. The Bancroft tailings exhibit a smaller range in surface pH values, ranging from 4.0 to 5.5. The ionic strength (expressed as electrical conductivity) of tailings slurries is generally higher than that of control soils, but values encountered in inactive or abandoned uranium tailings are lower, compared with base-metal tailings.

The concentration ranges of long-lived radionuclides radium-226 and lead-210 were the same order of magnitude in the surface of the tailings as those reported as being typical for mineralized areas. The mean concentration of radium-226 ranged from 41 to 69 pCi/g (1517 to 2553 mBq/g) in the tailings, with minimum values of <1 pCi/g (<37 mBq/g) and maximum values of 281 pCi/g (10 397 mBq/g). For lead-210, the mean concentrations ranged from 20 to 67 pCi/g (740 to 2479 mBq/g), with minimum values of <1 pCi/g (<37 mBq/g) and maximum values of 366 pCi/g (13 542 mBq/g). The concentrations of both radionuclides were found to be highest in the Uranium City tailings, followed by those in the Bancroft and Elliot Lake areas. The mean uranium concentrations determined for the tailings are in the same range as those determined in mineralized areas and are generally higher in wetlands with higher organic matter than in dry areas.

The metals cobalt, copper, and nickel, for both wetland and terrestrial areas on tailings, are present within ranges quoted in the literature. Lead concentrations could be considered to be slightly elevated in isolated locations. However, these metal concentrations determined in uranium tailings are below the ranges reported for base-metal tailings.

Concentrations of Group II elements (barium, calcium, and magnesium) in tailings are used to differentiate the Bancroft tailings from those of Elliot Lake. Different concentrations are also noted for wet and dry areas of the tailings. Furthermore, concentrations of other elements (e.g., aluminum, chlorine, manganese, and sodium) are also reported.

Surface Waters on Tailings. The pH of the surface waters on tailings exhibits a large range of values (1.8 to 9.8). The range is due to neutralization of surface waters. In general, the surface waters of the Elliot Lake tailings and Nero Lake (Uranium City area) are acidic, whereas the Bancroft tailings waters are neutral to alkaline. The electrical conductivity of the surface waters is within the same order of magnitude for all tailings areas investigated and is similar to the nontailings locations, with a mean range from 750 to 2833 μmhos/cm (750 to 2833 μS/cm).

Radium-226 concentrations in nontailings locations and in surface waters on tailings range from <1 to 867 pCi/L (<37 to 32 079 mBq/L) and <1 to 177 pCi/L (<37 to 6549 mBq/L) respectively. This suggests that elevated radium concentrations can be localized on tailings as well as in natural areas of mineralized regions. The tailings surface waters of the Bancroft area had higher radium concentrations than those of Elliot Lake or Uranium City. Lead-210 concentrations in surface waters are higher in the Elliot Lake tailings areas than those in the Bancroft and Uranium City areas. The concentrations of lead-210 in individual samples ranged from <1 to 276 pCi/L (<37 to 10 212 mBq/L) in the tailings areas and from <1 to 203 pCi/L (<37 to 7511 mBq/L) in nontailings areas. These ranges were similar to the large ranges encountered for radium-226. Uranium concentrations in surface waters were one order of magnitude higher than those reported for nonmineralized areas. However, the concentrations in nontailings locations sampled in this investigation were within the same range as those in the waters on the tailings, with 0.01 to 94 mg/L for the tailings waters and 0.0002 to 6.0 mg/L for the nontailings waters.

The mean concentrations of copper, nickel, and lead in surface waters on the tailings are within recommended water quality concentrations for surface waters used as raw public water supplies, with mean concentrations of 0.5 mg/L for copper, 0.25 mg/L for nickel, and 0.25 mg/L for lead. The concentrations of Al, Ba, Ca, Mg, and Mn, as well as their detection limits, are also reported.

Trees and Wetland Vegetation Growing on Tailings. Aerial deposition of radium-226 and lead-210 from windblown tailings, and particulate matter on the leaves of white birches, did not contribute to the concentrations on the vegetation based on a comparison of washed and unwashed leaf material. The concentrations of radium-226 and lead-210 were found to be higher in white birches growing on tailings than in trembling aspens. The distribution of radium-226 and lead-210 differed within white birches; radium-226 concentrations were higher in the leaves than in the stems, whereas the reverse appeared true for lead-210. Such compartmentalization of radionuclides within the cattails from wetland sites was not observed. The rhizomes of the cattails appeared to present a barrier to radionuclide transport from the tailings into the upper portions of the plants. Uranium concentrations tended to be low in most vegetation samples analyzed.

These results clearly suggest that the uptake of radionuclides by plants is a species-specific phenomenon and cannot be related to the physical and chemical conditions of the tailings sites per se.

UNITS OF MEASUREMENT

In this report, older units of measurement have been used to be consistent with the previous two reports in this series. Presently in Canada, however, the International System of Units (SI) is being used. Basic equivalent SI units are defined as follows:

Becquerel (Bq): A unit of measure of radioactivity corresponding to one disintegration (transformation) per second (dps).

1 Curie (Ci) is equal to 3.7×10^{10} dps, or Bq
1 pCi is equal to 37 mBq

Siemens (S): The siemens is the electrical conductance between two points of a conductor when a constant current of one ampere in the conductor produces a difference of potential of one volt between these two points and when the conductor itself is not the seat of any electromotive force.

1 mmhos/cm is equal to 1 dS/m

1 INTRODUCTION

1.1 Background

In Canada, uranium mining has been located mainly in the provinces of Saskatchewan and Ontario, where the total land disturbance, due to all mining activities, is estimated to be about 50 000 ha (Marshall, 1983). Of this disturbed land, 1100 ha (or 2.5 percent) can be attributed directly to uranium mining. Although this represents a rather small fraction of the total land disturbance and waste production, uranium wastes have received a disproportionate amount of environmental attention because they contain radioactive elements.

Uranium mining started in the mid-1930s when radium was the goal. It accelerated during and immediately after World War II, as a result of increasing interest in atomic energy, but experienced a major decline in the late 1950s. During this period, about 40 million tonnes of uranium tailings, which occupied about 300 ha, were produced. They are presently abandoned (not monitored) or inactive (still subject to regular monitoring) waste sites, predominantly in Ontario and Saskatchewan. Active producers have since generated about 100 million tonnes of tailings in Ontario and 30 million tonnes in Saskatchewan (NUTP, 1985), although the land area disturbed by recent production has not increased significantly because waste disposal methods have been improved. At present, it is estimated that about 10 million tonnes of uranium tailings are generated annually.

Disposal methods for wastes relating to the "back end" of the nuclear fuel cycle have been investigated extensively and are major issues of public concern in Canada and elsewhere (Aikin et al., 1977; Porter, 1978; Hincks, 1979). Uranium tailings, which are wastes created at the "front end" of the cycle, have also raised questions about potential environmental implications. About 15 percent of the total radioactivity contained in the ore is extracted during the production of "yellowcake" (uranium oxide); the remaining 85 percent goes in the waste as uranium mill tailings. Of this 85 percent, 15 percent is composed of short-lived radionuclides and the remaining 85 percent is long-lived radionuclides (IAEA, 1981).

Although the specific radioactivity in the mine tailings is low, concerns are raised mainly in relation to long-term environmental implications. These concerns originate from the changed location of the long-lived natural decay products previously contained in the ore underground. After the extraction of uranium, these finely ground tailings remain exposed at the surface where they are subjected to chemical changes. As a result, some of the components contained in the ore become potentially more available to the ecosphere. Furthermore, there are those concerns that are related to any nuclear issue, namely society's perception of environmental dangers and risks. The combination of all of these concerns requires that the same waste-management practices be applied to uranium tailings as are applied to all other nuclear wastes.

Radiological protection in Canada and internationally is based on the so-called ALARA (As Low As Reasonably Achievable, with social and economic factors taken into account) principle. This principle is also applied to the potential long-term implications of uranium mill tailings disposal to ensure the well-being of future generations in an acceptably healthy environment.

In the early 1980s, three uranium mines ceased operation: two in Ontario (Agnew Lake and Madawaska) and one in Saskatchewan (Beaverlodge). In each case, a site-specific decommissioning plan was implemented.

Decommissioning plans consist of two phases. The first is a short-term phase comprising the termination of active waste dumping and the establishment of a program to monitor all effluents and emissions in the passive waste management area. For several years, periodic monitoring is continued. Then, when the situation appears to be stable and satisfactory, the second phase is initiated. At this point, when all required adjustments have been made, monitoring is terminated and the waste site is closed using the best available technology.

While the above-mentioned operations are being finalized, further technical understanding of environmental processes is being accumulated, new information is being generated, knowledge is being refined, and improvements in the ability to predict the long-term consequences are being made. The uranium tailings that were decommissioned recently or those that were reclaimed and are considered inactive, as well as those that were earlier left abandoned to natural recovery, are subject not only to the ALARA principle but also to processes of nature that will inevitably affect the conditions of the waste-site environment and influence potential impacts of the wastes. Natural processes, especially those involving contamination of the food chain with long-lived radionuclides, must be predicted to assess any possible adverse environmental impacts in the future.

Predictions of changes that may affect the fate of contaminants in the environment are generally based on an understanding of the ecosystem, assisted by models of "pathways." The creation of such models requires detailed knowledge of the system; in this case, the specific ecosystem of the waste-site environment that will develop after decommissioning. Furthermore, to obtain reliable predictions and make valid judgements, realistic input and baseline parameters are required. These can be assumed for future systems and appropriate conclusions can be reached by making measurements on existing ecosystems. In this way, inactive or abandoned uranium tailings can be considered useful resources from which valuable information can be obtained to aid in predicting the long-term fate of contaminants from the tailings and the changes expected in the tailings environment.

The major portion (approximately 39 million tonnes) of the inactive or abandoned uranium tailings is located in three areas: (1) the Uranium City area in the Lake Athabasca region of northern Saskatchewan; (2) the Bancroft area of central Ontario; and (3) the Elliot Lake area of north-central Ontario. About 1.1 million tonnes are located in the Northwest Territories, originating mainly from the operations at Port Radium and, to a lesser extent, Rayrock.

The Port Radium uranium tailings, estimated at about 1 million tonnes, were deposited in the deep, cold waters of the McTavish Arm of Great Bear Lake. The short-lived operation of Rayrock Mines produced some 0.07 million tonnes, which cover approximately 14 ha of land. The tailings form a cover on a slope and some have been moved down into a small depression. They are underlain by muskeg in discontinuous permafrost.

In the Uranium City area, the Lorado operation produced about 0.5 million tonnes of tailings, most of which were discharged into Nero Lake. Investigations of the lake revealed that a dense cover of aquatic moss had invaded the bottom of the lake, effectively separating the tailings from the water and depriving them of oxygen (Kalin, 1982).

The tailings from the Port Radium and Lorado operations were fortuitously disposed of by the recently defined underwater method (UI, 1984), which proved to be very satisfactory. The tailings from both operations contain pyrite and, in the presence of oxygen, would generate acid, which is possibly the most serious potential environmental impact resulting from all methods of tailings disposal. Investigations have shown that acid generation has been curtailed effectively in both tailings-disposal sites by the combination of a moss cover and an overlying water layer (Kalin, 1982, 1984b).

In Saskatchewan, in addition to the tailings in Nero Lake and at the recently decommissioned site of the Beaverlodge operation in the Uranium City area, there are tailings from Gunnar Mines. Five million tonnes of tailings cover about 65 ha of land and form a small beach in a bay of Lake Athabasca.

In Ontario, in the Elliot Lake area, several tailings sites are inactive, where the surface has been reclaimed and the effluents are treated and monitored. None of these sites is considered abandoned and decommissioning procedures have yet to be defined. In the Bancroft area, two tailings sites are abandoned and one site has been decommissioned. Tailings sites that have been inactive or abandoned for one or more decades are present in all areas where uranium tailings are still being generated today. Investigations of these inactive or abandoned waste sites provide valuable technical and scientific information on the natural processes that affect these sites. This information will lead to a better understanding of the long-term environmental concerns and facilitate development of decommissioning plans for currently active sites.

1.2 Objectives

A research program was initiated that addressed the long-term ecological behaviour of abandoned and inactive uranium tailings areas in both uranium-producing provinces of Canada. The first task was to describe the ecosystems that had developed at these inactive or abandoned waste sites over the past two decades, and to determine which plant species are dominant and might be significant as potential pathways for long-lived radionuclides. Wetland plants growing in wet areas of the tailings and pioneering trees growing in dry areas were identified as the dominant natural colonizers of these waste sites, regardless of the reclamation measures that had been implemented at these inactive sites (Kalin, 1984a).

The second task was to determine if these populations would persist on the waste sites over the long term. It was found that some wetlands had reached an ecological equilibrium. Although tree growth was stunted and colonization was restricted to certain periods, the populations of invading tree species developed stable communities on terrestrial areas of the waste sites (Kalin and Smith, 1985).

The third task was to examine selected chemical aspects of these waste-site ecosystems and determine the concentrations of long-lived radionuclides in those components of the system that could contribute to aquatic and terrestrial pathways. The objective of this report is to summarize the information related to this third task.

2 DESCRIPTION OF STUDY AREAS, TAILINGS SITES, AND SAMPLE TYPES

2.1 Description of Study Areas

Map 1 illustrates the three uranium mining districts in which the inactive or abandoned uranium mill tailings sites examined in this study are located. The climate and surrounding flora of these regions influence the type of indigenous vegetation that eventually colonizes the tailings sites.

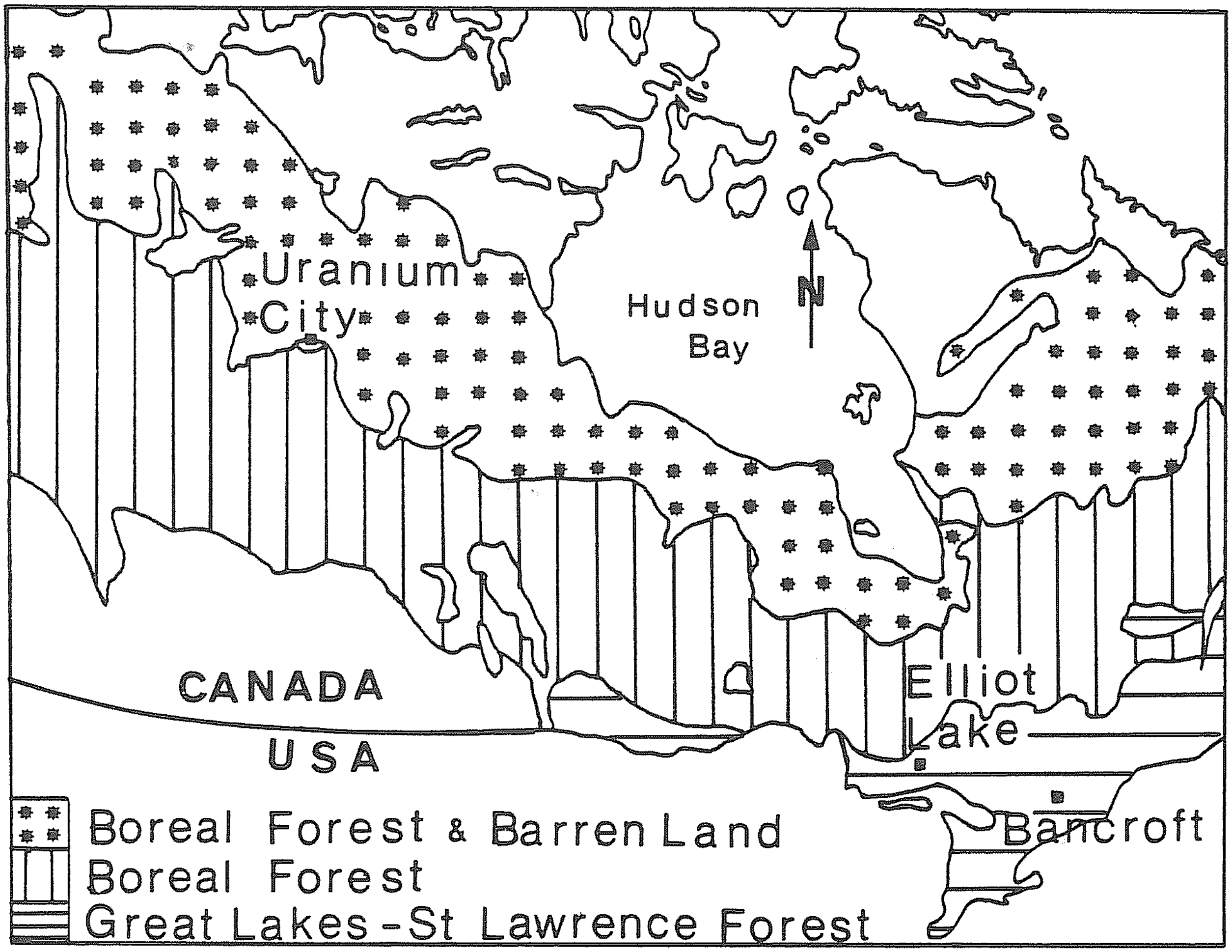
The climatic regimes of the three mining areas are different. The average annual precipitation is 879.8 mm for Bancroft, 926.3 mm for Elliot Lake, and 354.1 mm for Uranium City. The Uranium City area receives significantly less precipitation than either Bancroft or Elliot Lake. Furthermore, approximately half of the precipitation at the northern Saskatchewan site falls as snow, compared with about one-third for the Ontario sites.

The period available for plant growth in the three areas also differs. The growing season is shortest in the Uranium City area and longest in the Bancroft area (Atmospheric Environment Service, 1971a,b).

The Bancroft area in central Ontario is characterized by mixed deciduous-coniferous forest, referred to as the Great Lakes - St. Lawrence forest region. The forest of this area is transitional between the boreal forest to the north and deciduous forest to the south. Elliot Lake is in north-central Ontario, still within the Great Lakes - St. Lawrence forest region, but much closer to the southern limits of the boreal forest. The boreal and mixed deciduous-coniferous forests are characterized by different tree species. The dominant trees in the boreal forest region are coniferous species, whereas there is a higher proportion of deciduous trees in the Great Lakes - St. Lawrence forest region (Scudder, 1980). The Uranium City mining area is located on the north shore of Lake Athabasca. The sites are surrounded by boreal forest, a mosaic of woodlands, and barren country.

2.2 Description of Inactive or Abandoned Uranium Tailings Sites

In the early 1960s, many uranium operations in the provinces of Saskatchewan and Ontario ceased discharging tailings slurries. Some tailings sites were completely "abandoned" at that time and have not been revegetated. Other sites, which were associated with operating uranium producers, have been improved and revegetated and are, therefore, considered as "inactive" sites that are still being maintained and monitored.



MAP 1 STUDY AREAS AND FOREST REGIONS OF CENTRAL CANADA

All mills grind the uranium ore to a particle size of approximately 50 percent under 200 mesh and use a sulphuric acid leaching process to extract the uranium (Griffith, 1967). The tailings slurries were generally neutralized before discharge in most operations, with the exception of slurries from the mills in the Uranium City area.

In Elliot Lake, because of the pyrite content of the ore, the tailings generate acid when oxygen and moisture are present, in contrast to those of the Bancroft area, which result in alkaline wastes. The abandoned tailings in the Uranium City area are located at two sites - at Gunnar, where they are alkaline, and at Lorado where they are acidic. However, the latter were discharged into Nero Lake and only a small area of tailings lies exposed on the shore. Therefore, Nero Lake was investigated only as an abandoned aquatic waste site.

TABLE 1 SITE HISTORY AND DESCRIPTIONS OF ABANDONED OR INACTIVE URANIUM MILL TAILINGS

Site Name	Dry Surface Area (ha)	Years of Operation	Year Reclamation Initiated	Estimated Area with Vegetation (percent)	Habitat Present	
					Terrestrial	Wet
<u>Bancroft Area</u>						
Madawaska no. 2	16	1957-1964	1978	90	X	-
Auger Lake	2	1957-1963	Unamended	70	-	X
Bicroft Proper	4	1956-1957	Unamended	50	X	X
Dyno	3	1957-1960	Unamended	90	X	X
<u>Elliot Lake Area</u>						
Williams	2	1959	1976	100	X	-
Nordic	101	1957-1968	1970	80	X	-
Stanleigh/Milliken*	53	1957-1964	1970	-	X	X
Stanrock Main	63	1958-1964	1978	40	X	X
Olive	5	1958-1959	1977	80	X	X
Lacnor	24	1957-1960	1978	60	X	X
<u>Uranium City Area</u>						
Gunnar Main	45	1955-1964	Unamended	60	X	-
Langely Bay	11	1959-1964	Unamended	60	X	X
Gunnar Central	12	1955-1964	Unamended	70	X	-
Nero Lake	8	1957-1960	Unamended	-	-	X

Source: modified after Kalin and Caza (1982)
* reactivated in 1982

The histories of the inactive or abandoned tailings sites and some relevant surface characteristics are summarized in Table 1. The surface area, which was evaluated during the course of these investigations, includes the majority of inactive tailings areas in Canada. The Elliot Lake camp has the largest accumulation of uranium tailings and, because of current production, will probably remain in this position. The Stanleigh/Milliken tailings area has been reopened since 1982, but data from the terrestrial and wetland tailings areas from the previous operations were also collected from this site during the present study.

The periods of operation at all three sites were similar due to the uranium "boom" in the mid-1950s, which resulted from the expected high demand for nuclear energy production. By the mid-1960s, many uranium mining operations were suspended because of the oversupply of uranium and the increasing public concern about nuclear energy. All of the Elliot Lake tailings sites received some form of reclamation from reclamation programs initiated in the early to mid-1970s. Reclamation practices improved as a result of continued research and increased experience, which led to the successful establishment of an introduced vegetation cover at most inactive tailings sites.

In the Bancroft and Uranium City areas, the abandoned tailings sites are not acidic, in contrast to those in the Elliot Lake area, so natural colonization has taken place. Tailings areas, such as Dyno and Madawaska no. 2, where sufficient moisture was present, had virtually complete indigenous cover. Of interest, however, is the fact that nearly all inactive or abandoned tailings areas, whether reclaimed or colonized naturally, have both wetland and terrestrial ecosystems developing or established on their surfaces. The exact location of the sites and detailed descriptions of site surfaces with indigenous and introduced vegetation have been reported earlier (Kalin, 1982, 1983).

The inactive or abandoned uranium tailings summarized in this report represent all but two abandoned Canadian sites, those of Port Radium and Rayrock in the Northwest Territories. Those sites have been investigated and their characteristics reported (Kalin, 1984b,c). In the case of Port Radium, the uranium tailings were deposited offshore during the period of operation. The tailings from Rayrock covered a small area as the operation lasted for only a short time. Neither of these sites has been included in the present evaluation.

2.3 Description of Control Sites

The wetland and terrestrial control sites were located at least 200 m away from roadsides to minimize or prevent possible dust contamination. Disturbance of the control sites by beavers and/or hunters could not be prevented. The locations of all study sites in the Elliot Lake and Bancroft areas are shown in Kalin (1983, 1984a).

For the wetlands, three control sites were selected in the Elliot Lake area and two in the Bancroft area. No wetland control sites were investigated in the Uranium City area.

The terrestrial control sites for the collection of trees were established in such areas as gravel pits, roadsides, and open fields. At these locations, colonization occurred after a local disturbance, e.g., earth movement due to construction or quarry activities.

Not all of the control sites selected received amendments; thus, they represent a natural colonization sequence of disturbed nontailings environments. The exact locations of these control sites are reported in Kalin (1983).

2.4 Description of Sample Types Collected and Analyzed

This report contains descriptive data on water, solids (tailings or soil), and vegetation derived from studies on inactive uranium mill tailings in Elliot Lake, Bancroft, Uranium City, and various control areas. Control samples were collected from the same geographical areas as the uranium tailings samples. The samples are of the same types, but are from nontailings environments. Thus, the characteristics of these control samples reflect natural concentrations in areas with uranium mineralization, in contrast to those samples collected directly from uranium mill tailings.

Table 2 summarizes, by area, the total number of samples of surface waters, leachate solutions, vegetation samples, and solids (either tailings or soils) that were collected from the wetland and terrestrial regions of each of the study areas.

TABLE 2 SUMMARY OF SAMPLE TYPES COLLECTED

Area	Sample Type	Number of Samples
Bancroft	Water	50
	Leachate	12
	Vegetation	101
	Tailings	74
Elliot Lake	Water	71
	Leachate	25
	Vegetation	165
	Tailings	132
Uranium City	Water	53
	Leachate	45
	Vegetation	59
	Tailings	100
Control Sites	Water	63
	Leachate	16
	Vegetation	117
	Soil/sediment	60

The surface water sample was taken from ponds or creeks located on the tailings. It would always be the part of a water column in which biological activity is possible, i.e., where light penetration is sufficient for primary productivity.

The leachate water sample was experimentally derived water. The tailings collected from around the root zone of the wetland and terrestrial plants were washed with distilled water. This tailings water slurry was leached for 48 hours and the resulting leachate was filtered and analyzed. These samples are intended to give an empirical indication of the solubility in water and, hence, bioavailability of the elements considered in the environmental pathway(s) from the tailings to the plants.

The vegetation sample consisted of above-ground biomass or vegetable matter, which was, in most cases, separated into the different components of the plants (i.e., leaves, fruits, stems), and below-ground biomass, which was separated into roots and rhizomes (below-ground stems).

The tailings or soil samples included those samples in which the vegetation collected for analysis was rooted. Generally, two samples were taken for each collection of a plant. One sample consisted of the first 5 cm and the second sample was associated with the root zone, i.e., the same material from which the leachate sample was derived.

3 METHODS

3.1 Field Methods

3.1.1 Sample Collection.

Tailings/soil. The tailings were collected with regard to the type of surface cover present. Bare tailings (i.e., tailings devoid of vegetation) and tailings associated with vegetation were sampled at the surface (0 to 5 cm) and in the root region (20 to 25 cm). The samples were collected using a hand trowel after a pit was excavated using a spade. Tailings directly associated with the root zone were collected by shaking the tailings or soil around the roots into a plastic bag or onto a cloth sheet.

Surface water. In the Elliot Lake and Bancroft areas, water was sampled three times during 1980: in March, before the runoff; in April or May; and in September. In March, samples were collected through a hole in the ice. Ice chips were removed from the hole and a water sampler on a stick was submerged to a depth of 1 m.

Water was collected from the uppermost layer of the water body to a depth of 1 to 1.5 m. Samples in deeper locations were collected using a "student" water sampler. Seepages from tailings and creeks running on the tailings were sampled directly into the collection bottles.

In the Uranium City area, sampling was carried out three times during 1981 in several locations in Nero Lake. Limnological measurements were taken for oxygen concentration, pH, and electrical conductivity profiles and light penetration. Oxygen profiles were obtained using a Y.S.I. Model 4 R.C. oxygen meter with a combined temperature and oxygen probe and automatic stirrer. Electrical conductivity profiles were determined using Y.S.I. Model 33 S.C.T. Light penetration was determined by secchi-disk readings. Water at each measurement depth was collected in a horizontal Van-Dorne sampler for pH determinations. Water for radiochemical and elemental analyses was collected from a depth of 2.5 m from each station and acidified immediately with concentrated nitric acid.

Terrestrial plants. Around the trees, plant associations and type of surface cover were described and/or collected. The height of the trees was measured, the trunk diameters were recorded, and part of the trunk was collected for age determination. The soil and the tailings were then removed from the roots of the trees and root morphology was recorded photographically. The roots were separated in the field from the stems and the leaves. Grasses from the Uranium City area were collected using a shovel. The exposed parts of the plants were protected from contamination during the excavation by a plastic bag. The roots and above-ground parts were separated immediately in the field.

Terrestrial vegetation - trees collected from a single site. A previously investigated stand of trees (Kalin and Smith, 1985) on the Stanleigh/Milliken site in the Elliot Lake area was selected for further study. The entire stand and its ground cover biomass were harvested and trees taller than 1 m were analyzed. These trees were cut either with clippers or a chain saw. The basal portion of each tree was collected and tagged for age determination.

In a 3000-m^2 area, surrounding the plot of 52 m^2 where all trees and biomass were harvested, trees with heights greater than 1 m were sampled for age, height, and ground cover biomass. A set of 45 trees, representing different heights of trembling aspen *(Populus tremuloides)* and white birch *(Betula papyrifera)* was selected from this area of the tailings for analysis.

Nontailings sites, with apparently similar poor growth conditions for trees, were chosen as control sites from which trees were collected for analysis. An abandoned gravel pit, without topsoil, which was populated with aspens and birches of heights similar to those on the tailings site, was sampled. This control site was located northeast of the town of Elliot Lake.

Terrestrial vegetation - trees collected from several sites. Individual white birches, about 1 m tall, were collected from sites where they were rooted in tailings in both the Bancroft and Elliot Lake areas. They were excavated using a spade and the above-ground portion was separated from the roots immediately in the field. The plant material was stored in plastic bags and transported in coolers.

Terrestrial vegetation - grass, herb, and shrub biomass. In the square metre surrounding each tree taller than 1 m, the above-ground vegetation was cut with clippers and separated into grass, shrub, and herb components. If moderate amounts of ground vegetation existed in the surrounding square metre, all of the biomass was collected and sorted into shrub, herb, and grass components.

Wetland plants. Cattails and sedges were excavated using a shovel and immediately separated into leaves, stems, seeds, roots, and rhizomes, with the latter two components being transported with the growth substrate (tailings or soil) intact. The collected materials were transported in coolers and were refrigerated upon arrival at the laboratory.

Cattail annual biomass and litter. All of the previously accumulated litter was removed from six quadrats (squares with sides of 1 m length) within the cattail stands. Only stands on the Bancroft and Elliot Lake sites were investigated. At the end of the growing season, exposed growth was harvested and separated into different vegetable components. No cattail stands were sampled in this manner at the Uranium City site.

3.1.2 Sample Preparation.

Tailings and soil. The entire grab sample was removed from the bag and emptied onto a sieve. Stones and other large objects were removed and the material was homogenized in a mortar. A subsample was then removed for analysis. Determinations of moisture content and loss-on-ignition (LOI) were made for most samples using approximately 5 g of homogenized material. When the sample had reached a dry point, approximately 1 g of the material was removed for atomic absorption spectrophotometry (AAS); 0.5 g was removed for neutron activation analysis (NAA); and 1 g was removed for radiochemical analysis (RCA). The remainder of the dried material was reweighed and ignited at 450°C for 4 hours. The ignited samples were then reweighed after cooling to determine loss-on-ignition.

Water. At each sampling location, 3 L of water were collected. One litre was filtered through 0.45 μm filter paper. The filtrate was acidified using concentrated nitric acid and retained for heavy metal and radionuclide analyses. The second litre was acidified without filtration to obtain total concentrations. Filtration was carried out within 6 to 8 hours after collection of the sample.

Vegetation. Samples of all vegetation components (terrestrial and wetland) were rinsed under tap water with pressure. The roots were scrubbed with a brush to ensure complete removal of particulates. The samples were then cut into small pieces and homogenized in a commercial blender. Certain plant parts required the addition of distilled water during blending. The samples were dried at 70°C in a drying oven until a constant weight was obtained. From a subset of trees, leaves and stems were analyzed without washing to determine aerial deposition on above-ground parts. Trees were pulverized using a Wiley mill.

3.2 Laboratory Methods

3.2.1 Analytical Methods. All sample types (water, vegetation, and soil/tailings) were analyzed by three methods: radiochemical analysis, atomic absorption spectrophotometry, and neutron activation analysis. Each analytical method produces total concentrations with analytical errors that vary for each sample type. Furthermore, each method has different detection limits. Therefore, values from samples in which the concentration was at or below the detection limits are reported as "less than or equal to" values. A concentration is reported when the analytical error is at least two times smaller than the determined value. This method of reporting data will facilitate a realistic comparison of the total concentrations of the sample set analyzed and an evaluation of the frequency at which concentrations below the detection limit are encountered. The detection limit is dependent on the analytical method used and on the composition of the sample matrix.

The radiochemical analyses were performed at the University of Waterloo for radium-226 and lead-210. The error at which a value is considered as an actual concentration for radiochemical analysis for both radium-226 and lead-210 in solids (e.g., tailings and soils), water, and vegetation has been set at 1 pCi/L (37 mBq/L) or 1 pCi/g (37 mBq/g) for both radionuclides. Results of radium-226 and lead-210 analyses yielded a concentration plus an error value unique to each sample that, depending on the background level, could be lower than 1 pCi (37 mBq). Details on the radiochemical procedures used have been published by Kalin (1981).

Atomic absorption spectrophotometry was carried out at the University of Toronto, Institute for Environmental Studies (for cobalt, copper, lead, and nickel). The detection limits for these metals vary both with the element and the sample type (Table 3). The atomic absorption spectrophotometry results gave a concentration or detection limit. Errors were calculated for each metal and each sample type.

The multielemental analysis by neutron activation analysis was carried out at the Slowpoke Reactor Facility, Department of Chemical Engineering, University of Toronto. An irradiation scheme to optimize the number of elements for which concentrations or detection limits could be obtained was tested for the three sample types. The irradiation parameters used were published in an earlier report (Kalin, 1983).

TABLE 3 DETECTION LIMITS FOR METALS ANALYZED BY ATOMIC ABSORPTION SPECTROPHOTOMETRY

Sample Type	Lead	Nickel	Copper	Cobalt
Water (mg/L)	<0.2	<0.008	<0.003	<0.007
Vegetation (μg/g)	<0.5	<0.2	<0.12	<0.2
Tailings/soils (μg/g)	<1.0	<0.4	<0.25	<0.4

Multielemental determinations in water, tailings/soil, and vegetation were carried out for the following elements: aluminum, barium, bromine, calcium, chlorine, cobalt, dysprosium, iodine, magnesium, manganese, sodium, strontium, uranium, and vanadium. The detection limits for the elements analyzed by neutron activation analysis vary with the sample type, the irradiation scheme, and the actual sample; hence, each value determined can have a unique detection limit. A sample has either a concentration or a detection limit for those elements analyzed by neutron activation analysis. The concentrations of the 14 elements are considered either as "less than" values (i.e., detection limits) or as concentrations for which analytical errors unique to the samples are determined. Error calculations and individual detection limits have been published previously by Kalin (1983).

All of the values determined were entered into the Statistical Analysis System (SAS), which facilitated evaluation of the data. The results are summarized in this report. The data base contains the location, time of sampling and all concentrations, detection limits, and errors for each sample analyzed during the research program. An evaluation of the data for inconsistencies and overall quality by the National Uranium Tailings Program found these to be of satisfactory quality (NUTP, 1985).

3.2.2 Determination of pH and Conductivity in Tailings and Soils. The pH of the tailings was measured in the field at wet locations by immersing the pH electrode in excavated pits where the samples had been collected. Many sampling locations were relatively close to the water table. The thixotropic tailings formed a slurry in which the determinations were carried out.

For dry tailings, the pH and conductivity had to be determined in the laboratory. A series of different solid/liquid ratios was tested for wet and dry tailings and cross-referenced with field determinations for each area (Elliot Lake, Bancroft, and Uranium City). A 1:1 slurry (solid/liquid) was prepared by combining 20 g (fresh weight) of tailings/soil with 20 mL of distilled water and mixing the solution with a vortex mixer. The slurry was allowed to sit for 30 minutes, after which time it was mixed again and the determinations were repeated. Both measurements were also recorded after the slurry had been allowed to stand for 24 hours at room temperature. The results of the ratio experiments are reported in the Appendix.

All pH measurements were made with an I.L. Portomatic pH meter (Model No. 175), using a Canlab gel combination electrode. Conductivity of the water and tailings is reported as electrical conductivity (µmhos/cm (µS/cm)) throughout this report.

3.2.3 Static Leaching Experiments. Tailings were removed from the root region of trees, cattails, and grass hummocks by washing the roots with distilled water. Samples had been collected from the same sources in the field. From the resulting slurry, a 500-mL subsample was removed and leached statically for 48 hours while being continuously stirred using a magnetic stirrer. The pH and electrical conductivity were determined after 30 minutes, 24 hours, and 48 hours. A Radiometer pH meter (Model PHM53), equipped with a Canlab combination electrode (Cat. No. H5503-30), was used for the pH determinations. Electrical conductivity was determined using a Hach conductivity meter (Model No. 17250).

The supernatant leach water was filtered through Whatman filter paper (numbers 1, 42, and 44) and finally through a 0.45 μm Millipore filter. The final filtrate was acidified using concentrated nitric acid to pH 1 or less and examined by all three analytical methods (radiochemical analysis, atomic absorption spectrophotometry, and neutron activation analysis).

4 RESULTS AND DISCUSSION

To deal with the problems of mill tailings in general, and uranium mill tailings in particular, it is necessary to address the various characteristics of these wastes. [illegible] is often requires a multidisciplinary approach to permit a detailed description of the site(s) involved. Therefore, it is necessary to collect as much information (e.g., physical, chemical, hydrological, geological, biological, and ecological data) as possible. In undertaking a study such as the present one, it soon becomes apparent that to collect all the information that one would like is an unrealistic and costly goal. Choices have to be made as to the type(s) of information that would be most useful. Inevitably, some data prove to be less useful than expected and, frequently, information is not collected that "should" have been collected.

For this study, basic physical and chemical information were collected, in addition to biological data, to address the impact of biological or ecological processes on contaminant transport from tailings areas. The data presented in this summary include many of the factors that are considered relevant to possible biological/ecological transport processes and that may influence the growth and long-term performance of indigenous "volunteer" vegetation.

Two types of factors were examined. The first factors were those believed to affect the uptake of long-lived radionuclides (e.g., radium-226, lead-210, and uranium) and were used to characterize the tailings themselves. They included physical and chemical factors primarily as most aspects of contaminant availability and transport can generally be described in these terms. The second factors related more directly to plant growth and ecosystem development and included those that influence the colonization and establishment of biological communities in inactive or abandoned tailings environments.

A description of selected physical and chemical characteristics of inactive or abandoned uranium tailings, as well as the possible differences between mining regions, the tailings, and the soils of the surrounding environment, is provided in this report. This description can be used to define the specific environmental pathways from the inactive or abandoned tailings and to provide reference information for validation of environmental pathway models. Validation, the process whereby the results from the model are compared with the numerical data derived from observations of the relevant environment, is essential in evaluating the long-term impact of uranium mill tailings following decommissioning.

The surface of these waste sites will remain the potential source of contamination to those indigenous colonizing plants that have rooted, and will continue to root, in both the wet and dry areas of the tailings. The vegetation, associated tailings, and surface water selected for analysis have been identified as major, long-lasting components of such waste-site ecosystems and, therefore, are important in long-term predictions. The concentrations of radionuclides in the surface water, surface tailings, and indigenous vegetation at these 10 to 20 year old uranium mill tailings sites reflect an environmental equilibrium that has been established after several years with no additional tailings input.

The description of the surface of the waste sites is divided into three sections: surface tailings, surface water, and vegetation. Radionuclide concentration factors, or distribution coefficients, that can be calculated for selected vegetation are discussed for each vegetation type. Long-lived radionuclides, which are adsorbed or absorbed by the vegetation, originate from the tailings, the pore waters in the root zone, the surface waters, and the air. No attempt was made during this investigation to identify the actual sources.

4.1 Characteristics and Elemental Composition of Inactive or Abandoned Uranium Tailings - Terrestrial and Wetland Areas

Reviews of the characteristics of mill tailings in general identify many problems in relation to plant growth (Murray, 1977; Bradshaw and Chadwick, 1980; Peters, 1984; Marshall, 1983). Fundamentally, uranium mill tailings do not differ from other base-metal tailings, with drought, low moisture retention, and low water storage capacity being some of the common characteristics of tailings. These characteristics are related to the particle size of the tailings. Blakeman (1976) performed grain size analyses of surface tailings (at the same depth as was used for this study) on 51 abandoned base-metal sites in Ontario and Quebec. He found that the surface material on 38 of the 51 sites consisted of a sandy, granular texture and that the surface of the remaining sites consisted of clay or silty particles.

The distribution of the surface particle size at a specific inactive or abandoned uranium mill tailings site will be similar to that of base-metal tailings investigated by Blakeman (1976). The distribution depends on many factors, predominantly the mill grind, the tailings discharge methods, the topography of the containment site, and the erosion pattern that develops after abandonment. Because finer particles generally settle at the lowest point of the containment area, farthest from the discharge source, most tailings sites have one section that has a higher fraction of clay-sized particles. Those sections are frequently completely waterlogged and are thixotropic.

For uranium tailings, the separation of "fine" from "coarse" particles on the surface results not only in a separation of moisture content but also in a separation of radionuclide concentration. The fine portions of uranium tailings contain more radionuclides than the coarse fractions (Moffett and Tellier, 1977). Moisture content of tailings is related to the percentage of clay particles, which usually contain more water. In turn, moisture availability on abandoned or inactive tailings sites is a major factor affecting the colonization pattern of indigenous plants. Therefore, it follows that, in the evaluation of contaminant transport, distinction between moisture content in different sections of the tailings site is of primary importance because it can also be expected to reflect increased radionuclide concentrations.

4.1.1 Moisture Content, Organic Matter Content, pH, and Conductivity.

In Table 4, moisture distribution is described in terrestrial (trees and grasses) and wetland (cattails and sedges) plants. Differentiation is made between samples taken directly from the tailings surface (0 to 5 cm depth) and those of particulate material surrounding the roots (20 to 25 cm depth). As expected for the terrestrial plants, the moisture content

TABLE 4 MOISTURE CONTENT (percent) OF WETLAND AND TERRESTRIAL TAILINGS

	Bancroft			Elliot Lake			Control*		
	Mean	SD	N	Mean	SD	N	Mean	SD	N
Terrestrial									
Surface	10	1.3	3	16	16	8	22.9	25	4
Root	14	7.6	6	12	9	8	24.6	25	4
Wetland									
Surface	42	14	15	40	13	21	85.9	6.5	13
Root	36	11	12	28	6	17	81	13	13

* Control sites include disturbed, nontailings areas (e.g., gravel pits, roadside ditches, etc.) that are close to the tailings sites at Bancroft and Elliot Lake, Ontario. No control sites at Uranium City, Saskatchewan, were examined.

generally increases somewhat with depth. The overall moisture content is somewhat higher in soils than in the tailings. Because moisture content in a sample also reflects precipitation history, these values cannot be considered absolute. A comparison is possible between the control values in soils and tailings because all samples were collected in the same region on the same day.

In the wet areas and in the cattail stands, the moisture content is higher; however, it is not as high in the tailings as in the control cattail stands. The root region of the wetlands on the tailings is slightly lower in moisture content than the surface. An explanation of this may lie in the fact that a film of water was present on the tailings surface in most cattail stands; whereas in the root region, water was likely held in the pores and no free water was available.

When comparing the wet and dry areas on the tailings, no significant differences were found between the Bancroft and Elliot Lake tailings. The higher moisture content of the wet areas was clearly expected.

The tailings surface can be considered an extremely primitive soil, similar to material left by the retreat of a glacier or washed up on the shoreline. uch materials also have low moisture content and are initially devoid of vegetation and free of organic matter. The factors affecting the colonization processes of those materials, e.g., sand dunes, can be considered similar to those that will affect tailings sites. The moisture content, one of the controlling factors in the colonization and establishment of vegetation and subsequent litter production, promotes decomposition activity, which results in the production of organic matter. As the organic matter content increases in a soil material, the moisture content and the nutrient content are expected to rise. Furthermore, organic matter concentrates radionuclides and metals because organic matter generally acts as a binding or complexing agent for these contaminants.

Therefore, it was of interest to determine if the wet areas on the tailings, with their higher proportions of fine particles and higher concentrations of radionuclides, would, in fact, contain higher amounts of organic matter. This would potentially reduce the availability of radionuclides to surface water and wetland plants from this source.

In Table 5, the organic matter (expressed as loss-on-ignition) is reported for wet and dry areas in each of the uranium mining areas and for the corresponding control sites in nontailings areas. On the control sites, the higher organic matter content in wetlands is evident, with an average of 47 percent, compared with the terrestrial samples, which have an organic matter content of only 14 percent. In comparison with tailings

TABLE 5 ORGANIC MATTER CONTENT (percent) OF TERRESTRIAL AND WETLAND TAILINGS AND CONTROL SITES

	Bancroft					Elliot Lake					Uranium City					Control*				
	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N
Terrestrial	0.6	0.06	0.1	1.2	14	3.7	0.6	0.3	20.0	30	9.5	1.6	0.2	92.5	88	13.7	2.9	2.2	34.0	9
Wetland	2.6	0.34	0.3	10.9	33	3.0	0.28	0.2	20.1	68	No data					47.3	2.6	9.5	82.8	37

* Control sites include disturbed, nontailings areas (e.g., gravel pits, roadside ditches, etc.) that are close to the tailings sites at Bancroft and Elliot Lake, Ontario. No control sites at Uranium City, Saskatchewan, were examined.

elsewhere, organic matter is virtually absent on the dry areas of the Bancroft tailings (0.6 percent). There is virtually no great difference between the organic matter content of wet areas on the Bancroft tailings (2.6 percent) and that of the dry or wet areas on the Elliot Lake tailings (3.7 percent). However, the organic matter content is significantly lower at each of these locations than at the control sites or in the dry areas of the Uranium City tailings (9.5 percent). The higher maximum organic matter content found in the Gunnar tailings is ascribed to the fact that one section of that tailings site had received sewage from the bunkhouse and was also at a low point on the site with high moisture content. The range (92.3 percent) between the minimum and maximum organic contents is extremely large for this abandoned tailings area.

The organic matter content appears to differ slightly between wet and dry sections of the tailings site in the Bancroft area, but for Elliot Lake no significant differences can be observed. This may be related to one of the important factors that will influence the decomposition of plant litter, namely pH. This factor is of ecological significance because it affects the types of vegetation that colonize the tailings site as well as the chemical and physical processes that determine the form and solubility of contaminants.

In Table 6, the pH values are summarized for the three different mining areas for both surface and root zones. Roots are known to exert a chemical influence on the material in their immediate vicinity - the zone referred to as the rhizosphere - and differences in pH can be expected between the surface material and that of the rhizosphere.

For the Bancroft and Elliot Lake tailings areas and the control sites, it appears that the wet areas are more alkaline, with pH differences of 0.5 to 1 unit. The dry areas on the Elliot Lake and Uranium City tailings exhibit a large range of pH values, from 2.7 to 7.0 and 5.2 to 9.0 respectively. The dry Bancroft tailings are more uniform in surface pH, with values ranging from 4.0 to 5.5. Differences in pH between the surface and the rhizosphere in dry tailings are slight; on Elliot Lake and Uranium City tailings, the root zone is less acidic than the surface. A detailed analysis of the pH values in cattail stands was carried out in an earlier report (Kalin, 1984a). The differences were interpreted as the possible result of a combined effect of the roots and reduced acid generation in wetlands.

A comparison of the pH values from both wet and dry areas on the three tailings sites with the pH values from the control sites indicates that the pH for the

TABLE 6 pH OF INACTIVE URANIUM TAILINGS IN WETLAND AND TERRESTRIAL AREAS

	Bancroft				Elliot Lake				Uranium City				Control*			
	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N
Terrestrial																
Surface	4.5	4.0	5.5	6	2.6	2.7	7.0	12	5.8	5.2	9.0	17	4.8	4.4	5.9	4
Root	4.2	3.7	5.5	8	2.9	2.0	7.3	12	6.6	5.8	9.0	11	4.9	4.5	6.1	4
Wetland																
Surface	5.4	4.6	6.9	19	3.0	1.8	7.7	35	No data				5.8	5.2	8.8	17
Root	5.5	4.7	7.4	19	3.9	3.0	7.3	42	No data				4.9	3.8	9.0	22

* Control sites include disturbed, nontailings areas (e.g., gravel pits, roadside ditches, etc.) that are close to the tailings sites at Bancroft and Elliot Lake, Ontario. No control sites at Uranium City, Saskatchewan, were examined.

Uranium City area is most alkaline, slightly above control site values, the Bancroft tailings are in the same pH range as the control sites, and the Elliot Lake tailings are generally two pH units lower than those of the control sites.

Electrical conductivity of a solution gives a useful indication of the ionic strength of the water. Plant growth and uptake of contaminants are affected by the characteristics of the soil solution. Therefore, measurements of the electrical conductivity are not only indicative of the saline tolerances of the indigenous vegetation but are also indicative of the relative amount of soluble material released from the tailings. Some indication of the ionic strength of a solution can be gained from a comparison with a standard solution of 0.1 *M* KCl at 25°C. Such a solution has a conductivity value of 12 900 µ mhos/cm (12 900 µ S/cm).

In Table 7, the field measurements of electrical conductivity in wet tailings and in 1:1 (weight:volume) slurries of dry tailings are summarized. A distinct difference in conductivity can be noted between the tailings sites and the control sites, where the mean conductivity is generally severalfold lower than on the tailings sites. An electrical conductivity value for garden soil is quoted by Kuja (1980) as being around 34 µ mhos/cm (34 µ S/cm), which is even lower than the values determined for terrestrial and wetland soils in this study.

The Uranium City tailings have extremely high conductivities. A more detailed evaluation of the association of the soluble material indicated that some samples with a high content of fine tailings resulted in slurries with very high conductivity (Appendix). This association of fines and high conductivities was confirmed by Murray (1977) in his review of tailings problems. He described the accumulation of salts on the surface as most frequently occurring where fine particles lie exposed at the surface. Salts result from tailings solutions with high conductivities. At Gunnar, some areas have high accumulations of salts, which form a crystalline "encrustment" on the surface of the tailings. Electrical conductivities of base-metal tailings in the Yukon, the Northwest Territories, and Ontario had a much larger range of values, extending from 1700 to 106 000 µ mhos/cm (1700 to 106 000 µ S/cm) (Kuja, 1980). In Kuja's study, high conductivities were associated with the most acidic sites. No differentiation, however, was made between coarse and fine tailings. Uranium tailings, however, are at the lower end of the range of electrical conductivities that can be encountered in tailings material. Ionic strength of the tailings water, in general, can be considered higher than that of normal soil water.

TABLE 7 ELECTRICAL CONDUCTIVITY (μmhos/cm (μS/cm)) IN TERRESTRIAL AND WETLAND AREAS OF INACTIVE TAILINGS

	Bancroft					Elliot Lake					Uranium City					Control*				
	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N
Terrestrial	1071	165	16	5000	24	1267	109	90	5600	44	3333	200	940	10 000	54	354	97	40	1600	14
Wetland	790	81	34	2000	30	1599	130	0	8100	61	No data					386	20	82	790	31

* Control sites include disturbed, nontailings areas (e.g., gravel pits, roadside ditches, etc.) that are close to the tailings sites at Bancroft and Elliot Lake, Ontario. No control sites at Uranium City, Saskatchewan, were examined.

As discussed above, moisture content, organic matter levels, pH, and electrical conductivity are all factors that can be used to distinguish between wet and dry sections of the tailings sites. These factors will also influence the development of the ecosystem and can affect contaminant transport within and from the tailings sites. These factors also control soil development as a result of interactions among the physical, chemical, and biological processes that take place. The chemical reactivity of the tailings is governed not only by the presence or absence of water but also by the chemical composition of the tailings, which will determine the type of soil formed on the tailings sites. The concentrations of radionuclides, metals, Group II elements, and other selected elements from both wet and dry areas of the tailings were measured and the results of these analyses are discussed in the following sections.

4.1.2 **Radionuclides.** Samples were taken from both wetland and terrestrial areas of each of the three tailings sites as well as from the control sites. From these samples, the concentrations of long-lived radionuclides radium-226, lead-210, and uranium were determined at the surface (0 to 5 cm depth) and in the root zone (20 to 25 cm depth). No consistent trends between the two sample depths were observed. Therefore, the samples were pooled and the results summarized for wetland and terrestrial areas of the tailings without depth distinctions (Table 8).

The mean concentrations of radium-226 and lead-210 for terrestrial and wetland sections of the control areas are lower than those reported from the tailings in all three study areas. Twenty percent of the control soils had concentrations below 1 pCi/g (37 mBq/g) dry weight of radium-226. For lead-210, 51 percent of the samples had concentrations below the same value. Detection limits, or values at the limit of analytical precision, are consistently determined to be less than 1 pCi/g (37 mBq/g) for both radium-226 and lead-210 in the terrestrial sections of all areas investigated. In the wetland samples from the Bancroft area, however, the minimum concentrations of both radionuclides were above the detection limit. Although, in general, the mean concentrations of long-lived radionuclides are low in the nontailings control environments, higher concentrations, similar to those determined for the tailings, can occur in some areas as indicated by the maximum values reported in Table 8. This large range is to be expected, particularly in areas with uranium mineralization.

The control sites have a higher proportion of radionuclide values below the detection limits, e.g., 20 and 52 percent for radium-226 and lead-210 respectively. The fraction of samples encountered with radionuclide concentrations below the detection

TABLE 8 CONCENTRATIONS OF RADIONUCLIDES IN TERRESTRIAL AND WETLAND AREAS OF INACTIVE TAILINGS

	Bancroft					Elliot Lake					Uranium City					Control				
Radionuclide	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N
Radium-226 (pCi/g)																				
Terrestrial	42(1554)	6(222)	<1(<37)	203(7511)	33	41(1517)	6(222)	<1(<37)	281(10 397)	48	69(2553)	6(222)	<1(<37)	238(8806)	53	18(666)	6(222)	<1(<37)	136(5032)	16
Wetland	52(1924)	12(444)	5(185)	190(7030)	12	34(1258)	3(111)	<1(<37)	110(4070)	33	No data					17(629)	2(74)	<1(<37)	48(1776)	18
Lead-210 (pCi/g)																				
Terrestrial	49(1813)	10(370)	<1(<37)	366(13 542)	33	20(740)	3(111)	<1(<37)	122(4514)	48	64(2368)	6(222)	<1(<37)	229(8473)	53	12(444)	8(296)	<1(<37)	187(6919)	16
Wetland	67(2479)	14(518)	10(370)	188(6956)	12	34(1258)	5(185)	<1(<37)	173(6401)	33	No data					26(962)	6(222)	<1(<37)	106(3922)	18
Uranium (µg/g)																				
Terrestrial	37	7	<0.0001	342	33	36	7	1	444	51	135	16	7	1108	83	51	34	1	719	15
Wetland	231	38	12	1104	39	85	24	1	2673	79	No data					113	25	2	1037	43

Note: values in parentheses are mBq/g

limits for the three tailings sites was variable. In the tailings samples from Bancroft and Uranium City, none of the radium-226 concentrations was below the detection limit. For lead-210, 4 percent of the samples from these two areas had concentrations below 1 pCi/g (37 mBq/g). In Elliot Lake, 8.6 percent of the radium-226 concentrations and 9.8 percent of the lead-210 concentrations were below the 1 pCi/g (37 mBq/g) limit. Uranium was only encountered in one sample from the Bancroft tailings at a very low concentration below the detection limit (<0.0001 µg/g). This radionuclide is generally present above the detection limit.

The ranges of these radionuclides in the nonmineralized environment were large. For the soil/rock environment, radium-226, lead-210, and uranium concentrations have been summarized from the available literature (NUTP, 1985) for the Canadian Shield, the Rocky Mountains, and the Lake Athabasca basin. For radium-226 from nonuranium mining regions, a total of 84 values revealed a concentration range of less than 1 pCi/g (37 mBq/g) to 18.9 pCi/g (699.3 mBq/g) dry weight. In 73 samples of lead-210, the concentrations ranged from less than 1 pCi/g (37 mBq/g) to 17.8 pCi/g (658.6 mBq/g). For uranium, 897 675 samples of rock and soil from the previously mentioned areas of Canada, plus samples from the Maritimes, the Prairies, and the Great Lakes region, exhibited an individual concentration range of less than 0.02 to 3550 µg/g and a range of mean concentrations from 0.02 to 64.2 µg/g.

The concentration ranges for radium-226 and lead-210 are of the same order of magnitude as the concentrations determined for the environment in mineralized areas in this study. The mean uranium concentrations for the terrestrial environment are, indeed, very similar, with 51 µg/g reported for the terrestrial control areas in the mineralized areas of Elliot Lake and Bancroft. For the wetland control areas, a higher mean uranium concentration of 113 µg/g is expected because uranium is known to bind strongly to organic matter (Sheppard, 1980; Dunn et al., 1985).

A comparison of the terrestrial and wetland areas on the tailings shows that slightly higher concentrations of radium-226, lead-210, and uranium are apparent on the Bancroft tailings. This appears to agree with the higher organic matter content reported from these tailings (Table 5). However, on the Elliot Lake tailings, only lead-210 and uranium show differences in the mean concentrations. The mean radium-226 concentrations are higher in the terrestrial samples than in the wetland samples.

Generally, the differences in radionuclide concentrations between wet and dry areas on the tailings are small; the mean concentrations of long-lived radionuclides are low on the surface and the ranges of concentrations encountered are large. Dave et al. (1984a) reported similarly large ranges, although with higher maxima for radium-226 and lead-210 concentrations from the Elliot Lake tailings (8.8 to 522 pCi/g (325.6 to 19 314 mBq/g) for radium-226 and 5 to 441 pCi/g (185 to 16 317 mBq/g) for lead-210). These ranges are based on approximately 17 samples taken from cores of 37-cm depth. The higher maximum numbers are expected due to a larger fraction of fine material in the samples at greater depth than in the surface samples.

For radium-226 and lead-210, respective mean concentrations of 166 pCi/g (6142 mBq/g) and 36 pCi/g (1332 mBq/g) were reported for the coarse fraction of Elliot Lake tailings; whereas respective mean concentrations of 314 pCi/g (11 618 mBq/g) and 130 pCi/g (4810 mBq/g) were reported for the fine fraction (Moffett and Tellier, 1977). The generally low radionuclide concentrations in the tailings reported here (for depths of 0 to 25 cm) are probably a result of natural weathering processes, i.e., leaching of radionuclides to lower layers and uptake by the vegetation.

4.1.3 **Metals.** Heavy metals in tailings are also of concern because accumulation in the food chain and surface water contamination can also relate to potential long-term problems. These elements, including cobalt, copper, nickel, and lead, can be considered as persistent substances, and high concentrations of these elements may be toxic to plants, thereby affecting vegetation development on the tailings site.

In Table 9, metal concentrations of cobalt, copper, nickel, and lead are presented for the three mining areas and for the control sites. One of the most obvious differences is that noted between the concentrations of these elements in the terrestrial sections and the concentrations in the wetland sections for the tailings sites as well as the control sites. The concentrations of these four metals are generally as much as two to three times higher in the wetland areas than in the terrestrial areas.

All four metals occur in similar concentration ranges for both terrestrial and wetland areas on the control sites and the Bancroft tailings. The concentration ranges for cobalt, copper, and nickel on the control sites are well within those quoted in the literature. Average concentration ranges for copper are given as 5 to 100 µg/g for mineral soil and 6 to 40 µg/g for organic soil (Allen et al., 1974); whereas Kabata-Pendias and Pendias (1984) quote a range of 1 to 323 µg/g. For nickel, Allen et al. (1974) reported ranges of 5 to 500 µg/g and Kabata-Pendias and Pendias (1984) reported <5 to 200 µg/g. Background nickel concentrations were summarized specifically for Canada by NUTP (1985). Nickel concentrations in 7327 rock/soil samples from Canada had mean

TABLE 9 CONCENTRATIONS OF METALS (μg/g) IN TERRESTRIAL AND WETLAND AREAS OF INACTIVE TAILINGS

	Bancroft					Elliot Lake					Uranium City					Control				
	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N
Co																				
Terrestrial	5.7	0.6	<0.4	24.7	33	31.2	10.8	<0.4	591.0	46	No data					6.1	0.6	3.7	10.9	13
Wetland	7.7	0.9	3.1	15.4	13	122.3	21.5	<0.4	562.1	38	No data					16.8	1.6	5.8	45.0	18
Cu																				
Terrestrial	29	1.9	7.8	82.2	34	59.1	9.5	4.2	446.0	48	No data					17.0	2.2	4.3	45.2	14
Wetland	36.5	2.5	18.7	65.6	13	155.0	27.9	9.5	954.8	41	No data					67.6	11.3	19.0	317.2	18
Ni																				
Terrestrial	10.8	1.5	<0.4	44.8	33	7.8	1.0	<0.4	38.3	49	No data					9.1	2.8	<0.4	24.4	14
Wetland	23.8	4.4	3.2	75.8	13	22.9	2.2	<0.4	88.4	41	No data					30.7	2.4	13.1	62.8	18
Pb																				
Terrestrial	98	9	1.4	369	33	257	25	<1	1073	48	186	11	3	684	87	93.1	55	<1	1190	15
Wetland	165	20	44	309	13	195	23	1	1061	41	No data					120.2	16	20	432	18

concentration ranges of 3.5 to 605 µg/g, and a range in individual samples of 2 to >1000 µg/g. The average soil range for cobalt in surface soils is given by Allen et al. (1974) as 1 to 60 µg/g for mineral soils and 0.2 to 1 µg/g for organic soils; Kabata-Pendias and Pendias (1984) give cobalt concentration ranges of 0.1 to 122 µg/g for world soils, with an average range of 1 to 40 µg/g.

For these three metals (copper, nickel, and cobalt), both wetland and terrestrial control and Bancroft tailings samples analyzed are within the quoted literature ranges. However, lead concentrations appear to be slightly higher than the literature values. For lead, Allen et al. (1974) quoted a concentration range of 2 to 20 µg/g, which is substantially lower than the concentrations determined, with means of 93 and 120 µg/g in the terrestrial and wetland control sites respectively. Kabata-Pendias and Pendias (1984) quoted lead ranges for world soils between 1.5 and 189 µg/g, which would place the soils in this study in the upper range of world soil lead concentrations.

Lead has been studied extensively in the environment and elevated soil concentrations have been found to be associated with many industrial and human activities. Some values of lead concentrations in soil compared with values in natural undisturbed environments are given by John et al. (1975), e.g., for surface soils associated with the metal-processing industry in Canada, values ranged from 291 to 12 123 µg/g. Ormrond (1978) quoted lead concentrations in urban garden soil and urban vicinities in Canada as ranging from 6 to 888 µg/g.

These concentration ranges suggest, at least, that the lead concentrations found in the tailings are not unusual because the control sites are in the general area of the mining activity. They suggest, furthermore, that lead concentrations found in the tailings are at the low end of lead concentrations that can be found in soils associated with industrial activity. Because the inactive uranium tailings are waste material, it would be reasonable to say that these wastes are relatively clean with respect to cobalt, copper, nickel, and lead.

Elliot Lake tailings have slightly higher cobalt, copper, and lead concentrations than the other two tailings areas. Unfortunately, most heavy metals have not been determined for the Uranium City area. However, the mean lead concentration in terrestrial samples is similar to that of the Elliot Lake area.

The concentration ranges encountered for the heavy metals exhibit, in general, large variations similar to those reported earlier for the long-lived radionuclides. Large ranges of metal concentrations are also reported for other tailings, based on an extensive data set of tailings analyses (Murray, 1977). For 164 samples of tailings, Murray (1977) reported a mean copper concentration of 130 µg/g, with a range of 1 to 750 µg/g. Analysis of 139 tailings samples resulted in a mean lead concentration of 340 µg/g, with a range of 0.3 to 2810 µg/g. The mean nickel concentrations were reported as 96 µg/g for 132 samples, with a smaller range of variance of 10 to 546 µg/g. The cobalt concentrations for 39 samples ranged between 100 and 9999 µg/g, with a mean of 1140 µg/g.

These mean concentrations and their ranges indicate clearly that although the metal concentrations at the inactive uranium tailings sites in Elliot Lake, particularly in the wetland sections, are higher than those at the Bancroft sites and control sites, the metal concentrations are below the means for other tailings areas.

4.1.4 Other Elemental Concentrations. Plant uptake and accumulation of contaminants, such as heavy metals and radionuclides, are determined not only by the presence of these elements in the soil or their solubility and availability in the rhizosphere but also by the presence or absence of essential elements and other elements that could mimic essential elements and compete with them. Plants can discriminate to some degree between essential elements for growth, trace elements, and nonessential elements. However, chemical similarities can result in substitution of an essential element by a nonessential element. Hence, a chemically similar, possibly toxic, contaminant can mimic an essential element, often with deleterious results.

In the case of radium, chemically similar elements include those that belong to the Group II elements, i.e., the so-called alkaline-earth metals. In Table 10, the concentrations of some Group II elements (barium, calcium, and magnesium) are presented. Calcium and barium, in particular, are considered to be of significance in relation to plant uptake and transport of radium-226.

In the Elliot Lake tailings, generally, no differences in concentrations of these three elements can be noted between wet and dry sections of the site. In the control areas, the wetlands have more barium and magnesium, but the calcium concentrations are in the same range. For Bancroft tailings, barium concentrations are lower in the wetlands compared with terrestrial areas, whereas the reverse is true for both calcium and magnesium. For the Uranium City area, no wetland samples are available. The Uranium City concentrations in the terrestrial samples are similar to those at the control sites and in the Bancroft tailings.

TABLE 10 CONCENTRATIONS (μg/g) OF BARIUM, CALCIUM, AND MAGNESIUM IN TERRESTRIAL AND WETLAND AREAS OF INACTIVE TAILINGS

	Bancroft					Elliot Lake					Uranium City					Control				
	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N
Ba																				
Terrestrial	1 439	432	328	18 679	33	4 682	2 951	113	188 248	45	974	77	55	6 152	73	1 769	541	505	10 078	12
Wetland	925	49	424	1 983	35	4 539	1 410	<1	110 325	71	No data					7 554	4 775	292	237 171	35
Ca																				
Terrestrial	25 186	1 965	256	77 666	34	11 996	3 182	<1	186 000	43	20 160	1 356	2 311	68 407	73	9 358	2 126	231	45 362	15
Wetland	32 283	996	16 000	58 010	39	18 257	8 775	6	646 692	52	No data					10 254	690	162	27 800	38
Mg																				
Terrestrial	10 621	543	0	23 061	34	4 933	579	0	26 722	51	19 350	740	2 196	41 302	67	8 257	657	0	12 541	14
Wetland	17 348	914	7 999	37 602	39	4 267	739	0	64 207	70	No data					27 434	15 409	1 542	710 493	34

Elliot Lake concentrations differ from those at the control sites most drastically in the case of barium and magnesium; barium, based on mean concentrations, is 2.6 times higher in the terrestrial tailings and 1.6 times higher in the wetland tailings. The calcium concentrations in the terrestrial samples are similar to those in the control soils, but in the wetland tailings calcium concentrations are 0.5 times higher than in the control wetlands. The Elliot Lake tailings are depleted of magnesium compared with the control sites; whereas in the Bancroft tailings, mean concentrations are higher in the terrestrial sections and lower in the wetland sections than in the control sections.

Most of the differences in mean concentrations of barium, calcium, and magnesium in the above cases are again associated with large ranges of concentrations, as indicated by the wide range of minimum and maximum values. Possibly the most important factors affecting a comparative evaluation of radium-226 uptake by plants are the clear differences expressed as higher barium concentrations and lower magnesium concentrations in the Elliot Lake tailings compared with the control areas and the other uranium tailings. Radium-226 transport from the tailings into the plants may be affected by the presence of other Group II elements. This aspect will be considered in the next section.

Magnesium concentrations in typical soils were quoted by Rutherford et al. (1982) as ranging from 1200 to 15 000 µg/g. Therefore, the control soil concentrations in the Elliot Lake tailings are, with respect to magnesium, within those ranges quoted in the literature. An average concentration of barium for world soils is reported by Kabata-Pendias and Pendias (1984) as 84 to 838 µg/g. In the Elliot Lake tailings, the control soil concentrations of barium ranged somewhat higher. Overall, therefore, the control soil concentrations determined in this study are higher than those quoted in the literature.

The last group of elemental concentrations summarized for inactive or abandoned uranium tailings includes those of aluminum, sodium, manganese, and chlorine (Table 11). These elements are important in relation to plant growth and/or toxicity, as are many other elements that were not determined in this investigation. Because multielemental methods were used throughout the investigation, the concentrations of these elements were relatively easy to determine, along with those of uranium and the Group II elements.

Aluminum is one of the main constituents of the Earth's crust and its hydroxides, which result from weathering, have the potential to adsorb anions and precipitate negatively charged particles. Aluminum hydroxides influence soil properties.

TABLE 11 CONCENTRATIONS (µg/g) OF ALUMINUM, SODIUM, MANGANESE, AND CHLORINE IN TERRESTRIAL AND WETLAND AREAS OF INACTIVE TAILINGS

	Bancroft					Elliot Lake					Uranium City					Control				
	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N	Mean	SD	Min	Max	N
Al																				
Terrestrial	49 794	1 183	17 662	71 828	34	31 190	1 606	2	60 123	49	66 451	2 179	14 566	255 048	83	50 947	3 740	3 444	91 396	15
Wetland	53 999	651	38 000	66 154	39	36 991	5 105	398	584 433	79	No data					30 806	1 962	3 047	71 131	43
Na																				
Terrestrial	29 178	586	16 094	39 749	33	2 875	624	206	25 997	50	43 085	1 713	5 395	119 771	83	22 507	1 121	10 597	28 326	14
Wetland	30 486	541	20 100	39 852	39	2 385	614	232	48 574	58	No data					9 753	788	688	26 903	42
Mn																				
Terrestrial	874	40	250	1 431	34	54	7	6	306	51	309	37	26	2 875	83	540	129	95	3 072	15
Wetland	1 048	33	364	1 642	39	193	100	5	10 826	76	No data					1 980	971	63	60 893	44
Cl																				
Terrestrial	542	21	290	1 200	31	227	21	39	1 150	44	668	49	66	2 008	35	447	32	245	757	13
Wetland	551	14	337	810	36	160	12	55	870	61	No data					562	53	16	1 838	34

In acidic soils with a pH below 5.5, aluminum is mobile and is readily taken up by plants. The presence of aluminum in plants interferes with the uptake of nutrients such as calcium and magnesium.

Sodium and chloride concentrations may be of importance in the determination of the alkalinity/salinity of the soil material. Chloride is also important for ionic balance in soils and for osmotic regulation in plants. Finally, manganese is an essential nutrient for plants.

The most striking difference between the three uranium tailings areas is that all of the concentration ranges are lower in the Elliot Lake area than at the control sites or in the Bancroft and Uranium City tailings areas. This is probably due to the acidic nature of the Elliot Lake tailings, because the elements determined in this study tend to be considerably more mobile under acidic conditions. The concentrations in the control soils and in the Bancroft and Uranium City tailings are within similar ranges for all elements, and within the ranges quoted in the literature (Allen et al., 1974) for aluminum, manganese, and chlorine. Sodium concentrations are slightly higher in the control soils. Allen et al. (1974) quoted average concentrations of 0.1 to 1 percent for sodium in soils. In this study, the control soils range, on average, from 0.9 to 2.2 percent for sodium. Aluminum, sodium, and chlorine concentrations do not differ much between the wet and dry sections for all areas. However, some differences can be noted for the micronutrient manganese, which is consistently higher in wetlands for all areas investigated.

4.2 Surface Waters on Inactive or Abandoned Uranium Tailings

The surface water samples from the Elliot Lake and Bancroft areas in Ontario originate from waters ponded at low points on the tailings sites or from waters remaining from former lakes that were not completely filled with tailings during milling operations. Seepages that emerge from tailings dams were also sampled.

The surface waters of the Elliot Lake area were acidified as a result of acid generation alone. The surface waters in the Bancroft area are neutral to slightly alkaline and have not experienced the effects of acid generation. Seasonal trends in water samples have been reported by Kalin (1983).

The surface water samples reported for the Uranium City area in Saskatchewan were collected during a 1-year study of Nero Lake, which had received unneutralized pyritic tailings from the Lorado mill (Table 1). The water in Nero Lake was initially acidified directly during the operation of the mill and later by the runoff from the small acid-generating tailings area nearby. Nero Lake is the largest body of water affected by uranium mill tailings that was investigated during this study. Seasonal trends in the water characteristics of Nero Lake have been reported previously (Kalin, 1983).

In the following section, the surface water characteristics that have developed on uranium mill tailings sites 10 to 20 years after the sites became inactive or abandoned are described. The characteristics of these waters might be indicative of conditions that can be expected in such areas over the long term. It is reasonable to assume, based on the time period involved, that these waste sites have reached some degree of equilibrium with the surrounding environment. Thus, the surface water characteristics, such as pH, electrical conductivity, and radionuclide and metal contents, as well as the concentrations of major ions, may be used as indicators of long-term trends in surface water characteristics for both inactive and abandoned uranium mill tailings sites in the three regions investigated.

Experimentally derived aqueous leach solutions from tailings, referred to as leachates, were originally intended to give some idea of the bioavailability of radionuclides and metals to plants rooted in the tailings. The leachates were derived from tailings adhering to the roots and rhizomes of cattails collected from the Bancroft and Elliot Lake areas and from soils in the control areas. Leachates were derived from tailings adhering to the roots of grasses collected from the Uranium City area (Gunnar tailings). The tailings or soils from the root zones were leached for 48 hours using distilled water at room temperature. In the following sections, the pH and conductivities as well as the elemental concentrations from these leaching experiments are compared with those of the surface waters from the tailings areas and the control areas.

4.2.1 pH and Electrical Conductivity. In Table 12, the pH values and electrical conductivities of the surface waters and leachates are presented. The pH of the surface water on the tailings is generally lower than the pH of the leachates. The pH values of the leachates are, as expected, within the same range as those values reported for the tailings in the wetlands as the tailings from the root zone of cattail stands were used to derive the leachates. This indicates that pH determinations made in the laboratory from soil slurries are representative of pH values determined in the field.

The surface waters in the Uranium City area originate from the acidic waters of Nero Lake and the leachates from the alkaline Gunnar tailings, and they are not directly comparable as was the case for the other study areas where surface water samples and tailings samples had similar pH values. The pH of the leachate solution from the Gunnar site, with a mean pH of 6, is similar to the pH range of 5.8 to 6.6 for the

TABLE 12 pH AND ELECTRICAL CONDUCTIVITY (µmhos/cm (µS/cm)) OF SURFACE WATERS ON TAILINGS COMPARED WITH 48-HOUR STATIC LEACHING SOLUTIONS

	Bancroft				Elliot Lake				Uranium City				Control*			
	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N
pH																
Surface	6.4	3.8	8.5	49	2.9	1.8	9.8	63	3.5	2.7	7.1	35	3.7	2.5	9.5	63
Leachate	5.5	4.3	7.2	6	4.2	3.6	6.4	11	6.6	5.9	8.1	15**	4.9	5.1	7.3	8
Conductivity	1140	34	3500	39	2833	80	>10 000	57	1166	100	7500	33	750	30	4150	56

* Control sites include disturbed, nontailings areas (e.g., gravel pits, roadside ditches, etc.) that are close to the tailings sites at Bancroft and Elliot Lake, Ontario. No control sites at Uranium City, Saskatchewan, were examined.

** Leaching time is 7 days.

tailings slurries (Table 6). These comparisons suggest that, generally, the pH values reported here from the leachate experiments are similar to the corresponding field measurements and can be considered characteristic for the tailings area, regardless of the slurry ratio used. However, some differences in pH values are evident with respect to location at the tailings site. There were differences in pH, as discussed earlier, between the values reported for the surface and the root zone in wetland and terrestrial tailings, as well as differences between the surface waters and the leachates (Table 12).

Field measurements of pH in the root region of cattail stands on the Elliot Lake tailings indicated lower pH values in the surface tailings than in the root region (Kalin, 1983). These results are similar to those noted above for surface waters and leachates.

The pH ranges encountered in the surface waters are generally large, ranging from 1.8 to 9.8, and are considerably larger than the ranges associated with the leachates (3.6 to 8.1). This suggests that more factors affect the surface water characteristics than affect solutions derived from tailings and soil materials associated with plant roots. The large range of pH values in control surface waters is due to the variety of water bodies and types sampled, particularly in the Uranium City area where naturally acidic muskeg as well as very alkaline surface waters is found in the local nontailings environment. The large ranges in the tailings surface waters are due, in part, to extensive liming of the tailings, which is the case for the Elliot Lake area where the pH may be as high as 8.0 for the surface waters. In general, however, the Elliot Lake surface waters and seepages are acidic. The pH ranges determined for Nero Lake indicate that, although this large water body is acidic, it is less acidic than most locations in the Elliot Lake area. The more uniform pH for the Uranium City area may be due to the fact that all water samples have been collected from the same water body, i.e., Nero Lake; whereas in the Elliot Lake area, samples were collected from eight different water bodies on the tailings, thus giving a wider range of pH.

The electrical conductivities of the surface waters are essentially the same order of magnitude for both tailings and control sites in all areas; only the mean value for the controls is slightly lower than values for the three tailings areas. The ranges of conductivity values encountered are very large for all areas, indicating that, along with the large ranges of pH, the ionic strength of the surface waters is extremely variable. A comparison of the conductivities of the tailings slurries (Table 12) suggests that for the control, Bancroft, and Elliot Lake areas the average ionic strength of surface water is higher and the ranges are larger than those determined for wetland and terrestrial tailings slurries. The Uranium City tailings conductivities from Gunnar cannot be compared with those of the surface waters of Nero Lake for the same reasons as stated for pH. However, the conductivities of the Nero Lake water are not as high as the surface waters of Elliot Lake tailings. These conductivities suggest that the surface waters of the Elliot Lake tailings contain a higher amount of salts, which increase the electrical conductivity of the water and which may be due to the extreme pH ranges.

4.2.2 **Radionuclides.** The most important pathway of concern to environmental and human health involves water by which long-lived radionuclides, such as radium-226, could reach and accumulate in the food chain. Therefore, many workers have addressed the mobility of radium-226 and other radionuclides from uranium tailings. Benes (1982b) summarized laboratory experiments and studies that particularly address the factors that exert control over radium-226 dissolution from uranium tailings. Some of the more important factors are the ratios of liquids to solid, the concentrations of sulphate and cations, and the pH of the leaching solutions. However, the nature, composition, and pretreatment of the tailings; the dispersion of the solids; and the volume and flow rate of the leachate solution are equally influential on the dissolution of radium-226. Benes stated that field data on the actual release processes of radium-226 from the tailings solids are scarce.

This multiplicity of factors, examined carefully in the laboratory under controlled conditions, will also affect, in varying degrees, the rate of radium-226 dissolution from the tailings to the surface water in the field. Given the complexity of these factors, the radium-226 concentrations presented in Table 13 cannot be related directly to the concentrations in the tailings. The same holds for the comparisons of radium concentrations in the leachates. Both concentrations only lend themselves to empirical interpretation. The two types of water, leachates and surface waters on tailings, are the result of completely different processes as virtually all factors affecting radium-226 dissolutions determined experimentally in the laboratory are different not only between individual leachates but also for the different surface water bodies.

The average concentrations of radium-226 in surface waters in all three tailings areas are lower (12 to 29 pCi/L (444 to 1073 mBq/L)) than the control site concentrations (35 pCi/L (1295 mBq/L)). Background surface water concentrations have been summarized for nonmineralized areas in Canada (NUTP, 1985). They are reported as having a mean of 0.5 pCi/L (18.5 mBq/L), with a range for 863 individual samples from

TABLE 13 RADIONUCLIDE CONCENTRATIONS IN SURFACE WATERS OF INACTIVE TAILINGS AREAS COMPARED WITH 48-HOUR STATIC LEACHING SOLUTIONS

	Bancroft				Elliot Lake				Uranium City				Control*			
	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N
Radium-226 (pCi/L)																
Surface Waters	29(1073)	<1(<37)	170(6290)	47	15 (555)	<1(<37)	177(6549)	64	12 (444)	<1(<37)	43(1591)	53	35(1295)	<1(<37)	867(32 079)	52
Leachate	99(3663)	17(629)	230(8510)	12	38(1406)	<1(<37)	231(8547)	22	40(1480)	11(407)	78(2886)	9	11 (407)	<1(<37)	55 (2035)	16
Lead-210 (pCi/L)																
Surface Waters	13 (481)	<1(<37)	194(7178)	46	21 (777)	<1(<37)	276(10 212)	64	13 (481)	<1 (<37)	44(1628)	53	10(370)	<1(<37)	203 (7511)	52
Leachate	14 (518)	<1(<37)	32(1184)	12	213(7881)	<1(<37)	1743(64 491)	22	46(1702)	2.6(96.2)	136(5032)	9	9(333)	<1(<37)	48 (1776)	16
Uranium (mg/L)																
Surface Waters	0.1	<0.04	1.1	22	0.6	<0.01	10.1	50	3.7	0.02	94	53	0.3	0.0001	6	36
Leachate	0.2	<0.04	1.1	9	0.04	<0.01	0.3	22	No data				0.04	0.0001	0.02	15

Note: Values in parentheses are mBq/L.

* Control sites include disturbed, nontailings areas (e.g., gravel pits, roadside ditches, etc.) that are close to the tailings sites at Bancroft and Elliot Lake, Ontario. No control sites at Uranium City, Saskatchewan, were examined.

<0.27 to 9.4 pCi/L (<9.99 to 347.8 mBq/L). The concentration range of radium for the nontailings environment control samples, i.e., representative of background water concentrations determined in mineralized areas, is considerably larger (<1 to 867 pCi/L (<37 to 32 079 mBq/L)). This suggests that the surface water on the tailings, which includes seepages from dams, generally has concentrations similar to those of surface water from mineralized regions. The maximum radium-226 concentration in surface water on tailings (177 pCi/L (6549 mBq/L)) is well below the upper value of the control background concentration of 867 pCi/L (32 079 mBq/L).

The Ontario Ministry of the Environment water quality monitoring program on the Serpent River Basin reports in 1980, for example, that surface water concentrations of dissolved radium-226 do not exceed 11 pCi/L (407 mBq/L). In the Elliot Lake district, these monitoring samples are generally collected at outflows of lakes and in rivers within the Serpent River Basin. In this study, mainly wetlands with slow-flowing waters were sampled. The mean radium-226 concentration determined as background in the Elliot Lake area was 3.7 pCi/L (136.9 mBq/L), with a standard deviation of ±5.5 pCi/L (±203.5 mBq/L) based on 26 samples. This concentration range is similar to the monitoring data. The large range of radium-226 background concentrations reported in Table 13 originates from control water collected in the Bancroft area. Here, the mean radium-226 concentration in water in the wetlands is 85±219 pCi/L (3145±8103 mBq/L), based on 20 samples. It is likely that one of the wetlands sampled was associated with an outcropping of uranium-bearing rock, causing water samples from this location to have high radium-226 concentrations.

The ranges in radium-226 concentration encountered in nontailings areas and surface waters on uranium tailings are extremely large. This indicates that in localized areas high radium-226 concentrations are possible in mineralized areas as well as on the tailings. Comparing the surface waters of the different tailings areas, it is found that the mean radium-226 concentrations in the surface water of the Bancroft tailings area are higher than those in the Elliot Lake area or in the Uranium City area (Nero Lake). When the individual site mean concentrations are evaluated, the means and standard deviations range from 12±16 pCi/L (444±592 mBq/L) to 51±55 pCi/L (1887±2035 mBq/L) for the five sites located in the Bancroft area. For the eight sites in the Elliot Lake area, the means are lower, ranging from 6±18 pCi/L (222±666 mBq/L) to 26±59 pCi/L (962±2183 mBq/L). These means, describing the variations within a tailings site, suggest that the surface waters associated with uranium tailings in the Bancroft area have higher concentrations more frequently than were found in the surface waters of uranium tailings in the Elliot Lake and Uranium City areas. A statistical evaluation, taking into account the fact that the radium concentrations are not normally distributed, would be required to confirm this observation.

The mean concentrations of radium-226 reported for tailings leachates range from 38 to 99 pCi/L (1406 to 3663 mBq/L). A large range of concentrations is also exhibited for individual samples (<1 to 231 pCi/L (<37 to 8547 mBq/L)). The control leachates are lower in radium-226, with a mean concentration of 11 pCi/L (407 mBq/L) and an individual sample range from <1 to 55 pCi/L (<37 to 2035 mBq/L). From lysimeter leaching experiments carried out by Ritcey and Silver (1982), concentrations ranging from 100 to 300 pCi/L (3700 to 11 100 mBq/L) were determined for the first 7.5 simulated years. The radium-226 concentrations were predicted to increase thereafter to concentrations as high as 500 pCi/L (18 500 mBq/L). The maximum values of the surface water in all three tailings areas are only close to the lower concentrations predicted by the lysimeter study. The time span experienced at the sites is between 10 and 20 years, considerably longer than the 7.5 years simulated in the lysimeter. The radium concentrations in the leachates have somewhat higher maximum concentrations but none reaches the upper range predicted by the lysimeter work. It is of interest to note that, under nonexperimental field conditions, generally lower concentrations of radium-226 are encountered. This only demonstrates the difficulty in simulating in the laboratory the conditions and processes that govern the natural environment. The problematic nature of long-term predictions based on laboratory results alone is self-evident.

It was noted that for radium-226 the concentrations in the surface water on the Bancroft tailings were higher than those in the other tailings areas. For the radionuclide lead-210, the mean concentrations in the Elliot Lake tailings surface waters are higher than those in the surface waters on the Bancroft tailings and in the acidic waters of Nero Lake (Uranium City). Although lead is generally not very mobile in soils and accumulates readily, it appears that the acidic conditions, due to acid generation in the Elliot Lake tailings, facilitate the release of lead-210 to surface waters, which can be expected to behave in a manner similar to natural, nonradioactive lead.

The concentrations of lead-210 in the leachates, compared with surface water concentrations, suggest that for the Bancroft tailings and the control areas the average concentration in the leachate is similar to that of the surface water. However, the range of concentrations is smaller in the leachates. For the acidic sites in the Elliot Lake area, leachate concentrations are higher than in the surface water and the ranges are larger. The same holds true for the metals and lead-210, which are discussed later. These results clearly suggest that both the radionuclide lead-210 and the metal lead are liberated more easily to water in acidic tailings than in alkaline tailings. Here, it should be noted that leachates from the Uranium City area cannot be compared with the surface water because the leachates are derived from Gunnar Lake (alkaline tailings) and the surface water is derived from Nero Lake (acidic tailings).

The uranium concentrations in the tailings water are low, ranging from 0.01 to 94 mg/L for all areas investigated (Table 13). The control sites had a mean concentration of 0.3 mg/L, with a range of 0.0001 to 6.0 mg/L for 36 surface water samples. This value is much higher than the mean natural background uranium concentration reported for nonmineralized areas in Canada (0.00045 mg/L) (NUTP, 1985). For this element, the ranges encountered in the surface waters are extremely large for control sites as well as for the tailings sites. The waters of Nero Lake appear to have the highest uranium concentration, with a mean of 3.7 mg/L and a range of 0.02 to 94 mg/L for a set of 53 samples. These higher uranium concentrations, compared with natural background concentrations in surface waters in nonmineralized areas, are not surprising.

The surface waters on tailings sites can be considered as only slightly higher in uranium concentrations than those on the control sites. The leachates generally have even lower uranium concentrations than the surface waters. Therefore, the uranium in the tailings does not appear to be very mobile.

4.2.3 **Metals.** Metals that could be released to the surface water are of concern, in addition to radionuclides, because they might accumulate in the food chain over the long term or affect water quality adversely. Recovery of the tailings areas and associated surface waters would be inhibited if metal concentrations reach toxic levels. The metals copper, nickel, and lead were analyzed in all three regions and the data are presented in Table 14 along with the concentrations obtained in the leachates. The average control concentrations determined during this investigation for all three metals are within those ranges reported as natural background for fresh water by Allen et al. (1974), i.e., 0.002 to 0.05 mg/L for copper, 0.005 to 0.1 mg/L for nickel, and 0.002 to 0.02 mg/L for lead. Interestingly, the average metal concentrations in the surface water of the tailings areas are within the water quality guidelines acceptable for short-term irrigation and for raw public water supplies for all of the metals considered (Reeder, 1979). The ranges of metal concentrations are, however, similar to those of the radionuclides, with large ranges over

TABLE 14 CONCENTRATIONS OF METALS (mg/L) IN SURFACE WATERS OF INACTIVE TAILINGS AREAS COMPARED WITH 48-HOUR STATIC LEACHING SOLUTIONS

	Bancroft				Elliot Lake				Uranium City				Control*			
	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N
Cu																
Surface waters	0.7	<0.003	26.6	40	0.2	<0.003	3.0	57	No data				0.009	<0.003	0.02	36
Leachate	0.02	<0.003	0.4	12	0.12	<0.003	0.8	24	0.09	0.04	0.17	15	0.03	<0.003	0.09	16
Ni																
Surface waters	0.2	<0.008	5.4	40	0.3	<0.008	4.5	57	No data				0.009	<0.008	0.03	36
Leachate	0.04	<0.008	0.12	12	0.3	<0.008	2.7	24	0.21	0.04	1.01	15	0.05	<0.008	0.15	16
Pb																
Surface waters	2.6	<0.2	117	46	0.1	<0.2	1.4	63	0.04	<0.2	0.11	28	0.0	<0.2	0.5	48
Leachate	0.01	<0.2	0.04	11	0.78	<0.2	3.7	24	0.14	0.05	0.34	15	<0.007	<0.2	0.5	16

* Control sites include disturbed, nontailings areas (e.g., gravel pits, roadside ditches, etc.) that are close to the tailings sites at Bancroft and Elliot Lake, Ontario. No control sites at Uranium City, Saskatchewan, were examined.

several orders of magnitude between the lowest and highest values determined. In local water bodies, the concentration ranges determined indicated elevated levels of the metals copper, nickel, and lead.

Ionic species of copper are soluble over a wide range of pH and are strongly controlled by chelating and complexing reactions. Therefore, organic substances control the soluble and insoluble complexes of copper, so copper solubility is highly dependent on the amount of organic matter present in the soil (Kabata-Pendias and Pendias, 1984). Tailings are low in organic matter; hence, copper solubility in tailings will differ from that in soils. The copper leachate concentrations for the control soils and the Bancroft tailings have the same average concentrations and similar ranges. They are somewhat lower than the leachate concentrations from Elliot Lake and Uranium City (Gunnar). The mean leachate concentrations are slightly lower than those in the surface waters of the Bancroft and Elliot Lake tailings.

The mobility of nickel in soils is inversely related to pH (Kabata-Pendias and Pendias, 1984). Therefore, lower concentrations of nickel would be expected in the leachates from the alkaline Uranium City and Bancroft tailings than in those from the acidic Elliot Lake area tailings. The average concentrations of nickel in the control and Bancroft leachates are lower than that in the Elliot Lake leachates; however, the nickel released in the Uranium City leachates is the same order of magnitude as that in the acidic Elliot Lake leachates.

This could possibly indicate that nickel in Uranium City tailings might be more bioavailable than expected based on mobility predictions from pH alone.

The metal concentrations in the leachates reflect the chemical behaviour of these metals in soil. Lead is generally not very mobile in soils and, therefore, tends to accumulate. In the Bancroft tailings, lead concentrations are lower than those in the surface waters.

4.2.4 Other Elements in Surface Waters. Because the electrical conductivities of the surface waters on tailings were generally higher than those in the control water, it was of interest to determine some of the other constituents of these waters. Furthermore, the multielemental techniques, such as atomic absorption spectrophotometry and neutron activation analysis, used during this investigation permitted the determination of other components in addition to metals and radionuclides. In Table 15, the concentrations of aluminum, barium, calcium, magnesium, manganese, and sodium are given for the three tailings areas and the control waters.

TABLE 15 CONCENTRATIONS (mg/L) AND DETECTION LIMITS (mg/L) OF SELECTED ELEMENTS IN SURFACE WATERS OF INACTIVE URANIUM TAILINGS AREAS COMPARED WITH CONTROL AREAS

	Bancroft				Elliot Lake				Uranium City				Control*			
	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N
Al	1.4	0.04	6.3	29	19.2	0.1	234	49	109.2	0.1	1235	53	79.9	0.0	1444	39
Detection limit	(<5.9)			(1)	(<0.6)			(10)	(--)			(0)	(<0.07)			(1)
Ba		1.0		5	14.8	0.4	128	12	0.9	0.8	1.0	2	0.7	0.4	1.1	5
Detection limit	(<1.5)			(20)	(<1.4)			(30)	(<13.6)			(51)	(<5.7)			(31)
Ca	112.8	6.3	396	29	232.6	1.4	1280	58	1087.9	9.0	19 386	53	246.3	0.6	3275	43
Detection limit	(<15)			(1)	(<31.0)			(1)	(--)			(0)	(--)			(0)
Mn	1.5	0.003	6.7	26	2.5	0.02	22.3	45	34.8	0.0	587.7	52	7.3	0.001	127.3	36
Detection limit	(<0.4)			(4)	(<0.43)			(14)	(<0.04)			(1)	(<0.02)			(7)
Mg	36.3	2.0	112	21	47.5	2.7	265	37	733.0	4.3	17 553	52	251.2	1.66	2674	21
Detection limit	(<4.9)			(9)	(<33.1)			(22)	(<7.2)			(1)	(<6.0)			(21)
Na	10.3	1.2	35.1	29	80.1	1.2	529	57	177.8	2.4	1987	53	17.3	1.0	91.2	38
Detection limit	(<4.6)			(1)	(<16.1)			(2)	(--)			(0)	(<43)			(4)

* Control sites include disturbed, nontailings areas (e.g., gravel pits, roadside ditches, etc.) that are close to the tailings sites at Bancroft and Elliot Lake, Ontario. No control sites at Uranium City, Saskatchewan, were examined.

In Table 15, the detection limits and the number of samples encountered at that limit are listed in parentheses. For the elements barium and magnesium, a large fraction of the samples in all areas were at the detection limit. The different detection limits are due to the variable composition of the waters analyzed, which changes the background of the sample undergoing neutron activation analysis.

The mean concentrations of these elements (Al, Ba, Ca, Mg, Mn, and Na) in the water are only of interest in noting some differences between the study areas. The aluminum concentrations are highest in the control and Uranium City areas and lowest in the Bancroft area. Barium concentrations are highest in Elliot Lake waters, probably due to the treatment of water in this area with barium sulphate to remove radium-226. Calcium concentrations in the Uranium City area are very high due to one spurious sample with an extremely high calcium content. Calcium concentrations in the other three areas are all the same order of magnitude. Manganese concentrations are higher in waters from the Uranium City area than in waters from the other three locations. A similar pattern has been found for the element magnesium. The concentration of sodium is also highest in the Uranium City area.

In summary, the surface water on the Bancroft tailings generally contains the lowest concentrations of the elements investigated. The control site concentrations vary with respect to all three areas and for each element. Background freshwater concentrations reported by Allen et al. (1974) are in the same range for barium and sodium, with reported concentrations of 0.005 to 0.1 mg/L and 2 to 100 mg/L respectively. The other elements are higher than the reported background concentrations, likely due to the fact that they are mainly wetland samples; whereas larger freshwater bodies, such as rivers and lakes, are usually used to determine the background concentrations reported in the literature. Clearly, the concentrations of these elements vary between the control sites and the tailings sites, as well as among the tailings sites themselves, because the areas differ in physical and chemical characteristics and because of differences in the behaviour of the individual elements.

4.3 Radionuclide Concentrations in Plants

4.3.1 Uptake and Aerial Deposition of Radium-226 and Lead-210. Movement of radionuclides from the tailings into plant roots and their subsequent distribution within the plant are governed by a multitude of factors, some of which are environmental and some of which are inherent characteristics of the plants involved. These factors apply to most elements, including radionuclides.

The availability of elements in the soil (or tailings) solution, especially in the region close to the roots, known as the rhizosphere, is affected by numerous physical and chemical environmental factors, some of which have already been discussed (e.g., pH, conductivity, and moisture and organic matter content), as well as biological factors (e.g., microflora and fauna). One of the most important factors to consider is the availability of elements from the soil, such as radionuclides, that affect the transfer of the element(s) from the soil into the plants.

The ability of the plants to take up and/or accumulate these elements is dependent upon the uptake mechanisms of the plants, which can either be active or passive. This ability is often an inherent characteristic of the plants, which must also be considered when examining the potential of biological transport of elements in the biosphere. The translocation of elements within the plant is subsequently controlled by the plant's metabolism. The metabolic function of the element in question becomes important (e.g., Is it essential for growth? Is it toxic?).

In the present investigation, the concentrations of three radionuclides (radium-226, lead-210, and uranium) were determined in various parts of both terrestrial and wetland plants collected from tailings sites. No attempt was made to determine what concentrations of these elements in the various plant components (e.g., roots, stems, leaves) are the result of actual uptake from the soil by the roots or to trace the route of subsequent translocation within the plant. Studies examining these pathways for individual elements are required to describe the details of uptake and transport given the complexity of the rhizosphere (Harley and Russell, 1979).

Elements contained in the above-ground parts of the plants can originate from two sources: the soil environment (through root uptake and translocation) and through aerial deposition. Whicker and Schultz (1982) suggest that aerial deposition may be of particular importance for radionuclide accumulation in plants. Trace substances deposited on the surface of plants can be assimilated through stomata or epidermal tissues. It is technically difficult to differentiate between root uptake and surface deposition, particularly in material collected from the field. In this study, any contribution of radionuclide particles from windblown tailings could affect the concentrations determined in the plants growing on these waste sites. Aerial deposition of gaseous radon-222, the precursor of particulate polonium-218, which decays to lead-210, could also be significant.

Because aerial deposition of radionuclides from the tailings environment was considered an important potential contributor to the concentrations determined in plants growing directly on tailings areas, all plant material was washed prior to analysis. When washed and unwashed leaves of wihte birches were compared, however, no significant differences were determined at the 0.95 confidence level of a Student's t-test for radium-226 (Kalin and Smith, 1984).

The frequency distributions of concentrations of radium-226 and lead-210 for the same data set of washed and unwashed leaves and stems of white birch are presented in Figures 1 and 2 respectively. For radium-226, the distributions show that the concentrations are similar for leaves and stems from both sample sets. If significant amounts of particulate matter had adhered to the surface of the leaves, the unwashed leaves would have shown higher concentrations of radium-226; this would, as a result, have altered the ratios between concentrations in the upright stems and those in the more horizontal leaves. Within the data set, there are, in fact, washed leaves with higher radium-226 concentrations than in the unwashed set.

The lead-210 distributions presented in Figure 2 indicate a similar distribution to that of radium-226. It does not appear that aerial deposition of tailings and particulates is a major contributor to an increase in the concentrations of lead-210 on leaves of white birch. The differences between stems and leaves in the unwashed and washed sample sets again suggest that some trees have higher concentrations in the stems. Frequently, concentrations of 8 to 10 pCi/g (296 to 370 mBq/g) dry matter were encountered. However, the unwashed sample set displays a more uniform frequency distribution for stems and leaves than the washed sample set. Leaves have a larger surface area than stems. If significant fractions of tailings or particulates adhere to the leaves, the relative concentration of radionuclides should be noticeably different between washed and unwashed samples. Clearly, other factors must exert greater control over the radionuclide concentrations within individual trees than differences that could be attributed to morphological and physical factors. Linear correlations between concentrations of radium-226 in both leaves and stems and the age of white birch trees were noted, suggesting that young trees have higher radium-226 concentrations than older trees.

It was not unexpected that lead-210 concentrations would be higher on leaves than on stems. Hinton (1983) reported increased radon-222 flux on vegetated uranium tailings, which was associated with precipitation events. However, a recent study comparing vegetated plots with those from which vegetation had been removed did not

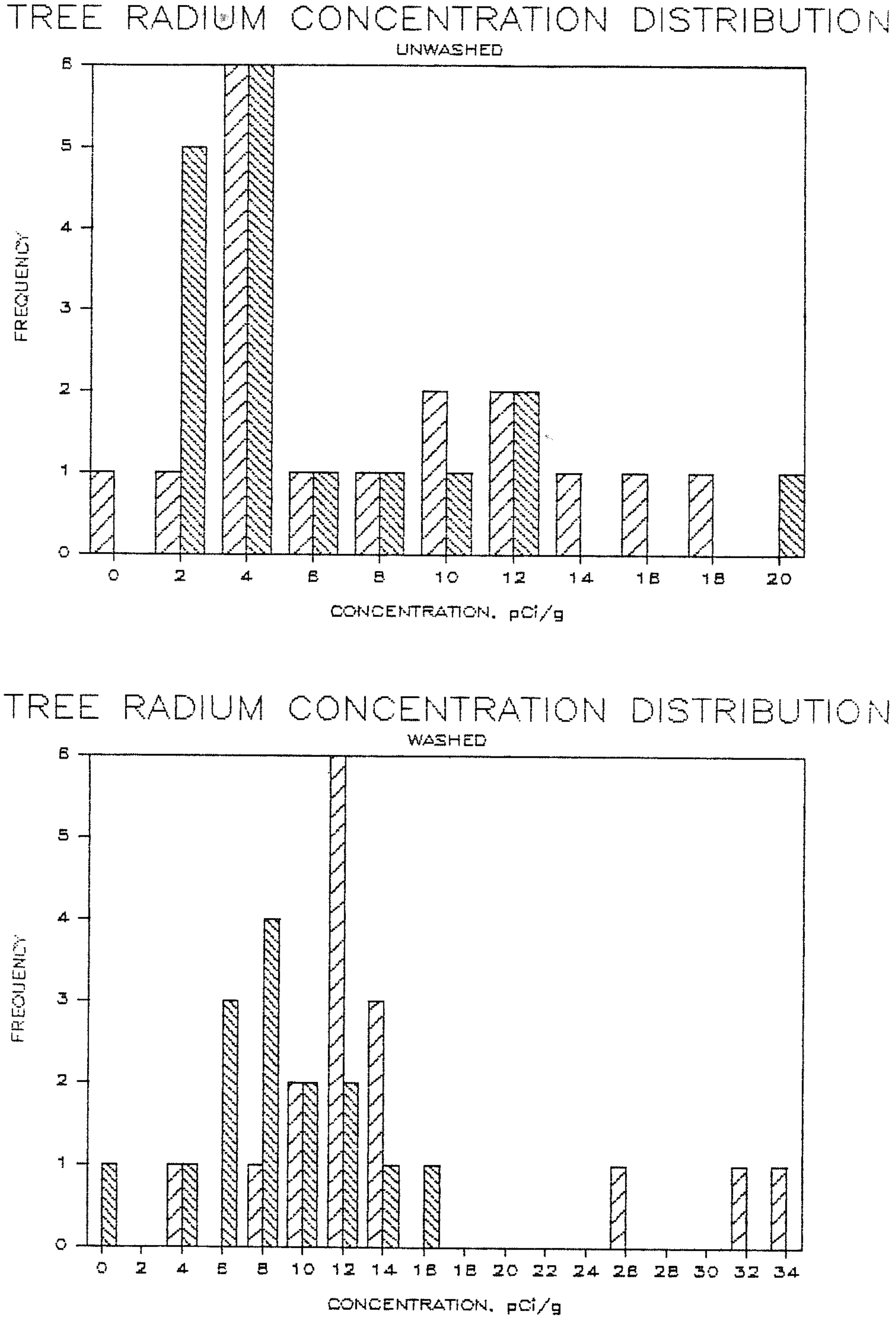


FIGURE 1 FREQUENCY DISTRIBUTIONS OF RADIUM-226 CONCENTRATIONS IN UNWASHED AND WASHED LEAVES (▨) AND STEMS (▧) OF WHITE BIRCHES GROWING ON URANIUM TAILINGS. (Note: 1 pCi = 37 mBq.)

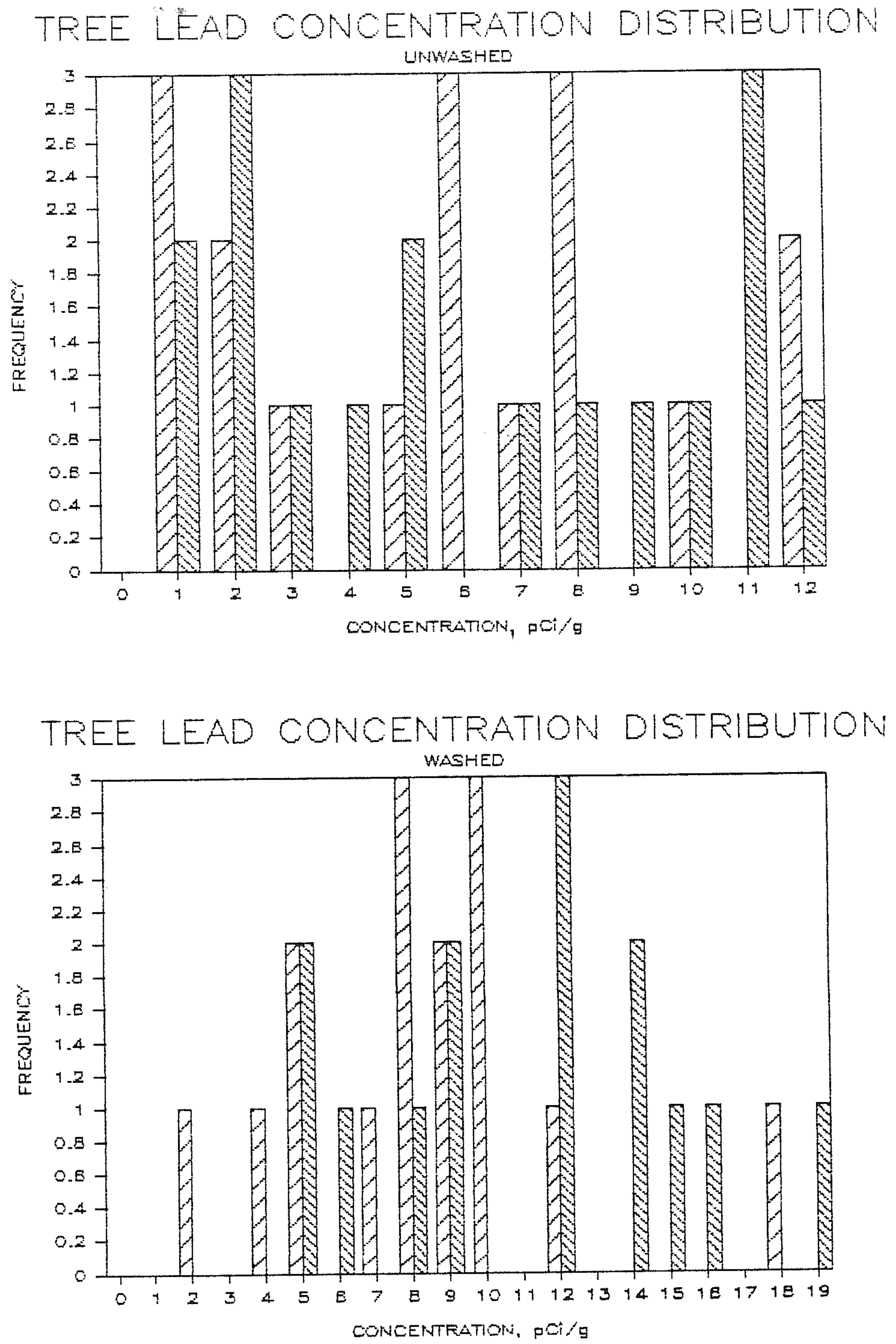


FIGURE 2 FREQUENCY DISTRIBUTIONS OF LEAD-210 CONCENTRATIONS IN UNWASHED AND WASHED LEAVES (▨) AND STEMS (▧) OF WHITE BIRCHES GROWING ON URANIUM TAILINGS. (Note: 1 pCi = 37 mBq.)

show any differences (NUTP, 1985). Flux increases might be expected due to respiration by the plants. Nevertheless, the decay product of the gaseous radon-222 is a particulate, so leaves, with their larger surface area compared with stems, could attract higher proportions of polonium-218, which decays to lead-210 within an hour. Should this process contribute significantly to aerial deposition of lead-210, leaves of trees on uranium tailings should reveal evidence of increased lead-210 concentrations. This data set clearly does not lend any support to this position. The 50th percentile of lead-210 concentrations from the cumulative frequency distribution plotted for both unwashed and washed leaves and stems in Figure 3 indicates that the stem concentrations are slightly higher than those of the leaves in both sample sets. The results of these comparisons of washed and unwashed leaves strongly suggest that aerial contamination by radium-226 and lead-210 from tailings particulates cannot be substantiated.

All leaves collected for this evaluation were sampled from the same tree stand. This stand, a remnant of revegetation test plots, was located in the central part of a bare, i.e., unvegetated, tailings area in Elliot Lake, where it was exposed to windblown tailings (Kalin and Smith, 1985). Given the conditions of the sampling location and the absence of evidence suggesting significant aerial deposition of both radionuclides from tailings or particulate matter on leaves in this exposed stand, it is reasonable to assume that the same lack of aerial contamination would be the case for all other plants collected during this study. Hence, radionuclide concentrations presented in the following sections for terrestrial and wetland plants growing on uranium mill tailings represent concentrations that are likely to result from actual uptake, either through the roots or through incorporation from the plant surface. If aerial deposition of tailings does take place on leafy matter, precipitation appears to be sufficient to remove the particulates, similar to washing the leafy parts of the plants, so that the overall concentration in the plant material is not affected.

4.3.2 Radium-226 and Lead-210 Concentrations in Terrestrial Vegetation. In Tables 16 and 17, the concentrations of radium-226 and lead-210 in trembling aspens, white birches, and some ground cover vegetation from both tailings (Bancroft and Elliot Lake) and control areas are presented. It is possible to compare the concentrations determined for the control populations, i.e., those growing in the nontailings environment, with those from the tailings areas. Two groups of concentration means and ranges are given. One mean is for trees collected from different tailings and control locations; the second mean is for the same species of trees collected from a single tailings or control

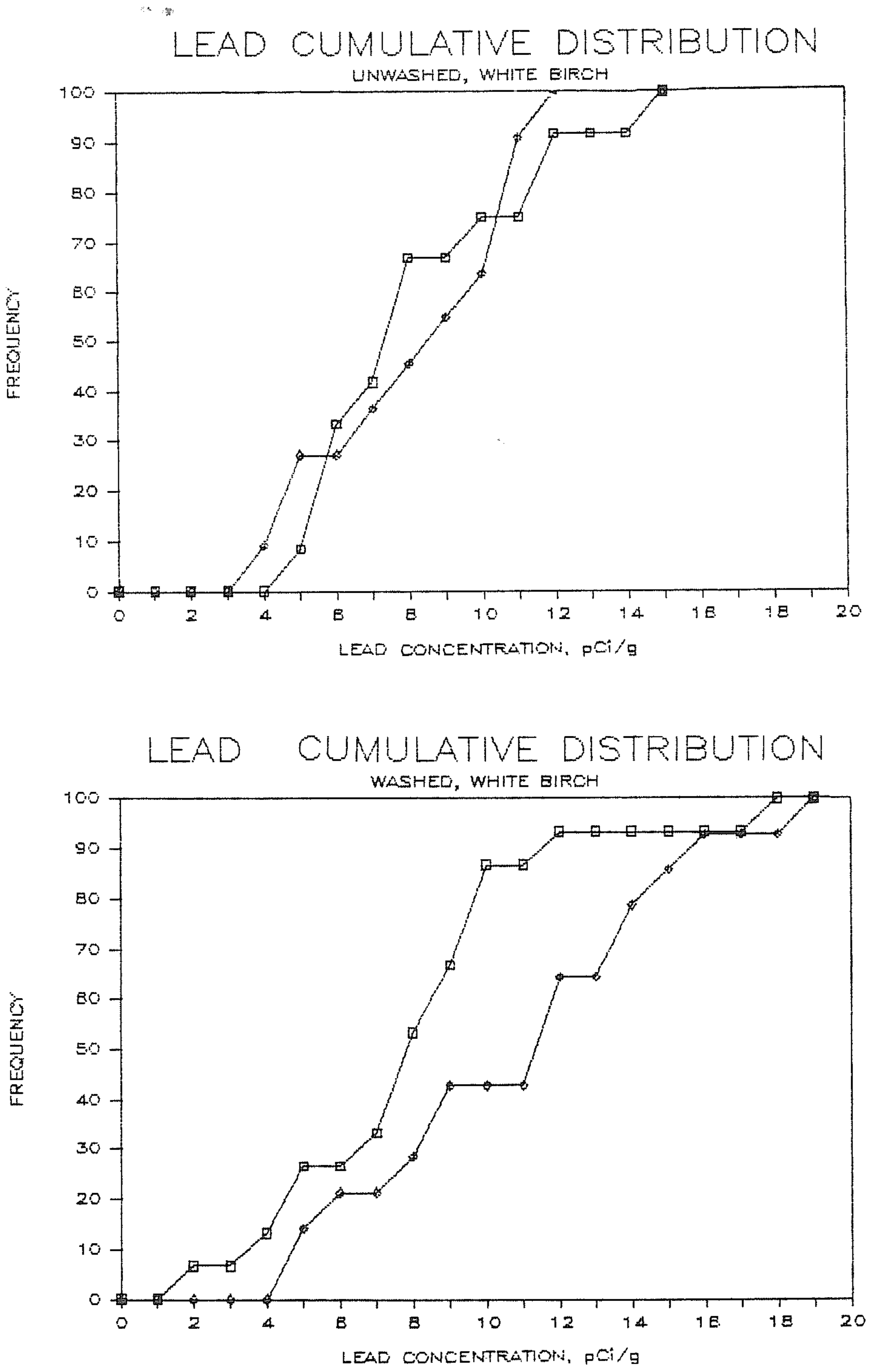


FIGURE 3 CUMULATIVE FREQUENCY DISTRIBUTIONS OF LEAD-210 IN UNWASHED AND WASHED LEAVES (□) AND STEMS (◇) OF WHITE BIRCHES GROWING ON TAILINGS. (Note: 1 pCi = 37 mBq.)

TABLE 16 CONCENTRATIONS OF RADIUM-226 (pCi/g dry weight) IN TERRESTRIAL PLANTS

	Bancroft				Control				Elliot Lake			
	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N
Trembling Aspen Collected from Several Sites												
Stems	24.0(888.0)	2.8(103.6)	45.2(1672.4)	4	1.0 (37.0)	<1(<37)	2.9 (107.3)	3	2.6 (96.2)	<1(<37)	6.7 (247.9)	4
Leaves	17.2(636.4)	<1(<37)	33.3(1232.1)	4	1.7 (62.9)	<1(<37)	3.4 (125.8)	3	2.5 (92.5)	1.3 (48.1)	5.3 (196.1)	4
Roots	14.7(543.9)	1.1 (40.7)	38.5(1424.5)	4	1.4 (51.8)	<1(<37)	2.3 (85.1)	3	3.4(125.8)	1.0 (37.0)	5.5 (203.5)	4
Trembling Aspen Collected from a Single Site												
Stems	No data				3.1 (114.7)	<1(<37)	6.5 (240.5)	6	3.7(136.9)	1.6 (59.2)	7.5 (277.5)	5
Leaves	No data				4.7 (173.9)	1.4 (51.8)	9.5 (351.5)	6	5.2(192.4)	<1(<37)	8.1 (299.7)	3
Roots	No data				No data				No data			
White Birch Collected from Several Sites												
Stems	41.2(1524.4)	7.3(270.1)	74.3(2749.1)	4	34.1(1261.7)	<1(<37)	99.4(3677.8)	3	8.7(321.9)	<1(<37)	39.2(1450.4)	8
Leaves	56.7(2097.9)	8.3(307.1)	135.1(4998.7)	4	16.8 (621.6)	<1(<37)	44.0(1628.0)	3	8.8(325.6)	<1(<37)	24.5 (906.5)	8
Roots	36.7(1357.9)	8.1(299.7)	76.7(2837.9)	4	21.0 (777.0)	<1(<37)	60.1(2223.7)	3	6.1(225.7)	<1(<37)	12.2 (451.4)	8
White Birch Collected from a Single Site												
Stems	No data				3.2 (118.4)	1.1 (40.7)	8.6 (318.2)	10	7.0(259.0)	<1(<37)	19.6 (725.2)	24
Leaves	No data				4.9 (181.3)	<1(<37)	24.6 (910.2)	9	12.0(444.0)	<1(<37)	33.5(1239.5)	25
Roots	No data				6.6 (244.2)	3.1(114.7)	10.1 (373.7)	2	4.9(181.3)	4.7(173.9)	5.2 (192.4)	2

	Grass *		Herbs *		Shrubs *	
	Control	Tailings	Control	Tailings	Control	Tailings
Individual Samples						
Ra-226	<1(<37)	14(518)	1 (37)	1 (37)	1 (37)	34(1258)
	<1(<37)	8(296)	3(111)	2 (74)	4(148)	8 (296)
		2 (74)		5(185)	<1(<37)	6 (222)
		7(259)				8 (296)
		14(518)				
Mean	<1(<37)	9(333)	2 (74)	3(111)	3(111)	14 (518)

Note: values in parentheses are mBq/g

* grasses, herbs, and shrubs were collected from a single site

TABLE 17 CONCENTRATIONS OF LEAD-210 (pCi/g dry weight) IN TERRESTRIAL PLANTS

	Bancroft				Control				Elliot Lake			
	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N
Trembling Aspen Collected from Several Sites												
Stems	2.1 (77.7)	<1(<37)	2.8(103.6)	4	0.3 (11.1)	<1(<37)	0.8 (29.6)	3	1.2 (44.4)	<1(<37)	2.8(103.6)	4
Leaves	1.7 (62.9)	<1(<37)	2.3 (85.1)	4	0.2 (7.4)	<1(<37)	0.5 (18.5)	3	0.8 (29.6)	<1(<37)	2.3 (85.1)	4
Roots	1.4 (51.8)	1.1(40.7)	2.0 (74.0)	4	0.5 (18.5)	<1(<37)	1.3 (48.1)	3	2.8(103.6)	<1(<37)	7.5(277.5)	4
Trembling Aspen Collected from a Single Site												
Stems	No data				1.8 (66.6)	<1(<37)	4.1 (151.7)	6	3.0(111.0)	<1(<37)	5.9(218.3)	4
Leaves	No data				3.5(129.5)	<1(<37)	8.1 (299.7)	6	4.3(159.1)	1.5 (55.5)	5.5(203.5)	4
White Birch Collected from Several Sites												
Stems	6.5(240.5)	1.4(51.8)	18.7(691.9)	4	13.4(495.8)	<1(<37)	38.0(1406.0)	3	7.4(273.8)	<1(<37)	25.6(947.2)	8
Leaves	6.0(222.0)	<1(<37)	16.0(592.0)	4	2.6 (96.2)	<1(<37)	5.4 (199.8)	3	2.4 (88.8)	<1(<37)	5.9(218.3)	8
Roots	3.8(140.6)	<1(<37)	10.1(373.7)	4	13.0(481.0)	<1(<37)	37.2(1376.4)	3	7.5(277.5)	<1(<37)	24.0(888.0)	8
White Birch Collected from a Single Site												
Stems	No data				2.5 (92.5)	<1(<37)	8.6 (318.2)	9	9.3(344.1)	3.7(136.9)	18.9(699.3)	8
Leaves	No data				2.4 (88.8)	<1(<37)	8.7 (321.9)	9	7.3(270.1)	1.7 (62.9)	14.2(525.4)	24
Roots	No data				No data				No data			

	Grass *		Herbs *		Shrubs *	
	Control	Tailings	Control	Tailings	Control	Tailings
Individual Samples						
Pb-210	1(37)	14(518)	0.6(22.2)	2 (74)	1(37)	2 (74)
	2(74)	8(296)	0.9(33.3)	2 (74)	<1(<37)	8(296)
		1 (37)		5(185)	2(74)	9(333)
		3(111)				11(407)
		7(259)				
Mean	1(37)	7(259)	0.7(25.9)	3(111)	2(74)	7(259)

Note: values in parentheses are mBq/g

* grasses, herbs, and shrubs were collected from a single site

location. This differentiation facilitates a comparison of the variations encountered within a sampling location with variations that might be due to different sampling locations. The single collection site is the same, namely the Stanleigh/Milliken or former Crotch site in the Elliot Lake area (Table 1), for both tree species as well as the ground cover species. The mean concentrations in trees at various sites in the Bancroft area were established from samples collected from four sites (Madawaska, Bicroft Proper, Auger Lake, and Dyno). One tree, taller than 1 m and rooted in tailings, was collected from each site. For the Elliot Lake area, trees were collected from Nordic Main and the West Arm, Stanrock and one spill area, Lacnor, Olive, Williams, and Stanleigh/Milliken. For the control populations investigated, the single population was collected from a gravel pit northwest of Elliot Lake and the populations from various sites were collected from cut-overs, old fields, and road sites identified earlier for the Bancroft and Elliot Lake areas (Kalin, 1984a).

Differences in radionuclide concentrations between tree species and ground cover. In the ground cover vegetation, the grass and shrub samples have higher mean values than the herbs. Herbs and grasses are the only nonwoody type of vegetation analyzed for the terrestrial environment. Only a relatively small number of samples was available for evaluation and a larger sample set would be needed to make further statements about the role of this type of vegetation.

Dave et al. (1984b) analyzed composite samples of two types of introduced grasses (fescue and redtop) and trefoil *(Lotus corniculatus)* collected from the revegetated Nordic tailings site in the Elliot Lake area. The harvest from several quadrats (each 1 m^2) was separated into leaves, stems, and flowers, thereby obtaining large quantities of biomass for each site (N.K. Dave, personal communication). The data suggest only slight differences in the concentrations of both radium-226 and lead-210 among these introduced species.

The radionuclide concentration ranges determined for all components of the ground cover were similar in both investigations. The highest radium-226 concentration reported by Dave et al. (1984b) was 11 pCi/g (407 mBq/g) in a summer sample of whole redtop; in the present investigation, the highest value for nonwoody ground cover was 14 pCi/g (518 mBq/g) for a whole grass sample. Similarly, the highest lead-210 concentration in the former study was 13 pCi/g (481 mBq/g) in stems of trefoil compared with 14 pCi/g (518 mBq/g) for a grass sample in this study.

The concentration ranges suggest that woody plants, i.e., trees and shrubs, generally contain higher amounts of radionuclides than nonwoody, herbaceous species. White birches generally have higher mean radionuclide concentrations and larger concentration ranges of both radionuclides (radium-226 and lead-210) than trembling aspens in all tree parts analyzed (e.g., roots, stems, and leaves). In the control location, the highest values of radium-226 and lead-210, 99 pCi/g (3663 mBq/g) and 38 pCi/g (1406 mBq/g), respectively, were encountered in the stem of an individual white birch. For the tailings sites, the highest concentrations reported were about half those given above for the control tree. These highest values were again associated with white birches and their woody component. Dave et al. (1984a,c) also reported concentrations for white birches and trembling aspens. Unlike this investigation, only one subsample, derived from composite samples of trees collected from four different tailings sites in the Elliot Lake area, was analyzed for each site (N.K. Dave, personal communication). The highest value of radium-226 (27 pCi/g (999 mBq/g)) was associated with white birch leaf samples from the revegetated Nordic tailings site, whereas the highest lead-210 value (7 pCi/g (259 mBq/g)) was determined in the stem sample from the same site (Dave et al., 1984a,c).

In the present study, 99 tree parts (e.g., stems, roots, and leaves), from 41 different trees on the Elliot Lake tailings, were analyzed. The concentrations of both radionuclides range from the detection limit (<1 pCi/g (<37 mBq/g) dry weight) to values of about 40 pCi/g (1480 mBq/g) (Tables 16 and 17). Although individual trees can display a large radionuclide concentration range, the highest concentrations reported are consistently associated with white birch, analyzed as a composite sample (Dave et al., 1984a,c) or as samples from individual trees. This difference in radionuclide concentrations between white birch and trembling aspen is found not only on the tailings sites but also on the control sites examined.

Differences in radionuclide uptake between tailings areas. As indicated in the previous section, white birch trees contain higher concentrations of both radium-226 and lead-210 than trembling aspen and the herbaceous species examined. Results of this study also indicate that white birch assimilates similar amounts of both radionuclides on control sites as well as tailings sites. The radium-226 concentrations in stems, leaves, and roots of white birch from the Elliot Lake tailings are higher than values for trees collected from several nearby control sites. However, the Bancroft tree concentrations are generally higher for both species than those of trees growing on Elliot Lake tailings sites.

The sample sets of trees from all three areas are not very large, usually consisting of three to eight trees. However, the white birches collected from the single control and single tailings site in the Elliot Lake area (N = 10 and 24 trees, respectively) have similar radium-226 concentration ranges. This may suggest that the trees on the Bancroft tailings, indeed, have higher concentrations of radium-226. On the other hand, it may also be a reflection of possible differences in bioavailability, which can be expected based on the consistently higher concentrations of radium-226 in surface water and leachates of the Bancroft tailings than those of the Elliot Lake tailings (Table 13).

For lead-210, the differences between the tailings areas and the control are not as striking as for radium-226; the averages of the stems, leaves, and roots in the Bancroft area have concentrations similar to those on the Elliot Lake tailings. Because the white birch control samples contain one individual tree with very high radionuclide concentrations and because the control collection of white birches from several sites consisted of only three trees, the impression that the control white birches have values in the same range as the trees from the tailings sites may be misleading. The control white birches (N=10) are clearly lower in radium-226 and lead-210 than the birches growing on the tailings.

For trembling aspens, basically the same pattern emerges for their radium-226 and lead-210 concentrations. The aspens on the Bancroft tailings contain higher concentrations of radium-226 than the trees on either the control or Elliot Lake tailings sites. The differences between the aspens growing on the Elliot Lake tailings and those on the control sites are very small for both radionuclides and are probably not statistically significant. The results, comparing the different tailings areas and the bioavailability of radium, based on concentrations in trees, indicate that radium-226 is transported to trees more readily in the Bancroft area than in the Elliot Lake area.

Radionuclide distribution within the trees. The average concentrations, as well as the concentration ranges of both radionuclides, in the fast-growing trembling aspens suggest that these radionuclides are distributed in similar concentrations throughout the stems, leaves, and roots. For the white birches, however, there is some indication that the average concentrations in the leaves and stems differ for both radionuclides (Tables 16 and 17). This is particularly suggested in the larger sample set available, where trees were collected from a single site. This data set was analyzed in some detail with respect to the distribution of both radium-226 and lead-210 within white birches.

In Figure 4, the cumulative frequency distributions are presented for white birch leaves and stems from both control and tailings sites. The concentrations in the control populations are definitely lower than those in the tailings. The slopes of the distribution of control stems and leaves are slightly separated for radium-226, suggesting lower concentrations in the stems than in the leaves. For lead-210, the curves are less separated but suggest some small differences between stems and leaves.

The slopes for leaves and stems of white birches growing on tailings are clearly separated, with a 50th percentile for radium-226 of about 7 pCi/g (259 mBq/g) for stems and 11 pCi/g (407 mBq/g) for leaves and a 50th percentile for lead-210 of 7 pCi/g (259 mBq/g) for leaves and 9 pCi/g (333 mBq/g) for stems. The compartmentalization of the two radionuclides, therefore, is different, i.e., lead-210 tends to associate with the woody parts of white birches, whereas radium-226 is associated with the leaves. These results suggest that radium-226 is more mobile within the plant and is associated with the annual leaf production, whereas lead-210 is less mobile and is associated with the perennial woody part of the white birches. This distribution pattern is clearly evident in the histogram presented in Figure 5 for radium-226. These distributions of radium concentrations in leaves and stems have different peaks - for leaves, 22 to 24 pCi/g (814 to 888 mBq/g); for stems, 6 to 8 pCi/g (222 to 296 mBq/g). For lead-210, the distributions in the leaves and stems are not as strikingly different as those for radium-226.

Concentration factors* of radionuclides in trees on tailings. The objective of determining radionuclide concentrations in vegetation is aimed at achieving a better understanding of the movement of these substances from the tailings into the indigenous vegetation to adequately predict the potential long-term effects. Models that are used to predict these long-term effects require an estimate of the parameters involved, e.g., concentration factors (Osborne, 1984). The ratio of the concentration of a radionuclide in the vegetation to that in the tailings can be calculated from the field data collected in this study. These ratios provide empirical values that are subject to some variability due to the influence of factors such as initial concentrations in the tailings and in the surface waters on tailings and growth characteristics of vegetation.

Consideration was given, during sample collection, to some of the problems frequently encountered with concentration factors (also referred to as transfer

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* The terms concentration factors, ratios, and coefficients have been used interchangeably in this report.

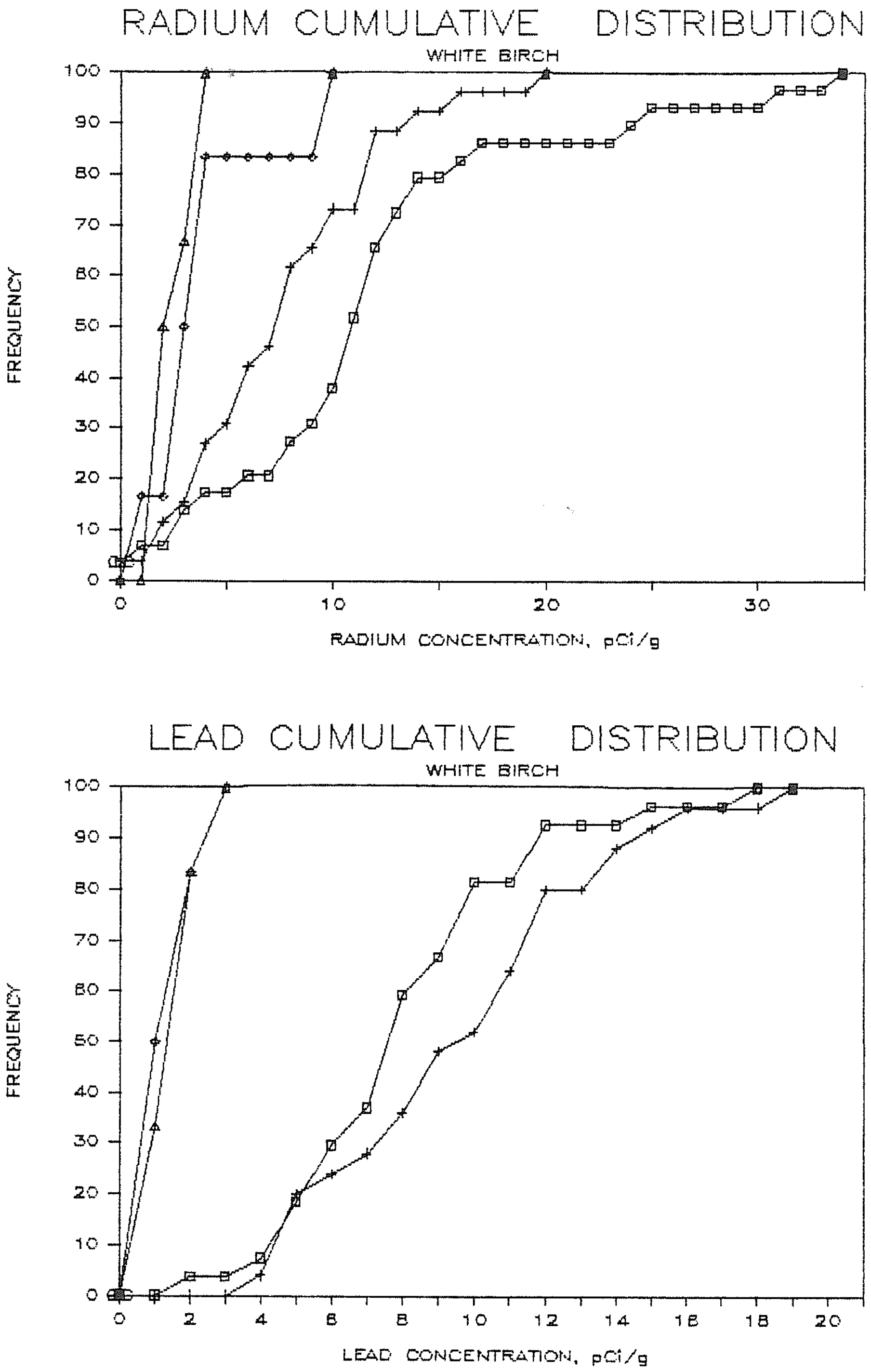

FIGURE 4 CUMULATIVE FREQUENCY DISTRIBUTION OF RADIUM-226 AND LEAD-210 IN LEAVES (□) AND STEMS (x) OF WHITE BIRCHES GROWING ON URANIUM TAILINGS AND LEAVES (◇) AND STEMS (Δ) OF WHITE BIRCHES GROWING ON CONTROL SITES. (Note: 1 pCi = 37 mBq.)

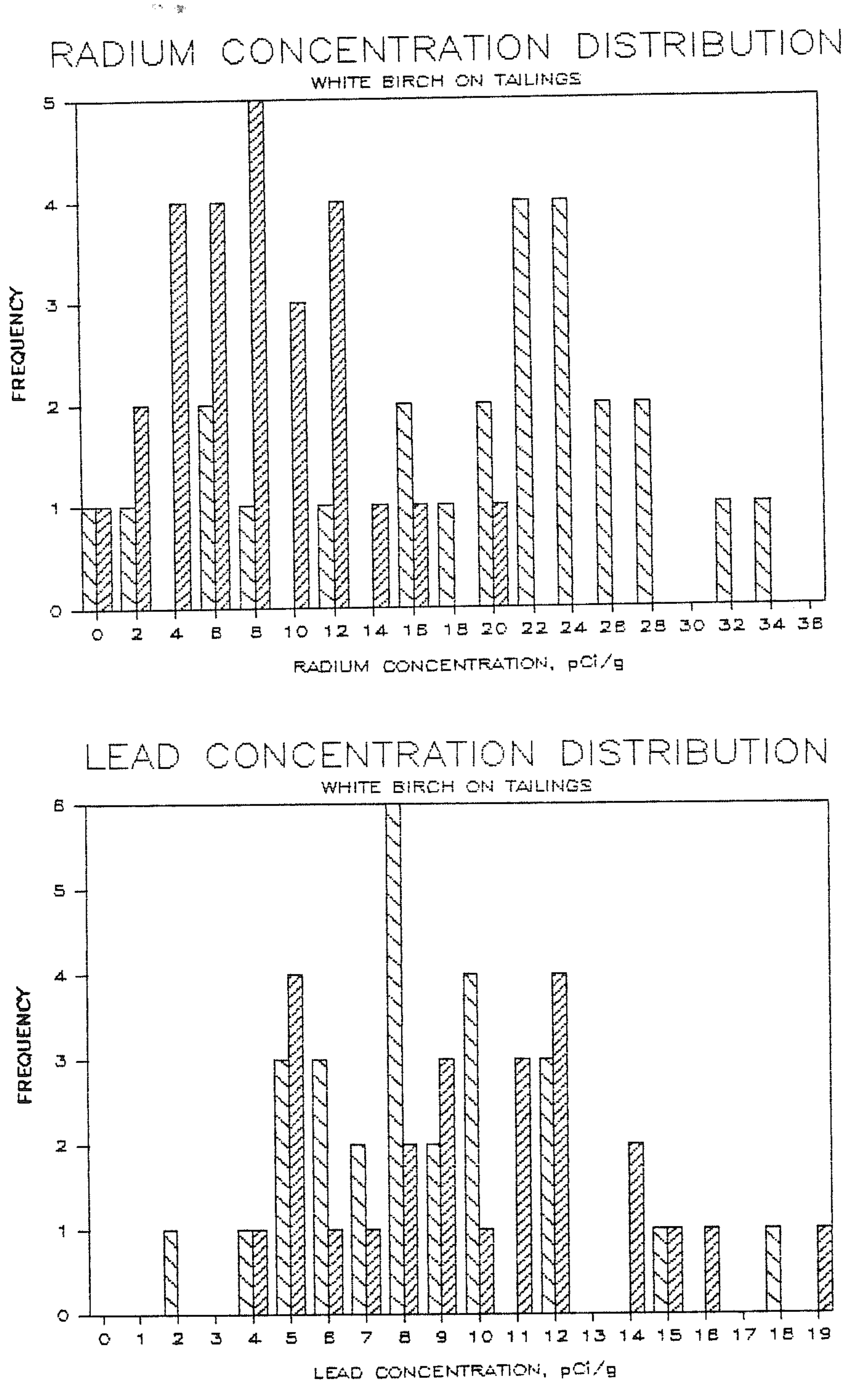

FIGURE 5 FREQUENCY DISTRIBUTION OF RADIUM-226 AND LEAD-210 CONCENTRATIONS IN LEAVES (▧) AND STEMS (▨) OF WHITE BIRCHES GROWING ON TAILINGS. (Note: 1 pCi = 37 mBq.)

coefficients). Correlations between concentrations of elements in plants and those in either soil extracts or soil solids have been found to vary extensively. Generally, less than 50 percent of the total variance can be explained by correlations of elemental concentrations in soils and in the plants (Gough et al., 1979). In this investigation, tailings and soil samples associated with vegetation have been separated into surface samples (0 to 5 cm depth) and rhizosphere samples (20 to 25 cm depth), which are directly associated with the plant roots. This sample separation was done in an attempt to distinguish any possible differences in vertical movement of radionuclides within the soil or tailings substrate and, furthermore, to establish more reliable transfer coefficients for all plants collected individually. Some considerations of the concentrations of radium-226 on the surface and in the root regions are presented below.

In Table 18, the results from both surface and root zone samples from tailings with a vegetation cover are presented, in addition to a sample set that was collected from tailings without a vegetation cover. The small data sets for mean radium-226 concentrations and their standard deviations for bare tailings, i.e., tailings without vegetation, and for tailings with vegetation show a variation in the concentrations that is consistent with the previously presented data, i.e., extremely large. No definite trends in radium-226 concentrations between the surface and the root zone can be established in the uranium tailings examined, confirming earlier findings. Some indication is given, however, that in the tailings in the Elliot Lake area the concentrations in the surface (0 to 5 cm depth) samples are frequently similar or only slightly lower than those in the tailings collected at 20 to 25 cm depth. If this small sample set can be taken as indicative of the conditions on the surface of the tailings in the Elliot Lake area, then the reverse is the case for the Bancroft tailings. Dave et al. (1984c) suggested a possible depletion of radionuclides in the surface zone of tailings compared with deeper zones for the Elliot Lake tailings site (Nordic).

A detailed evaluation of the ratios of concentrations in the surface and rhizosphere samples, based on values from individual samples showed no conclusive depletion of radionuclides in the surface tailings. These results led to the conclusion that the sample set presented in Table 18 is, indeed, insufficient to determine vertical movement of radium-226 in the uppermost 25 cm of the tailings. The results do demonstrate, however, that for concentration factors to be meaningful they should be calculated using the tailings directly associated with the root zone rather than material not in direct contact with the roots. This is particularly important to keep in mind

TABLE 18 CONCENTRATION OF RADIUM-226 (pCi/g) IN SURFACE AND ROOT-DEPTH TAILINGS

	Bancroft (Mean ± SD)	N	Elliot Lake (Mean ± SD)	N	Control (Mean ± SD)	N
Bare (Unvegetated) Tailings						
Surface (0 to 5 cm)	69 ± 73 (2553 ± 2701)	10	(45 ± 52) (1665 ± 1924)	12	20 ± 3 (740 ± 111)	3
20 to 25 cm root depth	39 ± 30 (1443 ± 1110)	9	62 ± 85 (2294 ± 3145)	10	21 ± 1 (777 ± 37)	3
Ratio: Root depth/surface	0.56		1.37		1.05	
Tailings with Vegetation						
Surface (with aspens)	52 (1924)	1	9 ± 8 (333 ± 296)	4	0.9 (33.3)	1
20 to 25 cm root depth	36 (1332)	1	15 ± 14 (555 ± 518)	4	0.6 (22.2)	1
Ratio: Root depth/surface	0.69		1.7		0.67	
Surface (with birch)	150 (5550)	1	44 ± 55 (1628 ± 2035)	7	4 ± 5 (148 ± 185)	3
20 to 25 cm root depth	-		48 ± 53 (1776 ± 1961)	7	3 ± 4 (111 ± 148)	3
Ratio: Root depth/surface	-		1.09		0.75	

Note: values in parentheses are mBq/g

because of the considerable variation reported, horizontally, over the tailings area, as well as vertically within the same sampling location.

Furthermore, an evaluation of radium-226 concentrations in the surface and root zones of wet and dry areas of the tailings from both the Bancroft and Elliot Lake areas clearly revealed that the concentration of this radionuclide had the highest variation between surface and root zone samples. In addition, the concentrations of the Group II elements (Ca, Mg, and Ba) were similarly variable (Kalin and Sharma, 1981b).

For lead-210, the surface concentrations, compared with concentrations in the deeper zone, should indicate differences based on the moisture differences between these depths. Moisture content has been implicated in the shifting lead-210 levels due to retention of radon-222. That this is, indeed, the case for some samples in the data set has been described previously (Kalin and Sharma, 1981a). Hence, surface samples in wet areas would indicate somewhat higher concentrations of lead-210 than surface samples in dry areas (Table 8).

From the concentrations presented above, it was felt necessary that for the trees collected from individual sites concentration factors should be calculated from the concentrations in roots and those in the soil or tailings directly associated with roots. Ratios were also calculated between the different parts of the trees. Using concentrations of radionuclides in tailings that are not directly associated with the vegetation is unsatisfactory and may lead to misrepresentation of the transfer coefficients.

The concentration ratios for radium-226 and lead-210 for white birch and trembling aspens are presented in Table 19. Because the white birches had higher concentrations of radium-226 and lead-210 than the trembling aspens, the concentration ratios should reflect these differences. However, for both species in both tailings areas, the concentration ratios are below unity and the sample size is too small to suggest differences. The roots of neither tree accumulate radium-226 or lead-210. The concentration factors for both radionuclides reflect the same differences discussed earlier in detail. If the uptake of radium-226 and lead-210 had resulted in a difference in root/tailings ratios between the white birches and trembling aspens, it would have suggested that one species actively accumulates the radionuclide. Given that the uptake ratios are similar, the differences between the species are more likely due to the different growth characteristics of these tree species, as suggested earlier. The fast-

TABLE 19 CONCENTRATION RATIOS OF RADIUM-226 AND LEAD-210 IN TERRESTRIAL PLANTS: BIRCHES AND ASPENS

	Bancroft Tailings		Elliot Lake Control		Elliot Lake Tailings	
	N	Ratio	N	Ratio	N	Ratio
Ra-226						
White Birch						
Roots*	4	0.25	3	4.95	8	0.14
Root zone	1		2		7	
Stem	4	1.12	3	1.62	8	1.42
Root	4		3		8	
Leaves	4	1.38	3	0.49	8	1.00
Stems	4		3		8	
Trembling Aspen						
Roots	4	0.41	3	2.28	4	0.23
Root zone	1		1		4	
Stem	4	1.63	3	0.71	4	0.77
Root	4		3		4	
Leaves	4	0.72	3	1.78	4	0.94
Stem	4		3		4	
Pb-210						
White Birch						
Roots	4	2.38	3	43.23**	8	0.72
Root zone	1		2		7	
Stem	4	1.71	3	1.03	8	0.99
Root	4		3		8	
Leaves	4	0.92	3	0.19	8	0.33
Stems	4		3		8	
Trembling Aspen						
Roots	4	0.78	3	1.33	4	0.62
Root zone	1		1		4	
Stem	4	1.51	3	0.51	4	0.41
Root	4		3		4	
Leaves	4	0.80	3	0.63	4	0.71
Stems	4		3		4	

* ratio of root/root zone concentration

** one tree root sample contained an excessively higher concentration of lead-210 growing trembling aspens, which propagate by suckering, accumulate less than the slower growing, stunted white birches.

These concentration factors, although based on a small set of samples that shows considerable variation, indicate that radium-226 and lead-210 are not accumulated in trees as the concentrations in the roots are lower than in the surrounding tailings, regardless of how closely the tailings are collected to the tree roots. Considering that washing the root material is difficult and is likely to result in concentrations reflecting those of the potentially adhering tailings, the lower concentrations, indeed, support the absence of active accumulation of radium-226 and lead-210.

4.3.3 Radium-226 and Lead-210 Concentrations in Wetland Plants. Reclamation techniques have been developed mainly for terrestrial areas of tailings. Dry areas of inactive uranium tailings, therefore, have been stabilized with introduced vegetation cover in many instances. This cover has been described in detail in previous reports, with particular emphasis on the colonization of indigenous species and their possible role in ecosystem stabilization over the long-term on these waste sites (Kalin, 1983).

Wetlands on tailings beaches, where the dominant vegetation was cattails (*Typha*), were believed to be of importance over the long term. The radionuclide concentrations in this indigenous vegetation were investigated in detail. Radionuclide concentrations in wetland vegetation can be of importance to waterfowl and wildlife. In these wetlands, it was possible to examine the litter produced by annual plant growth, thus giving some indication of radionuclide cycling within the wetlands, i.e., the partitioning of radionuclides between the tailings or surface waters, the annual plant growth, and the litter components.

Partitioning of radionuclides in cattail stands. In Tables 20 and 21, the concentrations of radium-226 and lead-210 are given for individual cattail plants. Cattail litter that had accumulated in the quadrats (1 m^2) evaluated for growth (Kalin, 1984a) was separated into the various components of the plants (leaves, stems, and fruits). These plant parts were then analyzed separately for radium-226 and lead-210. The above-ground parts were also separated into different components and analyzed to determine a value for a composite sample of annual biomass production in a 1-m^2 quadrat. These samples were collected from cattail stands on both Elliot Lake and Bancroft tailings, as well as from control stands.

The most striking difference for both radium-226 and lead-210 concentrations is seen between the roots and the rhizomes. The concentrations in the roots are

TABLE 20 CONCENTRATIONS OF RADIUM-226 (pCi/g dry weight) IN WETLAND PLANTS

	Bancroft				Control				Elliot Lake			
	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N
Individual Cattail Plants												
Fruits	1.6 (59.2)	<1(<37)	4.3 (159.1)	6	0.2 (7.4)	<1(<37)	0.5 (18.5)	6	1.4 (51.8)	<1(<37)	6.5 (240.5)	10
Stems	1.6 (59.2)	<1(<37)	4.3 (159.1)	6	0.1 (3.7)	<1(<37)	0.2 (7.4)	7	4.7 (173.9)	<1(<37)	34.7(1283.9)	10
Leaves	9.2 (340.4)	1.3 (48.1)	20.5 (758.5)	6	0.8 (29.6)	<1(<37)	2.5 (92.5)	8	2.4 (88.8)	<1(<37)	11.0 (407.0)	10
Roots	90.4(3344.8)	5.0 (185.0)	227.3(8410.1)	5	6.3(233.1)	<1(<37)	25.0(925.0)	8	28.0(1036.0)	<1(<37)	126.9(4695.3)	10
Rhizomes	3.6 (133.2)	<1(<37)	11.1 (410.7)	6	0.7 (25.9)	<1(<37)	2.3 (85.1)	8	6.7 (247.9)	<1(<37)	30.0(1110.0)	10
Annual Above-ground Biomass												
Brown leaves	13.0 (481.0)	2.9 (107.3)	34.0(1258.0)	5	0.9 (33.3)	<1(<37)	2.3 (85.1)	4	2.0 (74.0)	<1(<37)	4.1 (151.7)	5
Thick leaves	3.4 (125.8)	1.1 (40.7)	7.2 (266.4)	4	2.9(107.3)	<1(<37)	10.8(399.6)	4	2.6 (96.2)	<1(<37)	6.5 (240.5)	7
Green leaves	1.8 (66.6)	0.0 (0.0)	2.9 (107.3)	3	0.6 (22.2)	<1(<37)	1.7 (62.9)	4	2.0 (74.0)	<1(<37)	7.5 (277.5)	7
Stems	4.8 (177.6)	4.8(177.6)	4.8 (177.6)	1	0.5 (18.5)	<1(<37)	1.2 (44.4)	4	1.5 (55.5)	<1(<37)	5.9 (218.3)	7
Fruits	3.8 (140.6)	3.8(140.6)	3.8 (140.6)	1	0.3 (11.1)	<1(<37)	0.5 (18.5)	4	1.9 (70.3)	<1(<37)	6.6 (244.2)	6
Cattail Litter												
Leaves	16.4 (606.8)	3.9(144.3)	30.5(1128.5)	4	4.3(159.1)	<1(<37)	11.9(440.3)	3	7.1 (262.7)	<1(<37)	13.5 (499.5)	7
Stems	4.9 (181.3)	<1(<37)	9.1 (336.7)	3	0.7 (25.9)	<1(<37)	1.6 (59.2)	4	3.5 (129.5)	<1(<37)	9.9 (366.3)	6
Fruits	1.8 (66.6)	1.8 (66.6)	1.8 (66.6)	1	0.9 (33.3)	<1(<37)	2.6 (96.2)	3	6.7 (247.9)	<1(<37)	25.3 (936.1)	6
Individual Sedge Plants												
Fruits	19.3 (714.1)	6.0(222.0)	28.4(1050.8)	3	0.4 (14.8)	<1(<37)	0.8 (29.6)	2	4.1 (151.7)	<1(<37)	10.6 (392.2)	5
Stems	7.9 (292.3)	1.8 (66.6)	21.5 (795.5)	4	2.3 (85.1)	1.0(37.0)	3.3(122.1)	3	3.1 (114.7)	<1(<37)	8.5 (314.5)	5
Leaves	24.7 (913.9)	5.9(218.3)	60.9 (2253.3)	4	3.0(111.0)	<1(<37)	6.9(255.3)	3	5.1 (188.7)	1.5(55.5)	14.1 (521.7)	5
Roots	19.4 (717.8)	0.0 (0.0)	43.2(1598.4)	3	2.1 (77.7)	1.8(66.6)	2.5 (92.5)	3	9.9 (366.3)	<1(<37)	35.8(1324.6)	4

Note: values in parentheses are mBq/g

TABLE 21 CONCENTRATIONS OF LEAD-210 (pCi/g dry weight) IN WETLAND PLANTS

	Bancroft				Control				Elliot Lake			
	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N
Individual Cattail Plants												
Fruits	0.2 (7.4)	<1(<37)	0.3 (11.1)	6	0.1 (3.7)	<1(<37)	0.2 (7.4)	6	0.1 (3.7)	<1(<37)	0.4 (14.8)	10
Stems	0.3 (11.1)	<1(<37)	0.6 (22.2)	6	0.1 (3.7)	<1(<37)	0.3 (11.1)	7	0.3 (11.1)	<1(<37)	0.7 (25.9)	10
Leaves	2.2 (81.4)	<1(<37)	4.8 (177.6)	6	0.7 (25.9)	<1(<37)	2.2 (81.4)	8	0.6 (22.2)	<1(<37)	1.8 (66.6)	10
Roots	69.8(2582.6)	7.9(292.3)	198.3(7337.1)	5	8.3(307.1)	<1(<37)	33.4(1235.8)	8	73.0(2701.0)	<1(<37)	489.0(18 093.0)	10
Rhizomes	3.2 (118.4)	<1(<37)	10.4 (384.8)	6	0.4 (14.8)	<1(<37)	0.8 (29.6)	8	3.5 (129.5)	<1(<37)	17.3 (640.1)	10
Annual Above-ground Biomass												
Brown leaves	0.6 (22.2)	<1(<37)	1.0 (37.0)	5	0.3 (11.1)	<1(<37)	1.1 (40.7)	4	0.6 (22.2)	<1(<37)	1.0 (37.0)	5
Thick leaves	1.1 (40.7)	<1(<37)	3.3 (122.1)	5	<1(<37)	<1(<37)	<1(<37)	3	0.9 (33.3)	<1(<37)	3.2 (118.4)	7
Green leaves	0.7 (25.9)	<1(<37)	1.2 (44.4)	3	0.1 (3.7)	<1(<37)	0.5 (18.5)	4	0.7 (25.9)	<1(<37)	2.4 (88.8)	7
Stems	-	-	-	-	0.2 (7.4)	<1(<37)	0.8 (29.6)	4	1.1 (40.7)	<1(<37)	4.0 (148.0)	7
Fruits	-	-	-	-	0.2 (7.4)	<1(<37)	0.4 (14.8)	4	0.9 (33.3)	<1(<37)	3.0 (111.0)	6
Cattail Litter												
Leaves	5.9 (218.3)	1.3 (48.1)	11.1 (410.7)	4	0.8 (29.6)	<1(<37)	1.7 (62.9)	3	2.4 (88.8)	<1(<37)	5.5 (203.5)	7
Stems	1.5 (55.5)	0.8 (29.6)	2.7 (99.9)	3	0.6 (22.2)	<1(<37)	2.1 (77.7)	4	1.8 (66.6)	<1(<37)	3.9 (144.3)	6
Fruits	0.3 (11.1)	0.3 (11.1)	0.3 (11.1)	1	<1(<37)	<1(<37)	<1(<37)	2	3.3 (122.1)	<1(<37)	13.6 (503.2)	6
Individual Sedge Plants												
Fruits	4.4 (162.8)	<1(<37)	9.9 (366.3)	3	0.6 (22.2)	<1(<37)	0.9 (33.3)	2	0.8 (29.6)	<1(<37)	1.3 (48.1)	5
Stems	1.8 (66.6)	<1(<37)	3.2 (118.4)	4	0.4 (14.8)	<1(<37)	0.4 (14.8)	3	1.8 (66.6)	<1(<37)	5.5 (203.5)	5
Leaves	10.4 (384.8)	1.4 (51.8)	35.1(1298.7)	4	1.0 (37.0)	<1(<37)	1.6 (59.2)	3	1.7 (62.9)	<1(<37)	3.0 (111.0)	5
Roots	55.6(2057.2)	7.9(292.3)	147.1(5442.7)	3	1.8 (66.6)	<1(<37)	3.0 (111.0)	3	22.4 (828.8)	10.1(373.7)	43.7 (1616.9)	4

Note: values in parentheses are mBq/g

consistently higher than those in the rhizomes in plants from both tailings and control areas. Both parts of the plant are in direct contact with the tailings. It could be argued that the higher concentrations in the roots are artifactual due to the difficulty in washing. The larger rhizomes are easier to scrub free of tailings than the smaller roots. Both parts, however, were examined microscopically and were considered equally "clean." The differences in radium-226 and lead-210 concentrations are consistent and from the concentration factors discussed later it is indicated that the concentrations in the tailings are either close to those in the roots or are sufficiently different (either higher or lower) to suggest that the tailings or soils had different concentrations than the roots. It is believed that these findings support the relative reliability of the cleaning procedure that was used.

If the concentrations in the roots had been the same as in the tailings, it would not have been possible to suggest any real differences between the roots and rhizomes of the cattails. These concentrations, however, differ dramatically and consistently between the roots and the tailings. The rhizomes, a below-ground stem, thus appear to represent a barrier to further transport of radium-226 and lead-210 to above-ground parts of the cattails.

A second consistent result is shown by the radionuclide concentrations in the leaves, which are generally higher than those in the stems and fruits. The above-ground biomass was separated by leaf types. Brown leaves are early senescent leaves; thick leaves are those associated with nonfruit-bearing plants or vegetative shoots; and green leaves are those from plants with fruits. Because cattail stands on tailings were found to produce more fruit-bearing plants than those growing on control sites and their leaves age somewhat earlier due possibly to stressed growth conditions, the translocation of radionuclides between fruit-bearing and vegetative shoots could have been affected.

Thick leaves, i.e., those on vegetative shoots, may be slightly higher in radium-226 and lead-210. However, this difference might not be statistically significant (with the exception of the brown leaves from the Bancroft tailings). The differences are generally small between the various plant components and can vary between the tailings sites. It appears reasonable to suggest that the concentrations of radium-226 and lead-210 tend to decrease in the following order: roots > rhizomes > leaves > vegetative leaves > fruit-bearing leaves, fruits, and stems (all with similar concentration ranges).

The decomposing leaf litter clearly reflects the differences between the stems and the leaves, whereas the fruits seem to act as a sponge. Fruits that are submerged in the decaying layers of the cattail stands can have higher concentrations. These differences in the various components of the plant are of interest, particularly when food-chain connections are evaluated, as some animals will graze on the roots or shoots and others on the leaves of cattails.

When comparing the wetland cattail concentrations of radium-226 between the Bancroft and Elliot Lake tailings areas, differences based on the mean concentrations and their minimum and maximum values are difficult to substantiate. Clearly, the control cattails generally display lower average concentrations. This is not the case for lead-210, which is generally present in the same concentration ranges in the control cattails as in the cattails that have grown on the tailings in the Bancroft and Elliot Lake areas.

Differences in radionuclide uptake among wetland species. A final comparison, based on the available data, between radionuclide concentrations determined for sedges (*Scirpus cyperinus*) and cattails is possible. Sedges are common plant invaders of tailings sites and often provide some species diversity. Sedges do not possess a rhizome as the cattails do; however, they are perennials, growing from the same root stock every year. The concentrations of radium-226 and lead-210 in the sedges, particularly in those collected from the Bancroft tailings, suggest that these radionuclides are present in higher amounts than in the cattails from the same tailings site. In the Elliot Lake tailings, this difference between the species is less pronounced than in the Bancroft tailings. It might be of interest to note that in sedges the fruits contain concentration ranges similar to those in the leaves. The roots, as expected, display the highest concentrations of radionuclides. The concentration ratios for different parts of sedges are shown in Table 22. The ratios within the plant reflect those of the actual concentrations and differ, therefore, from those ratios determined for the cattail components (Tables 23 and 24). Further aspects of concentration ratios are considered below within the discussion about uranium concentrations in plants.

The transfer coefficients or concentration factors for the cattails are presented in Tables 23 and 24 for radium-226 and lead-210 respectively. They were calculated separately for control areas in Bancroft and in Elliot Lake, as the surface-water concentrations in one of the wetland stands were extremely high for both radionuclides. The average concentration factors for radium-226, based on the individually calculated concentrations in roots and root zone tailings, are 0.9 to 1.8 for the Bancroft and Elliot Lake areas. Thus, these ratios suggest that the roots generally have higher concentrations than the tailings. For lead-210, the factors or ratios are 0.9

TABLE 22 CONCENTRATION RATIOS OF RADIUM-226 AND LEAD-210 IN WETLAND PLANTS: SEDGES

	Bancroft Control		Bancroft Tailings		Elliot Lake Control		Elliot Lake Tailings	
	N	Ratio	N	Ratio	N	Ratio	N	Ratio
Ra-226								
<u>Individual Plants</u>								
Roots		-		-	1	0.48	4	0.23
Root zone	*		*		1		5	
Stem	2	1.37	4	0.41	1	0.50	1	0.36
Root	2		3		1		4	
Leaves	2	1.25	4	3.11	1	1.5	5	1.46
Stems	2		4		1		1	
Fruit	1	**	3	2.44	1	0.40	5	1.17
Stems	2		4		1		1	
Fruit	1	**	3	0.78	1	0.53	5	0.80
Leaves	2		4		1		5	
Pb-210								
<u>Individual Plants</u>								
Roots		-		-	1	**	4	2.11
Root zone	*		*		1		5	
Stem	2	0.22	4	0.03	1	0.22	5	0.08
Root	2		3		1		4	
Leaves	2	3.38	4	5.75	1	0.50	5	0.96
Stems	2		4		1		5	
Fruit	1	2.25	3	2.43	1	0.50	5	0.46
Stems	2		4		1		5	
Fruit	1	0.67	3	0.42	1	1.0	5	0.48
Leaves	2		4		1		5	

* root zone sample not collected

** below detection limit

TABLE 23 CONCENTRATION RATIOS OF RADIUM-226 IN WETLAND PLANTS: CATTAILS

	Bancroft Control		Bancroft Tailings		Elliot Lake				Bancroft + Elliot Lake Control	
					Control		Tailings			
	N	Ratio	N	Ratio	N	Ratio	N	Ratio	N	Ratio
Individual Plants										
Tailings/soil										
Root zone	1	14.43	6	0.95	7	0.86	13	0.99	8	0.98
Surface zone	1		6		7		9		8	
Plants										
Roots	1	*	5	1.79	7	0.39	10	0.94	8	0.33
Root zone	1		6		7		13		8	
Rhizome	1	*	6	0.04	7	0.04	10	0.24	8	0.12
Root	1		5		7		10		8	
Stem	2	0.86	7	0.56	9	0.19	17	0.50	11	0.31
Rhizome	1		6		7		10		8	
Stem	2	*	7	0.02	9	0.02	17	0.12	11	0.04
Root	1		5		7		10		8	
Leaves	2	1.42	9	3.35	10	5.07	17	0.67	12	3.17
Stems	2		7		9		17		11	
Fruit	2	0.08	7	0.93	8	2.21	16	0.46	10	1.13
Stems	2		7		9		17		11	
Fruit	2	0.06	7	0.28	8	0.44	16	0.69	10	0.36
Leaves	2		9		10		17		12	
Annual Above-ground Biomass										
Thick leaves	1	12.71	4	0.50	3	0.28	7	1.14	4	3.9
All green leaves	2		9		10		17		12	
Brown leaves	1	0.59	5	1.94	3	1.41	5	0.86	4	1.19
All green leaves	2		9		10		17		12	
Cattail Litter										
Leaf litter	1	14.0	4	2.43	2	0.70	7	3.11	3	5.89
All green leaves	2		9		10		17		12	
Stem litter	1	1.0	3	2.42	3	4.79	6	1.04	4	2.83
Stems	2		7		9		17		11	
Fruit litter	1	52.0	1	0.96	2	0	6	4.31	3	3.35
Fruits	2		7		8		16		10	

* below detection limit

TABLE 24 CONCENTRATION RATIOS OF LEAD-210 IN WETLAND PLANTS: CATTAILS

	Bancroft Control		Bancroft Tailings		Elliot Lake				Bancroft + Elliot Lake Control	
					Control		Tailings			
	N	Ratio	N	Ratio	N	Ratio	N	Ratio	N	Ratio
Individual Plants										
<u>Tailings/soil</u>										
Root zone	1	8.21	6	1.30	7	1.64	13	0.68	8	2.1
Surface zone	1		6		7		9		8	
<u>Plants</u>										
Roots	1	*	9	0.93	7	0.29	10	1.98	8	0.21
Root zone	1		6		7		13		8	
Rhizome	1	*	6	0.05	7	0.04	10	0.05	8	0.04
Root	1		9		7		10		8	
Stem	2	1.33	6	0.09	9	0.11	17	0.18	11	0.31
Rhizome	1		6		7		10		8	
Stem	2	*	6	0.004	9	0.004	17	0.01	11	0.01
Root	1		5		7		10		8	
Leaves	2	0.88	9	5.93	10	14.0	17	1.0	12	4.73
Stems	2		6		9		17		11	
Fruit	2	0.38	6	0.61	8	1.03	16	0.61	10	1.0
Stems	2		6		9		17		11	
Fruit	2	0.43	6	0.10	8	0.18	16	0.61	10	0.21
Leaves	2		9		10		17		12	
Annual Above-ground Biomass										
Thick leaves	0	3.14	5	0.69	3	*	7	1.47	3	*
All green leaves	2		9		10		17		12	
Brown leaves	1	3.14	5	0.37	3	*	5	0.91	4	0.52
All green leaves	2		9		10		17		12	
Cattail Litter										
Leaf litter	1	1.71	4	3.52	2	1.52	7	3.69	3	1.48
All green leaves	2		9		10		17		12	
Stem litter	1	0.25	3	5.36	3	17.50	6	2.78	4	5.0
Stems	2		6		9		17		11	
Fruit litter		-	1	1.76	2	*	6	8.46	2	*
Fruits			6		6		16		10	

* below detection limit

and 2.0 for Bancroft and Elliot Lake, respectively, indicating a similar uptake trend. The control ratios remain low for both radionuclides. Therefore, for cattail roots there is evidence for some degree of accumulation of radionuclides. The earlier-noted barrier between the roots and the rhizomes of the cattails is clearly expressed by the mean ratios, as they all range consistently from 0.04 to 0.24 for both radionuclides. The other ratios reflecting the distribution within the plants confirm the higher concentrations noted earlier in the leaves of cattails compared with those in other parts of the plant. The most important observation that can be derived from these concentration ratios is the distinct difference between control and tailings areas. Whether the tailings are acidic or alkaline, translocation within the cattail is not at all related to the tailings site per se, but appears to be specific to the cattail species.

4.3.4 Uranium Concentrations in Terrestrial and Wetland Plants. Investigation of uranium concentration in plants growing on uranium tailings has, in a technical sense, a somewhat contradictory angle. Historically, reports of uranium concentrations in plants date back to the early 1940s and the 1950s when Cannon and co-workers (in Dunn et al., 1985) established that plants can be used as indicator species for the exploration of elements, e.g., for selenium, which is in association with uranium sandstones. The world literature on uranium concentrations in plants was summarized by the former authors, in part with the objective of clarifying biogeochemical methods that have been developed for uranium exploration, i.e., detection of uranium mineralization through the determination of uranium concentrations in plants.

In many cases, this biogeochemical method has been used successfully and, therefore, determining uranium concentrations in plants growing on tailings from which the uranium has been extracted is somewhat predicated on the expectation of low concentrations. Uranium concentrations in aspens growing on uraniferous soils have been reported by Dunn et al. (1985), with values of 3 to 10 µg/g, 0.12 µg/g, 0.05 to 0.15 µg/g, and 15 µg/g, from four different references. For birches, numerous references have been reviewed, with uranium concentrations ranging from 0.1 to 860 µg/g.

The uranium concentrations in trembling aspens and white birches growing on uranium tailings (Table 25) are low. Although the sample sizes are very small, the concentrations of both species of trees are the same order of magnitude on both tailings areas and on the control sites.

TABLE 25 CONCENTRATIONS (µg/g dry weight) OF URANIUM IN TERRESTRIAL PLANTS: BIRCHES AND ASPENS

	Bancroft				Control				Elliot Lake			
	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N
Trembling Aspen Collected from Several Sites												
Stems	0.1	<0.0001	0.2	3	0.1	<0.0001	0.1	2	0.1	0.1	0.2	3
Leaves	0.3	0.2	0.3	3	0.4	0.4	0.4	1	0.3	0.2	0.4	4
Roots	1.8	0.2	6.0	4	1.8	0.1	3.6	2	1.9	0.2	3.5	4
White Birch Collected from Several Sites												
Stems	0.8	0.2	2.0	3	0.1	0.1	0.1	1	0.2	0.2	0.3	3
Leaves	3.9	0.8	7.0	2	0.7	0.5	0.8	2	0.8	0.1	3.0	6
Roots	0.9	0.1	2.0	4	2.6	0.5	5.0	3	1.0	0.1	2.0	7

The concentration factors between roots and tailings (Table 26) are below unity. However, factors calculated between roots and soils are at or above unity, as expected. The ratios between stems and leaves reflect the consistently higher concentrations of uranium in the leaves of the trees growing on both tailings and control sites; once again suggesting species-specific translocation within these plants.

Sheppard (1980) provided an excellent review on the environmental behaviour of uranium and thorium. She suggested some environmental importance for the uranium concentrations in plants growing on uranium tailings, referring to data by Moffett and Tellier (1977). Uranium concentrations in grasses and legumes, reported by these authors, ranged from 0.016 to 0.044 µg/g. Similarly, Dave et al. (1984a,b) reported consistently low concentrations in grasses of <0.2 µg/g, with one exception of 0.3 µg/g for plants from the Nordic site.

Normal background levels of uranium in vegetation are reported to be on the order of 0.5 to 2 µg/g, and Cannon (in Dunn et al. 1985) suggests that concentrations of uranium greater than 2 µg/g could be considered anomalous. Natural background concentrations for uranium in Canada were reported with an overall mean for terrestrial vegetation of 0.26 µg/g and a range of means from 0.007 to 3.42 µg/g (NUTP, 1985). This literature review of the natural background levels emphasizes nonmineralized areas in Canada.

TABLE 26 CONCENTRATION RATIOS OF URANIUM IN TERRESTRIAL PLANTS: BIRCHES AND ASPENS

	Bancroft Tailings		Elliot Lake Tailings		Bancroft + Elliot Lake Control	
	N	Ratio	N	Ratio	N	Ratio
White Birch						
Tailings/soil						
Root zone	1	0.51	8	1.10	3	0.58
Surface zone	1		8		2	
White Birch						
Roots	3	0.03	7	0.05	3	0.75
Root zone	1		8		3	
Stem	3	0.92	3	0.24	1	0.04
Root	4		7		3	
Leaves	2	4.88	6	3.61	2	6.50
Stems	3		3		1	
Trembling Aspen						
Tailings/soil						
Root zone	1	1.31	4	0.61	1	0.25
Surface zone	1		4		1	
Trembling Aspen						
Roots	4	0.038	4	0.19	2	1.82
Root zone	1		4		1	
Stem	3	0.079	3	0.062	2	0.033
Root	4		4		2	
Leaves	3	1.93	4	2.33	1	6.67
Stems	3		3		2	

The natural background review (NUTP, 1985) also reports values for aquatic vegetation, giving an overall mean uranium concentration of 2.3 μg/g and a range of means between 0.11 and 13.4 μg/g. In Table 27, uranium concentrations for wetland

TABLE 27 CONCENTRATIONS (µg/g dry weight) OF URANIUM IN WETLAND PLANTS

	Bancroft				Control				Elliot Lake			
	Mean	Min	Max	N	Mean	Min	Max	N	Mean	Min	Max	N
Individual Cattail Plants Collected from Several Sites												
Fruits	0.3	0.2	0.5	3	2.5	0.5	6.2	3	0.5	0.2	1.0	6
Stems	0.9	0.0	1.8	2	0.4	0.1	0.8	5	0.3	0.2	0.6	4
Leaves	5.0	5.0	5.0	1	1.0	0.7	1.3	5	0.7	0.3	1.4	7
Roots	1.5	1.5	1.5	1	1.3	0.5	2.8	3	76.2	1.5	368.0	7
Rhizomes	11.1	0.0	38.7	4	0.3	0.3	0.5	4	7.2	0.7	33.9	7
Annual Above-ground Cattail Biomass												
Brown Leaves	7.4	3.5	11.3	2	-	-	-	-	1.8	0.7	4.1	5
Thick Leaves	11.8	11.8	11.8	1	0.8	0.8	0.8	1	0.7	0.2	1.3	4
Green Leaves	2.1	2.1	2.1	1	-	-	-	-	1.0	1.0	1.0	1
Stems	0.3	0.3	0.3	1	112.0	112.0	112.0	1	0.8	0.5	1.0	2
Fruits	1.2	0.2	2.7	3	-	-	-	-	0.3	0.3	0.3	1
Cattail Litter												
Leaves	51.4	2.8	156.4	5	1.0	0.9	1.1	3	12.7	1.3	58.9	7
Stems	4.2	3.6	4.8	2	-	-	-	-	2.6	0.9	5.7	3
Fruits	-	-	-	-	-	-	-	-	41.7	0.8	188.1	5
Individual Sedge Plants Collected from Several Sites												
Fruits	36.5	1.3	95.9	3	1.2	0.2	2.7	3	0.5	0.1	0.9	4
Stems	2.1	0.3	5.3	3	0.5	0.5	0.5	1	3.5	0.4	9.7	3
Leaves	32.6	0.7	121.9	4	1.0	0.4	1.5	3	1.6	0.3	5.6	5
Roots	71.4	2.6	239.3	4	7.6	4.8	12.7	3	29.0	4.9	57.5	6

plants growing on uranium tailings and on control sites are presented. Above-ground parts of cattails (e.g., fruits, stems, and leaves) collected from individual plants or as a composite sample from the study quadrats described earlier have uranium concentrations within the natural background range. This is certainly the case for the Elliot Lake tailings. Cattails on the Bancroft tailings, however, contain somewhat higher concentrations of uranium, if any weight can be given to the above-ground biomass analysis of 1 m^2. Given that the overall uranium concentrations are <1 μg/g in cattails, with the exception of some individual root or rhizome concentrations and one control sample of stems, it is suggested that uranium concentrations are at or below natural background concentrations in both wetland and terrestrial plants growing on uranium tailings.

Two interesting observations can be made. Despite the low uranium concentrations in the plants discussed previously, the concentrations of uranium in the sedges, compared with those in cattails, appear to be higher. Sheppard et al. (1981) reported no significant differences in uranium concentrations for the same plant genera. Furthermore, uranium in cattail litter (Table 27) appears to be accumulating in decaying leaves and fruits. This is an expected trend due to the high affinity of uranium for organic substances (Taylor 1979).

Concentration ratios (also called transfer coefficients or concentration factors) for radionuclides are often reported, but their shortcomings are just as frequently discussed (Blaylock, 1982). For uranium, reported transfer ratios between plants and soils or organisms and waters are generally low (Tracey et al., 1983; Evans and Erikson, 1983; Osborne, 1984). However, uranium can be accumulated by certain biota and the concentration factors under these circumstances are exceedingly high. Osborne (1984) gives mean concentration factors for uranium between soil ash and plant ash ranging from 0.04 to 3.03. He concludes, based on a literature review, that a concentration factor for uranium of 1.5 is an educated estimate. He states: "The overall range in values was a factor of 4000 for 568 observations; the distribution of values was approximately log-normal. We noted that the observed concentration factors are much higher than average where the uranium concentrations in soil are very low." Given the generally low concentrations of uranium in uranium mill tailings and the low biological mobility (Whicker and Schultz, 1982), the concentration factors calculated for plants and presented in Tables 27, 28, and 29 are expected to be below unity (<1) if the species investigated do not accumulate uranium.

TABLE 28 CONCENTRATION RATIOS OF URANIUM IN WETLAND PLANTS: CATTAILS

	Bancroft Tailings		Elliot Lake Tailings		Elliot Lake Control	
	N	Ratio	N	Ratio	N	Ratio
Individual Plants						
Tailings/soil						
Root zone	18	0.65	36	0.44	21	1.87
Surface zone	21		31		20	
Plants						
Roots		-	7		3	0.0087
Root zone	*		36	**	21	
Rhizome	4	7.66	7	0.94	4	0.26
Root	1		7		3	
Stem	3	0.062	6	0.064	6	55.74
Rhizome	4		7		4	
Stem	3	0.48	6	0.0060	6	14.25
Root	1		7		3	
Fruit	3	0.48	7	0.98		
Stems	3		6			
Annual Above-ground Biomass						
All leaves	2	5.12	8	1.63		-
Stems	3		6			
Fruit	3	0.094	7	0.60		-
All leaves	2		8			
Thick leaves	1	3.33	4	0.87	1	0.86
All green leaves	2		8		5	
Brown leaves	2	2.10	5	2.36		-
All green leaves	2		8			
Cattail Litter						
Leaf litter	5	14.57	7	16.9		-
All green leaves	2		8			
Stem litter	2	6.09	3	5.54		-
Stems	3		6			
Fruit litter			5	92.76		-
Fruits			7			

* root zone sample not collected

** below detection limit

TABLE 29 CONCENTRATION RATIOS OF URANIUM IN WETLAND PLANTS: SEDGES

	Bancroft Tailings		Elliot Lake Tailings		Bancroft + Elliot Lake Control	
	N	Ratio	N	Ratio	N	Ratio
Individual Plants						
Tailings/soil						
Root zone	*	-	5	5.40	1	1.28
Surface zone			5		1	
Root interface		-	2	0.47		-
Root zone	*		5		*	
Plants						
Roots		-	6	0.47		-
Root interface	*		2		*	
Roots		-	6	0.22	3	0.42
Root zone	*		5		1	
Stem	3	0.29	3	0.12	1	0.066
Root	4		6		3	
Leaves	4	15.75	5	0.46	3	1.94
Stems	3		3		1	
Fruit	3	17.62	4	0.14	3	2.40
Stems	3		3		1	
Fruit	3	1.12	4	0.31	3	1.24
Leaves	4		5		3	

* root zone sample not collected

However, there are exceptions, as the ratios of fruit litter and above-ground fruits are high for the tailings in Elliot Lake. The mean uranium concentration in the fruit litter was 41.7 µg/g dry weight compared with an average of 0.45 µg/g in the above-ground fruits (Table 27). The fruits in the litter appear to act as sponges for uranium. The high ratios for the control location were also determined by dividing the stem concentrations by the concentrations of the rhizomes. These are associated with a wetland in the Bancroft area, which had consistently high radionuclide concentrations. It is suspected that this control water body is in close proximity to mineralization, resulting in high uranium concentrations as reflected in the ratios. These ratios, however, do not represent the general trends discussed earlier but rather are exceptional conditions.

Some attempt was made to identify the environmental compartment in which most uranium can be expected in wetlands on uranium tailings by calculating ratios, e.g., of the root zone tailings and those on the surface, or, for the litter, compared with the annual growth in the cattail stand. The sample set is too small and any further interpretation than previously given is not warranted. The ratios of leaf litter in the cattail stands compared with annual above-ground biomass clearly indicate that uranium is accumulated in the litter. The ratios of uranium distribution for the sedge plants (Table 29) also reflect the expected pattern of previous results, i.e., more uranium in the leaves of sedges from the Bancroft tailings than in those from the Elliot Lake tailings.

In summary, it appears, at least from an environmental point of view, that uranium is not accumulated by any of the plant species collected from uranium mill tailings that were investigated in this study. The concentrations reported in the literature for uranium tailings and those reported as natural background concentrations do not support any long-term environmental concern with respect to uranium transport in the food chain.

5 CONCLUSIONS

This collection of environmental data from inactive or abandoned uranium mill tailings surfaces, and their associated waters and vegetation, represents a starting point for evaluating the significance of long-term radionuclide transport from the tailings to the vegetation and surface waters. The data presented are descriptive and are discussed in a framework that allowed for comparisons with natural (control) environments in the same area, i.e., areas with uranium mineralization. For some of the characteristics, comparisons were made with base-metal tailings; whereas in other cases, comparisons were possible with nonmineralized areas.

The compiled data also facilitated a comparison of uranium tailings from the different uranium mining provinces, specifically Ontario and Saskatchewan. Furthermore, considering the time span during which uptake and/or accumulation of the radionuclides of concern, i.e., radium-226, lead-210, and uranium, could take place in either the surface waters or vegetation, this report describes some of the trends that are evident after the first 10 to 20 years of abandonment of the tailings sites and allows an empirical assessment of these areas.

The data display the typically large variations encountered when describing the physical and chemical characteristics of a waste environment. The concentrations of radium-226 and lead-210 range from detection limits (<1 pCi/g (<37 mBq/g)) to about 400 pCi/g (14 800 mBq/g) in tailings. The concentrations of these radionuclides appear to be higher in the Bancroft and Uranium City tailings than in those of Elliot Lake. Uranium concentrations in wetland areas of uranium tailings, as well as in nontailings control sites, are generally higher than those in terrestrial areas. The highest sample concentration of uranium in the data set was 2673 µg/g in a wetland area of the Elliot Lake tailings. However, the average concentration of uranium was <250 µg/g. For radium-226 and lead-210, it can be concluded that concentrations generally do not differ significantly between the wet and dry areas on the tailings and the mean concentrations are relatively low on the surface of the tailings in spite of their location, i.e., in an environment of uranium mineralization.

Concentrations of the metals cobalt, copper, nickel, and lead are higher in wetland areas on the Elliot Lake tailings than on the Bancroft and control sites. The concentrations of these metals in uranium tailings, however, are at or below the mean concentration ranges reported for base-metal tailings.

For the Elliot Lake tailings, it can be concluded that surface waters are more acidic than waters in the root zone of wetlands. For the alkaline tailings in the Bancroft area and at one site (Gunnar) in the Uranium City area, tailings pH values reflect those of the surface waters. Acid-generating tailings in Elliot Lake display a large range of pH values (1.8 to 9.8) compared with the same type of tailings deposited under the water in Nero Lake (Uranium City area), which have a pH range of 2.7 to 7.1. Liming of tailings areas for reclamation programs appears to produce extreme differences for an extended period of time.

The concentration ranges of radium-226 in surface waters on tailings are the same order of magnitude as those occurring in nontailings environments. The background concentrations in nonmineralized areas of Canada are reported to range between 0.5 and 9.4 pCi/L (18.5 and 347.8 mBq/L) and the concentrations determined for the surface waters on the uranium tailings, or those in seepages, have averages ranging from 12 to 29 pCi/L (444 to 1073 mBq/L). Concentrations derived experimentally from leaching tailings adhering to the root zone, referred to as leachates, indicate similar concentrations as those of surface waters. Radium-226 is potentially more bioavailable in alkaline tailings areas than under acidic conditions. Radium-226 concentrations determined in surface waters on tailings do not reflect concentrations predicted for the long term from experimental studies in the laboratory. The radionuclide lead-210 is more readily leached from acidic tailings, as reflected by higher concentrations in leachates and surface waters from the Elliot Lake area, than from tailings in the more neutral to alkaline areas. The uranium concentrations in waters are an order of magnitude higher than reported for nonmineralized areas in Canada. The water on the tailings, however, contains only slightly higher concentrations than water in the nontailings sampling locations or control areas.

Metal concentrations in surface waters are not of concern and the means are within recommended water quality guidelines for raw public water supplies and/or short-term irrigation. In general, it can be concluded that the concentrations of radionuclides and metals in the surface waters on tailings and seepages are rarely encountered at levels that may be considered hazardous.

One clear message emerges from describing characteristics and concentrations of long-lived radionuclides and metals. Inactive or abandoned uranium mill tailings environments have certain characteristics in common once a decade or two has passed, regardless of attempts to reclaim the sites. The radionuclide concentrations in surface waters on the tailings occur in similar ranges, as do the metal levels. Mineralized areas have localized, elevated levels of long-lived radionuclides. In this sense, then, the tailings surfaces are no different.

The uptake of radium-226 and lead-210 by vegetation (specifically cattails and trees) is quite a species-specific phenomenon and is not related to the tailings characteristics per se. The variations in concentrations of radionuclides in the vegetation are large within any single tailings site. Similar variations are found in nontailings environments as well. From the results obtained when washed and unwashed leaves of white birch were compared, no evidence could be found to suggest that significant contamination of the above-ground biomass occurred as a result of aerial deposition of tailings, which would increase radium-226 or lead-210 concentrations on the vegetation. Potential increased radon fluxes on the tailings did not result in higher lead-210 concentrations on leaves due to the decay product of radon-222.

It was concluded that white birch generally had higher concentrations of radionuclides than trembling aspen, a finding that was consistent on both the control and tailings sites. The concentrations of both radionuclides ranged from <1 to 40 pCi/g (<37 to 1480 mBq/g) in stems. The white birches growing on the Bancroft tailings had higher concentrations of radium-226 than those growing on the Elliot Lake tailings. The radionuclides in the white birch are compartmentalized differently; lead-210 tends to be found in higher concentrations in the stem, whereas radium-226 is associated with the leaves. For the cattails in wetland areas, compartmentalization of radionuclides within the plants does not occur. The rhizomes of the cattails present a barrier between the tailings and the upper parts of the plant. Differences in radionuclide transport between tailings areas are not evident, although concentrations in surface waters of the wetland areas and leachability differ between acidic and alkaline tailings. The uptake ratios for both terrestrial and wetland vegetation suggest that uptake of radionuclides is species specific and not related, necessarily, to the concentration differences encountered in the root zone.

Some interesting projections from these investigations emerge. In wetlands, the leaf litter components on uranium tailings are possible sinks for radium-226, lead-210, and uranium. The concentrations of radium-226 and lead-210 in the ground cover vegetation and in trembling aspens are generally lower than those in white birches. The latter displayed stunted growth on the tailings, based on previous investigations of these populations. However, because their radionuclide content is species specific, larger trees that grow in mineralized areas will produce more biomass over the long term, i.e., more radionuclides would be available for transfer into the food chain from the trees growing in uraniferous areas than from trees growing on the tailings due to their stunted growth.

Finally, it may be concluded that, based on various comparisons among sites and plant species, the differences that are discussed in this report may be of environmental significance over the long term.

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APPENDIX

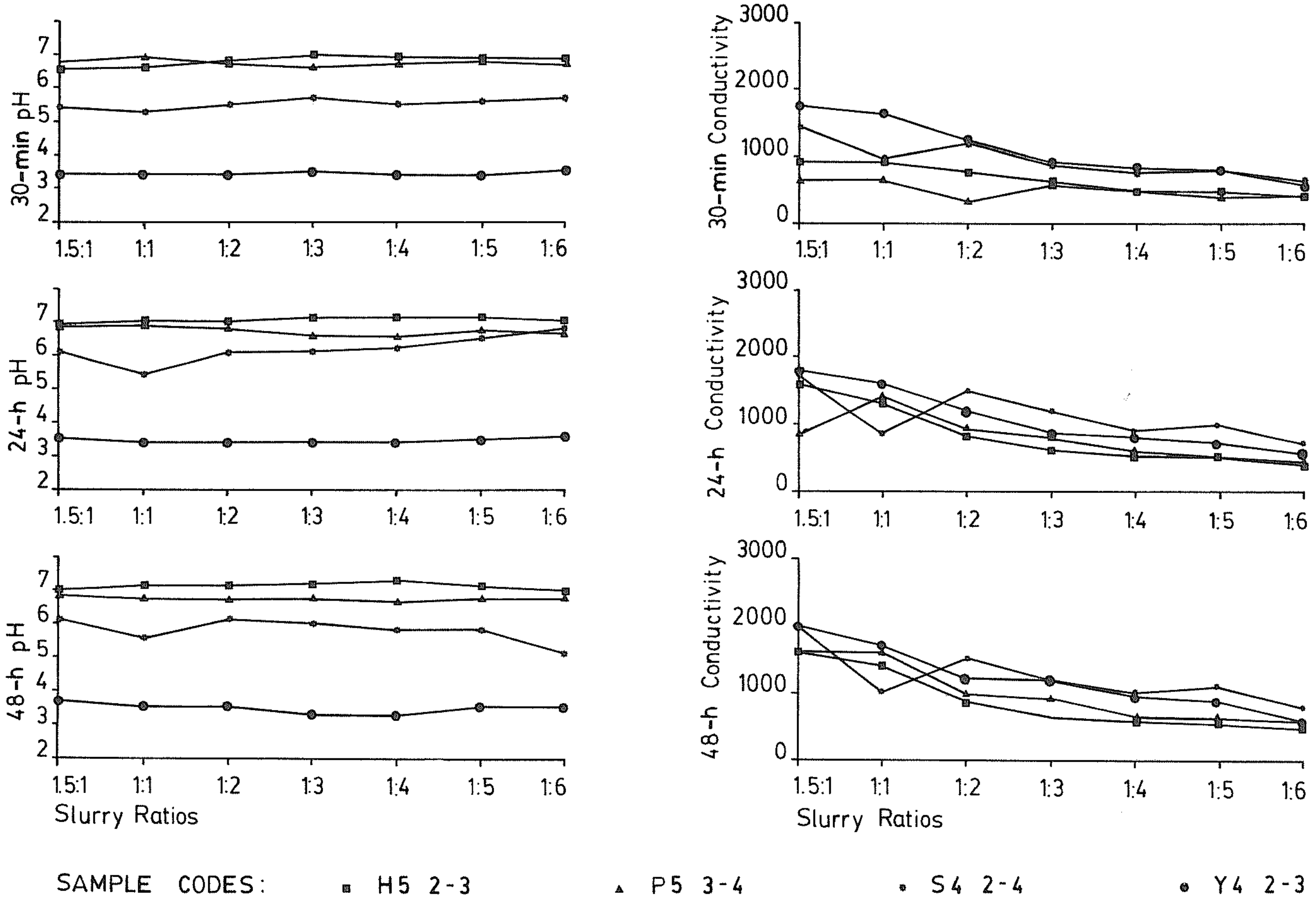

FIGURE A-1 DETERMINATION OF pH AND ELECTRICAL CONDUCTIVITY (µmhos/cm (µS/cm)) IN SURFACE TAILINGS SAMPLES (H5 2-3, Y4 2-3) AND ROOT REGION SAMPLES (P5 3-4, S4 2-4) FROM CATTAIL STANDS ON URANIUM TAILINGS IN THE ELLIOT LAKE AREA

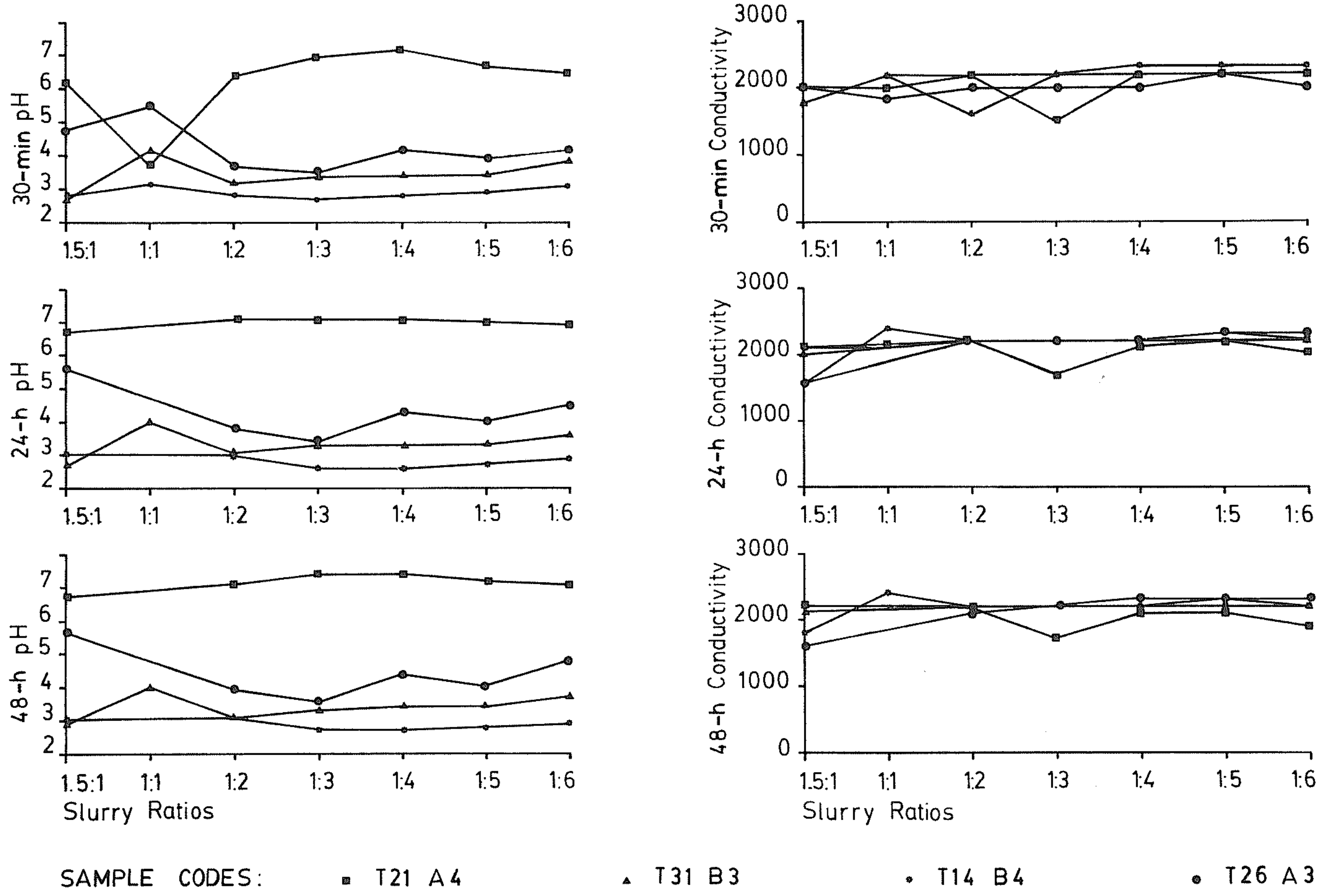

FIGURE A-2 DETERMINATION OF pH AND ELECTRICAL CONDUCTIVITY (μmhos/cm (μS/cm)) IN SURFACE (T26 A3, T31 B3) AND ROOT REGION (T21 A4, T14 B4) SAMPLES COLLECTED FROM WHITE BIRCH GROWING ON URANIUM TAILINGS IN THE ELLIOT LAKE AREA. The letters designate the tree transect (Kalin, 1984a).

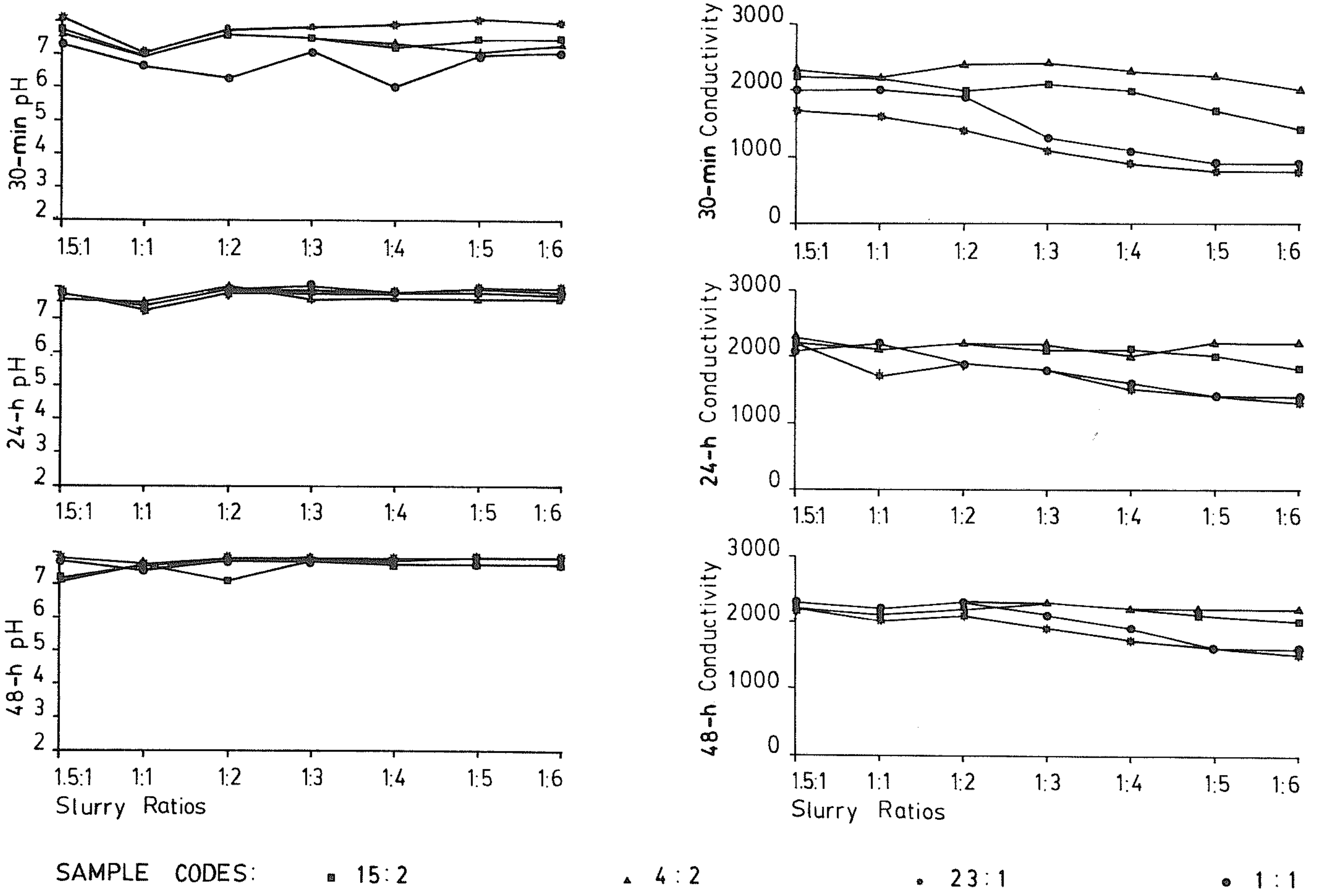

FIGURE A-3 DETERMINATION OF pH AND ELECTRICAL CONDUCTIVITY (µmhos/cm (µS/cm)) IN COARSE, SANDY TAILINGS SAMPLES COLLECTED AT THE SURFACE (23:1, 1:1) AND AT A DEPTH OF 25 cm (4:2, 15:2) IN AREAS WITH NO VEGETATION ON THE GUNNAR TAILINGS (URANIUM CITY AREA). The numbers designate the pit number, the location of which is given in Kalin (1982).

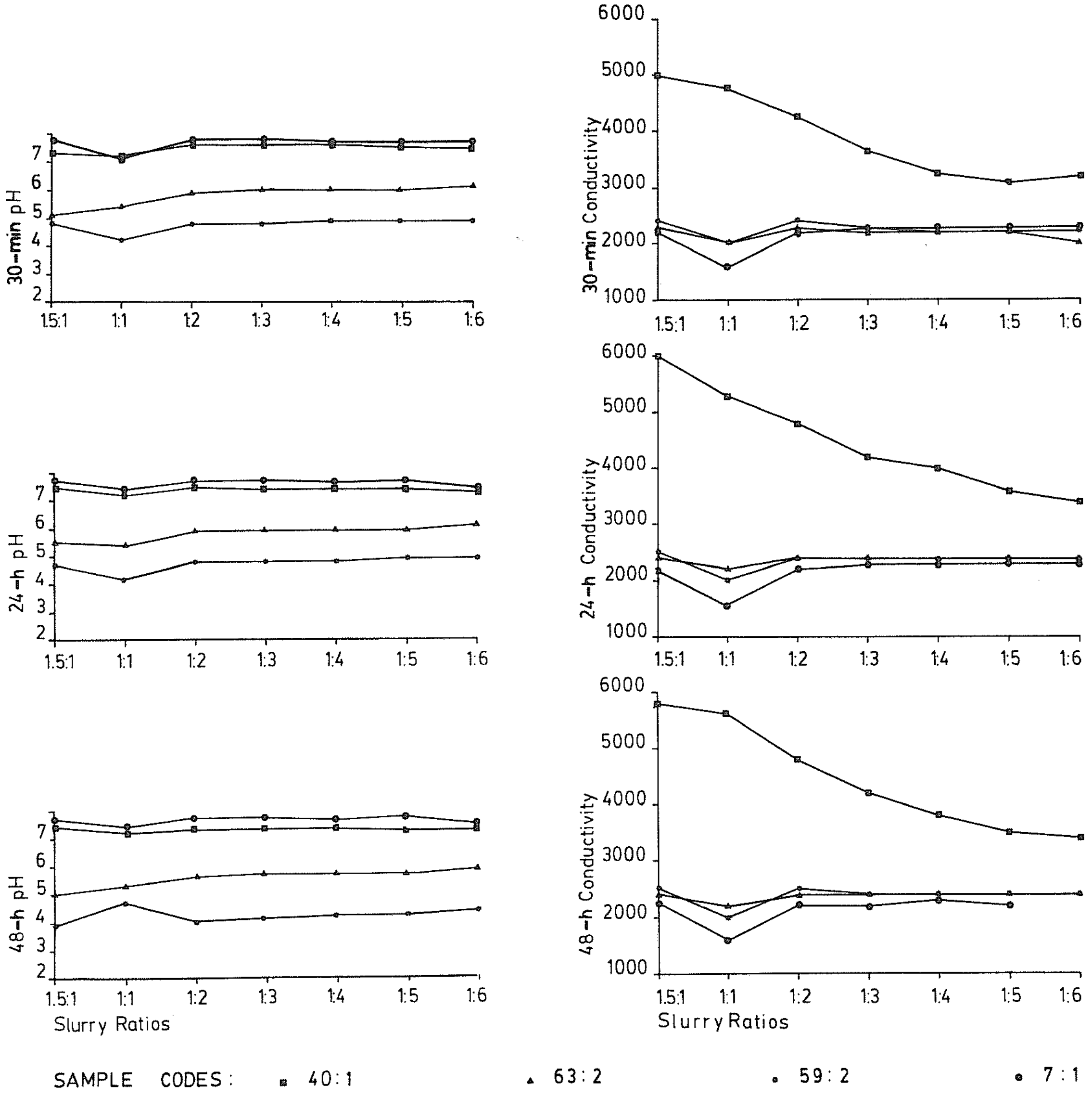

FIGURE A-4 DETERMINATION OF pH AND ELECTRICAL CONDUCTIVITY (µ mhos/cm (µ S/cm)) IN FINE TAILINGS SAMPLES COLLECTED AT THE SURFACE (40:1, 7:1) AND AT A DEPTH OF 25 cm (63:2, 59:2) IN AREAS WITH NO VEGETATION ON THE GUNNAR TAILINGS (URANIUM CITY AREA). The numbers designate the pit number, the location of which is given in Kalin (1982).

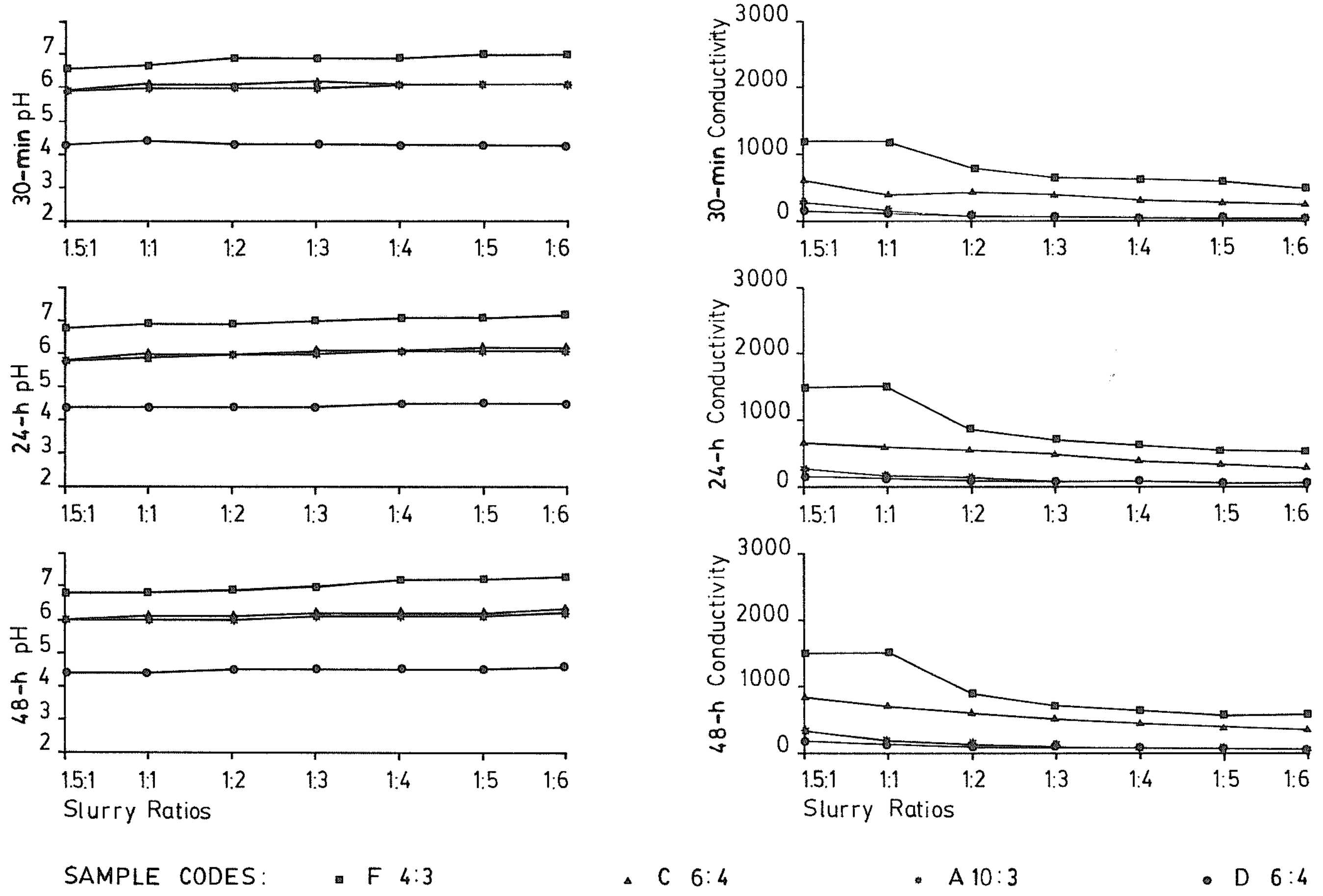

FIGURE A-5 DETERMINATION OF pH AND ELECTRICAL CONDUCTIVITY (µmhos/cm (µS/cm)) IN SURFACE TAILINGS SAMPLES (F 3:4, A 10:3) AND ROOT REGION SAMPLES (C 6:4, D 6:4) FROM SEDGE GROWING ON URANIUM TAILINGS IN THE BANCROFT AREA. The numbers designate the cattail quadrant (Kalin, 1984a).