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PHYSICAL AND CHEMICAL HYDROGEOLOGY OF URANIUM TAILINGS IN CANADA AND THE UNITED STATES OF AMERICA

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Physical and Chemical Hydrogeology of Uranium Tailings in Canada and the United States of America

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ABSTRACT

The common method of disposing of uranium mine/mill tailings in Canada and the United States of America is by surface impoundment. Because these tailings are readily able to interact with surrounding surface and near-surface environments, the impoundments in their operational state are not an acceptable method for long-term disposal. However, current research in Canada and the U.S.A. is addressing this problem and has dual emphasis: (1) delineation of environmental interactions and (2) stabilization or environmental isolation of tailings based on the defined mechanisms of interaction. This paper primarily addresses the first emphasis in the field of hydrogeology.

The physical and chemical hydrogeology of uranium tailings in Canada and the U.S.A. are described both through generalized conceptual models and through field studies at sites in Ontario, Saskatchewan, and Wyoming. From a physical hydrogeologic viewpoint, tailings impoundments often act as local recharge areas. From a chemical hydrogeologic viewpoint, impoundments and surrounding areas are highly reactive geochemical systems. Chemical precipitation-dissolution, co-precipitation, and sorption play a role in controlling environmental interaction. Through a thorough understanding of the mechanisms of environmental interaction, the predictions of environmental impact and the requirements for the environmental isolation of tailings can be better defined.

1. INTRODUCTION

The common method of disposing of uranium mine/mill tailings in Canada and the United States of America is by surface impoundments. Their conspicuous presence has lead to site-specific studies of impoundments and their surroundings. These studies concentrate on the delineation of environmental interactions with the eventual goal of stabilization or isolation of the tailings. Recent research on this topic is supervised and accelerated by the National Uranium Tailings Program (Lapp, 1981) under Energy, Mines, and Resources Canada in Canada and by the Uranium Mill Tailings Remedial Action Project in the U.S.

This paper discusses the physical and chemical hydrogeologic interactions of uranium tailings with surface and groundwater flow systems. Selected case studies are briefly presented and conceptual models of the mechanisms of hydrogeologic interaction are developed. These models are also applicable to other varieties of acidic and pH-neutral tailings. For ease of comprehension, the conceptual models are presented before the selected case studies.

2. CONCEPTUAL MODELS OF HYDROGEOLOGIC INTERACTIONS

2.1 Physical Hydrogeology

The conceptual model of water movement in and around uranium tailings impoundments begins with Figure 1 based on fifteen case studies (Table 1). The tailings are contained by man-made impoundment dams or by natural bedrock walls. In some cases, the tailings are underlain by a local low-permeability stratum such as peat. In other cases, there is no Stratum C (Figure 1) and the tailings lie directly over Stratum D. Depending on the site, Strata D, E, F, etc. may be consolidated rock, unconsolidated material, or upper unconsolidated layers lying over rock. In some cases, Stratum D is sufficiently thick to render deeper strata relatively unimportant for groundwater movement in the vicinity of the tailings.

Because tailings are usually discharged to an impoundment as a slurry with more than 50% water, the elevated tailings pile is a recharge zone: groundwater recharge occurs by seepage through the base of the tailings and surface water recharge occurs both by seepage through the dam or bedrock walls and by seepage in Stratum D discharging upwards into surface watercourses outside the impoundment area. Direct runoff from the tailings surface is often prevented from reaching surrounding natural watercourses because of the induced contamination of the runoff during its travel across the tailings surface.

In moist climates, the tailings form a water-table mound. In dry climates, a thick unsaturated zone in the underlying strata commonly results in a perched water table within the tailings. Depending on factors such as recharge rates, the unsaturated zone may eventually become saturated and a water-table mound would then exist as in moist climates.

Water movement within an impoundment is complex because of the complex stratigraphy of the tailings pile. Tailings are typically discharged to an impoundment through a pipe at one corner or along one side of the impoundment. As a result, coarse particles and high density minerals, such as pyrite, preferentially accumulate near the discharge pipe whereas silts and clays and lighter minerals are transported farther from the pipe. As fluctuations in discharge, ore mineralogy, and mill processing occur, the lateral boundaries between sand, silt, and clay migrate laterally as the pile grows vertically. In this way, the tailings pile displays irregular deltaic facies with interfingering of high and low permeability layers. This interfingering produces a vertical hydraulic conductivity which is significantly less than the horizontal conductivity, and water movement through the tailings pile thus has a significant horizontal component of flow.

The coarse particles remaining near the discharge pipe and dam produce a relatively high permeability zone. This phenomenon, combined with the preferential collection of high-density minerals such as pyrite near the pipe, can produce a zone which accounts for a large percentage of the contaminant-laden seepage leaving the impoundment. Such localized physical phenomenon and other chemical processes (discussed below) are often ignored by tests which determine whether tailings are potentially acid generating through the simple comparison of bulk acid-generation potential to acid-neutralization potential (e.g. Duncan and Walden, 1975). A more realistic approach is to anticipate the potential for localized acid problems.

2.2 Chemical Hydrogeology

Uranium tailings, like most metal-mine tailings, often contain acid-generating minerals such as sulfides. Because pyrite (FeS_2) is the typical sulfide found in uranium tailings, it will be used to illustrate acid generation in the chemical conceptual model. For non-acidic tailings, a subset of this conceptual model will apply.

In order to initiate significant acid generation through pyrite oxidation, there are three main inorganic ingredients: oxygen, water, and somewhat acidic (pH<6-7) conditions. As long as a significant quantity of neutralizing minerals (calcite, $CaCO_3$, for example) exists with the pyrite, the pH remains high and the pyrite may remain relatively dormant. However, as rainfall (generally at pH 4-6) infiltrates through the tailings, it is neutralized, thereby dissolving the calcite. Eventually the surficial tailings will be devoid of calcite and, with the presence of oxygen and infiltrating water, slowly oxidizing pyrite can begin to rapidly oxidize. Acid water is then produced and migrates downward into the tailings pile until it encounters deeper calcite and is neutralized. However, because the deeper calcite is dissolved, the acidification of the entire tailings pile may develop, with a downward migrating zone of pyrite oxidation through time. The rate of downward movement of the zone and the rate of acid generation can be expected to decrease with time because the distance for oxygen diffusion increases with depth and the volume flux of oxygen thus decreases with depth. If the tailings pile is disturbed, excavated, or moved at this point, the rate of acid generation may accelerate.

This scenario of acidification of tailings despite an initial presence of abundant neutralizing minerals represents a limitation mentioned in the previous section on tests for determining whether tailings are potentially acid generating. Through this scenario, tailings which have far more acid-neutralization capacity than acid-generating capacity, and are thus declared environmentally safe, may become acidic at a future time.

As explained in the previous section, a region adjacent to a discharge pipe and dam may have a relatively high permeability and a preferential accumulation of pyrite. Because of the greater flux of water and oxygen, neutralizing minerals may dissolve more rapidly and pyrite may oxidize faster than in the bulk tailings. Additionally, if the dam is composed of coarse-rock fill only, oxygen diffusion into the entire cross-section of the adjacent tailings could be significant and thus pyrite may oxidize simultaneously throughout the entire thickness of the pile adjacent to the dam.

Although pyrite oxidation is a multi-stage process with complexities such as intermediate sulfur species (e.g., Morin, 1986) and bacterial mediation, the overall reaction assuming oxygen is the only oxidizing agent is:

$$FeS_{2(s)} + 7/2\ O_2 + H_2O \qquad Fe^{2+} + 2SO_4{}^{2-} + 2H^+ \qquad (1)$$

Thus, two moles of H^+ are produced for each mole of pyrite plus the contribution of Fe to total acidity. If the aqueous iron oxidizes and precipitates, four moles of H^+ are produced for each mole of pyrite:

$$FeS_{2(s)} + 15/4\ O_2 + 7/2\ H_2O \qquad Fe(OH)_{3(s)} + 2SO_4{}^{2-} + 4H^+ \qquad (2)$$

For those sites which have insignificant levels of pyrite, but which had acidic mill water discharged directly into the impoundment, this stage of the conceptual model is reached without pyrite oxidation.

The low-pH condition of the tailings porewater induces heavy metal and radionuclide concentrations to increase by dissolution of minerals in the tailings and by the release of adsorbed species. This acidic contaminant-laden water migrates with a downward component of flow through the tailings pile and eventually encounters neutralizing minerals at some depth in the pile or natural strata. Upon neutralization, pH increases and concentrations of major ions, metals, and radionuclides decrease through geochemical processes of precipitation, co-precipitation, and adsorption (Morin and Cherry, 1986 and 1988). Eventually all neutralizing minerals at a particular depth are dissolved and acidic conditions then prevail. At this point, the precipitated, co-precipitated, and adsorbed contaminants are remobilized by the low-pH water and they are carried further into deeper tailings or the underlying natural flow systems until neutralizing minerals are again encountered.

The above sequence representing migration of acidic water is more complex than is apparent from bulk mixing of acidic water and neutralizing minerals such as in a laboratory batch test. This complexity can be explained through an example employing acidic seepage migrating laterally through an aquifer initially containing calcite (Figure 2).

The acidic, contaminated seepage begins to enter the calcareous aquifer and the pH is neutralized by the dissolution of calcite. If the neutralized pH is greater than 6.4, the neutralization reaction is:

$$H^+ + CaCO_{3(s)} \qquad Ca_{2+} + HCO_3^- \tag{3}$$

otherwise:

$$2H^+ + CaCO_{3(s)} \qquad Ca^{2+} + H_2CO_3^o \tag{4}$$

There is a difference of a factor of 2 in the neutralization capacities of Equations 3 and 4, highlighting the importance of identifying the neutralized pH. For the example based on Figure 2, calcite is arbitrarily assumed to neutralize pH from 2.0 to 5.5.

Because acidic uranium-tailings water is commonly high in aqueous sulfate and near gypsum saturation, the addition of aqueous calcium by neutralization initiates gypsum precipitation:

$$Ca^{2+} + SO_4^{2-} + 2H_2O \qquad CaSO_4 \cdot 2H_2O_{(s)} \tag{5}$$

Neutralization of pH also initiates the precipitation of minerals such as siderite:

$$Fe^{2+} + H_2CO_3^o \qquad 2H^+ + FeCO_{3(s)} \tag{6}$$

ferric hydroxide:

$$Fe^{3+} + 3H_2O \qquad 3H^+ + Fe(OH)_{3(s)} \tag{7}$$

and aluminum minerals, simplified here to $Al(OH)_3$:

$$Al^{3+} + 3H_2O \qquad 3H^+ + Al(OH)_{3(s)} \tag{8}$$

There are many aluminum minerals which may precipitate from this type of water (Nordstrom, 1982), but $Al(OH)_3$ is considered satisfactory for the purpose of this example. Co-precipitation with the above minerals and adsorption remove radionuclides and other metals from the water.

As all calcite near an impoundment dissolves, the acidic water then induces the precipitated siderite to dissolve (reverse of Equation 6) which neutralizes pH, for example, from 2.0 to 5.2 because of the lower solubility of siderite relative to calcite in this type of water. As this pH 5.2 water migrates away from the impoundment, it eventually encounters undissolved calcite, at which time the pH is raised from 5.2 to 5.5. Meanwhile, when all siderite is dissolved in the vicinity of the impoundment, the acidic water initiates the dissolution of precipitated $Al(OH)_3$ (reverse of Equation 8), thereby raising pH from 2.0 to 5.0 in this example. Similarly, when all $Al(OH)_3$ is dissolved, $Fe(OH)_3$ begins to dissolve, thereby raising pH to 3.5 in this example. Finally, when all $Fe(OH)_3$ is dissolved, the unaltered acidic water is free to move into this portion of the aquifer. Depending on solubility constraints and aqueous complexation, dissolution of the precipitated gypsum may contribute slightly to pH neutralization. Because this sequence of contaminant migration involves both spatial and temporal trends, a theoretical step profile develops such as depicted in Figure 2 and the length of each pH plateau increases with time.

For simplicity, each plateau is called a "sub-region" preceded by the name of the dissolving mineral of the conceptual model which is responsible for the pH. The pH with the highest pH is the calcite sub-region and the second plateau in Figure 2 is the siderite sub-region. Not all sub-regions exist at every tailings site. For example, if unaltered tailings seepage is at pH 4, then $Fe(OH)_3$ will not significantly dissolve.

The sub-regions form the "neutralization zone"; the unaltered acidic water is called the "inner core"; and the distant part of the calcite sub-region where no significant reactions are occurring is called the "outer zone".

Because of extensive aqueous complexation, competing pH buffering reactions, and mineral precipitation-dissolution, this geochemical conceptual model is difficult to visualize and requires the assistance of computer simulation for a clearer understanding. The details of sub-regions, contaminant migration, retardation factors, and simulations of past, present, and future conditions with "ADNEUT" computer programs are located in Morin (1983), Cherry et al. (1984), and Morin and Cherry (1986).

For tailings impoundments with seepage at neutral pH, either acid is being generated and neutralized within the tailings pile so that the seepage presently represents the calcite sub-region of the neutralization zone or no acid is being generated so that the seepage represents the geochemically quiet outer zone. In the latter case, infiltration of slightly acidic precipitation can create a neutralization zone. Nevertheless, the chemical conceptual model developed here can account for water quality found at acidic and pH-neutral tailings sites. In the event that highly alkaline, high-pH mill discharge is moving through a tailings pile, additional reactions such as calcite precipitation may be important, but this scenario is not addressed in this paper.

3. CASE STUDIES

3.1 Nordic Main Impoundment, Elliot Lake, Ontario

This impoundment has been studied since the mid-1970's and this site has provided detailed data for the initial formulation of the conceptual models. Descriptions of the physical and chemical hydrogeology of the Nordic Main area are presented in Dubrovsky (1986), Morin and Cherry (1986), Morin (1985), Dubrovsky et al. (1984), Morin (1983), and Morin et al. (1982).

Deposition of the tailings in the Nordic Main impoundment ended in 1968 and ponded water was subsequently drained from the tailings surface and a vegetation cover established. The water table elevation in the tailings generally decreases from the bedrock wall on the north towards the impoundment dam on the south and east (Figure 3). This configuration is the result of the relatively impermeable peat layer which underlies much of the tailings, except near the dam. As a result, tailings water generally moves towards the dam and into the underlying sand aquifer. In places, this seepage is acidic through pyrite oxidation.

Pyrite, which is represents 3 to 7 weight-percent (wt-%) of the tailings, typically oxidizes only within 1-2 meters of the surface in the unsaturated zone. The acidic water is neutralized at depth where trace amounts of carbonate minerals exist. In places, reactive pyrite has apparently been removed through oxidation from the shallow tailings and thus very acidic pH's are not observed. Evidence for the operation of the chemical conceptual model is present, but the $Al(OH)_3$ sub-region is complex because of the presence of several $Al\text{-}SO_4\text{-}OH$ minerals (Dubrovsky, 1986).

Near the coarse-fill rock dam, pyrite apparently oxidized at depth in the tailings pile and shallow, acidic seepage is observed in the aquifer. Because the aquifer contains up to 1.5 wt-% calcite, the many of the sub-regions of the conceptual model exist, although contacts of the sub-regions are not well-defined step functions because of the spacing of monitor points and temporal changes in the rate of acid generation. Because the pH is greater than 4 in many of the seepage areas around the impoundment, the $Fe(OH)_3$ sub-region rarely develops. At the main seepage site, Seepage Area A, inner-core pH is approximately 4.5 and outer-zone pH is about 6 (Figure 4). Within the neutralization zone, the calcite sub-region has a pH near 5.5 with a predicted retardation factor (R.F.) relative to the groundwater velocity of 14%, the siderite sub-region has a pH near 5.2 and an R.F. of 0.46%, and the $Al(OH)_3$ sub-region has a pH near 5.0 and an R.F. of 0.20%. The calcite-siderite solid solution (Morin and Cherry, 1986) and the apparent presence of three Al minerals ($Al(OH)_3$, AlOOH, and allophane) complicates the neutralization zone. Both co-precipitation and adsorption are important in removing aqueous metals and radionuclides within the neutralization zone.

3.2 Greyhawk Waste-Rock Dump, Bancroft, Ontario

This dump of uranium-mine waste rock was formed by the piling of rock onto a sandy plain during mining of a nearby ore zone in an intrusive batholith (Figure 5). This dump has been exposed to weathering since 1956. The hydrogeology of this site is discussed in detail in Veska (1983) and briefly in Morin (1983).

The inner-core pH is near 3.5 and the outer-zone pH is near 8.0 (Figure 5). The neutralization zone contains two sub-regions: calcite near pH 6.9 with a retardation factor (R.F.) relative to groundwater velocity of 7.2% and siderite near pH 6.0 with an R.F. of 3.8%. Either the inner core is located in and beneath the dump at pH 3.7 or the inner core still lies in the dump and a minor $Fe(OH)_3$ sub-region which raises inner-core pH to 3.7 beneath the dump. Because of the relatively small amount of mineral precipitation at this site, adsorption is the major mechanism for the attenuation of aqueous trace contaminants and radionuclides.

3.3 Federal American Partners Tailings Pond, Gas Hills, Wyoming

This site is described in Highland et al. (1981) and is evaluated through the conceptual models in Morin (1983). The tailings impoundment lies over the Wind River Formation sandstone (Figure 6), which is an unconfined aquifer in the area. In 1960, acidic seepage began draining into the unsaturated zone beneath the impoundment and, within one year, the aquifer beneath the pond was saturated and steady-state conditions established. The seepage has been found to generally migrate laterally in the aquifer towards the northwest.

The aquifer contains 0.1-1.0 wt-% equivalent $CaCO_3$, which probably exists as calcite, and, because surficial pond water (inner core) is at pH 1.9, several sub-regions have developed. The calcite sub-region has a pH near 6.0 with a calculated retardation factor (R.F.) of 14%. There is apparently no siderite sub-region at this site. The $Al(OH)_3$ sub-region has a pH near 4.3 and an R.F. of 14%. The $Fe(OH)_3$ sub-region has a pH near 3.2 and an R.F of 9%.

The relatively low pH of the $Al(OH)_3$ sub-region indicates the presence of a low-solubility aluminum mineral such as boehmite (AlOOH) and the results of a speciation model (Morin, 1983) suggests allophane and $AlOHSO_4$ exist at other locations at the site.

The importance of aluminum information for the proper simulation of contaminant migration at many sites is apparent, but is occasionally overlooked. At the Wyoming tailings impoundment described by Taylor and Antommaria (1978) and Taylor (1980), Morin (1983) demonstrated that the lack of aluminum analysis prevents the understanding and the simulation of contaminant migration.

3.4 Shirley Basin Uranium District, Wyoming

At this site, the tailings impoundment lies over an alluvial sand aquifer and a deeper clay layer (Figure 7). Seepage from the tailings, which began in 1976, flows eastward in the sand aquifer (Figure 8). This site is described in Cherry et al. (1982) and Morin (1983).

Because the pond water (inner core) has a pH of 1.8 and the observed seepage which has passed from beneath the impoundment is pH-neutral, a neutralization zone likely exists beneath the impoundment. Simulations with the ADNEUT programs indicate the present conditions can be matched if the hidden neutralization zone has two sub-regions: a calcite sub-region near pH 5.9 with a predicted R.F. of 30% and a $Fe(OH)_3$ sub-region with pH near 3.0 and an R.F. of 2.2%. With these retardation factors, the $Fe(OH)_3$ sub-region at pH 3 is predicted to pass from beneath the impoundment within a few years.

3.5 Amok Ltd./Cluff Mining Tailings Impoundment, Saskatchewan

Uranium tailings in northern Saskatchewan typically contain less pyrite than Elliot Lake tailings and are discharged at alkaline pH unlike older Wyoming tailings. As a result, acidic water is not common, although surficial acidic seepage of pH 3 with $Fe(OH)_3$ precipitate has been observed near some impoundment dams in Saskatchewan. Additionally, some locally ponded water on tailings has been found to be strongly acidic. These and other observations suggest the chemical conceptual model is operational at these locations, but the lack of data on solid-liquid interactions and on redox reactions in Saskatchewan tailings only allow a preliminary assessment of the sites in terms of the model.

The tailings impoundment (Figure 9) rests on a layer of peat which in turn lies over a sand stratum and bedrock. The peat is reportedly continuous beneath the tailings, minimizing seepage into the sand aquifer. Ground and surface waters move generally in a southwesterly direction into Snake Lake and no significant change in the water quality of Snake Lake has been observed.

The tailings pond water is generally near pH 7.3 and is in equilibrium with calcite, gypsum, and probably $Fe(OH)_3$. Therefore, if acidic conditions develop or acidic seepage is found, the conceptual model would likely apply. Some neutral-pH groundwater seepage with high iron concentrations produce a laboratory pH of 3.0-3.5 when oxidized, indicating discharge of this water to the surface would create an $Fe(OH)_3$ sub-region.

3.6 Key Lake Mining Tailings Impoundment, Saskatchewan

This impoundment represents a major advance in the design of impoundments. The fully-engineered impoundment (Figure 10) is built on a natural sand stratum, but includes a constructed basal clay layer for seepage control. A thin sand layer constructed between the clay and the overlying tailings drains tailings seepage by gravity towards the east side of the impoundment, beneath the dam, and into sumps. This area was recently investigated under the direction of the National Uranium Tailings Program (Knight and Piesold Ltd., 1985).

Knight and Piesold (1985) found that the tailings contain more than 0.1 wt-% of sulfide minerals such as FeS_2 and CoS; however in their analysis they did not distinguish between important minerals such as FeS_2 (acid generating) and $Fe(OH)_3$ (acid neutralizing at low pH). Nevertheless, the potential for the operation of the conceptual model exists. At this time, tailings seepage has a pH near 7.1 and is in equilibrium with calcite, gypsum, $Al(OH)_3$, and possibly $Fe(OH)_3$. This is typical of calcite sub-regions at other sites and, thus, a neutralization zone and inner core may be developing at some location in the tailings pile. However, the 5 wt-% calcite in the tailings should prevent any widespread acid development for many years.

4. CONCLUSION

This paper has compiled the physical and chemical hydrogeology of numerous uranium tailings sites and their surroundings into conceptual models. The physical conceptual model is relatively simple: the tailings impoundment acts as a recharge area for surface and groundwaters. Recharge occurs through seepage of tailings porewater through the base of the tailings pile and through impoundment walls.

The chemical conceptual model includes acid generation and precipitation-dissolution of calcite, gypsum, siderite, $Fe(OH)_3$, $Al(OH)_3$, and related minerals. These minerals combined with aqueous pH buffering reactions and aqueous complexation form a complex scenario for a theoretical step-function degradation of water quality. Aqueous concentrations of radionuclides and metals are reduced by precipitation, co-precipitation with various minerals of the conceptual model, and/or adsorption. The time- and distance-dependence of this conceptual model demonstrates the limitations and predicted errors of batch tests, acid-generation-potential tests, and bulk measurements for prediction for contaminant migration and degradation of water quality. Local acid anomalies should be anticipated at most sites.

The conceptual models draw on the results of fifteen field studies in Canada and the United States of America. Several studies are briefly presented to illustrate the application of the models and Table 2, which summarizes several simulations, indicates the calcite sub-region typically has an equilibrium pH of about 5.5 and greater, the siderite sub-region has an equilibrium pH in the range of 5.1-6.0, the $Al(OH)_3$ sub-region has an equilibrium pH of about 4.3-5.0, and the $Fe(OH)_3$ sub-region has an equilibrium pH in the range of 3.0-3.6 Not all sub-regions necessarily exist at a site and the appearance of a sub-region is dependent on aqueous reactions, solid-liquid interactions in upgradient sub-regions, and the chemistry of the inner core. Furthermore, processes such as dispersion and chemical kinetics can be expected to distort the boundaries of sub-regions to some extent so that the ideal step function does not appear along a flowpath. Lack of data such as Eh, aqueous Al concentrations, and calcite concentrations limit the understanding and simulation of water quality degradation at some sites.

Through the understanding of these conceptual models, more reliable predictions of environmental impact can be made and appropriate plans for the abandonment or isolation of tailings can be designed. The conceptual models described in this paper are applicable to other types of tailings and to acid drainage in general.

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TABLE 1
List of Field Sites Used in the Conceptual Models

NAME	LOCATION	REFERENCE
Nordic Main Impoundment	Ontario	Dubrovsky et al. (1984), Morin (1983)
Nordic West Arm Impoundment	Ontario	Blackport (1980), Dubrovsky (1986)
Lacnor Impoundment	Ontario	Dubrovsky (1986)
Quirke Impoundment	Ontario	Dubrovsky (1986)
Williams Lake Impoundment	Ontario	Feenstra et al. (1981)
Stanrock Impoundment	Ontario	Feenstra et al. (1981)
Greyhawk Waste-Rock Dump	Ontario	Veska (1983)
"Shirley Basin Uranium District"	Wyoming	Cherry et al. (1982)
Federal American Partners Imp.	Wyoming	Highland et al. (1981)
"South-central Wyoming" Imp.	Wyoming	Taylor (1980)
Petrotomics Tailings	Wyoming	Hoffman and Playton (1981)
Morton Ranch Experiments	Wyoming	Gee et al. (1980)
Amok/Cluff Mining Impoundment	Sask.	Open reports to gov't.
Key Lake Mining Impoundment	Sask.	Knight and Piesold (1985)
Eldor Mines Rabbit Lake Tailings	Sask.	SRK (1987)

TABLE 2
Results of Computer Simulations at Sites

	SUB-REGION								
	CALCITE		SIDERITE		$Al(OH)_3$		$Fe(OH)_3$		Inner C.
SITE	pH	RF[1]	pH	RF[1]	pH	RF[1]	pH	RF[1]	pH
Nordic Main	5.5	14%	5.2	0.46%	5.0	0.20%	NP[2]	NP	4.5
Greyhawk	6.9	7.2%	6.0	3.8%	NP	NP	3.7?	NP?	3.5
Federal American	6.0	14%	NP	NP	4.3	14%	3.2	9%	1.9
"Shirley Basin"	5.9	30%	NP	NP	NP	NP	3.0	2.2%	1.8
Petrotomics	5.9	3.5%	5.1	1.5%	5.0	1.1%	3.5	0.7%	2.2
"South central WY"[3]	6.4	3.7-5.4	5.3	10.7%	?	?	NP	NP	1.8
Morton Ranch[4]	6.1		NP		4.8		3.6		1.8

[1] = retardation factor relative to groundwater velocity
[2] = NP: not present at site
[3] = calibrated simulation not possible due to lack of aluminum data
[4] = laboratory column experiments; some experimental details lacking

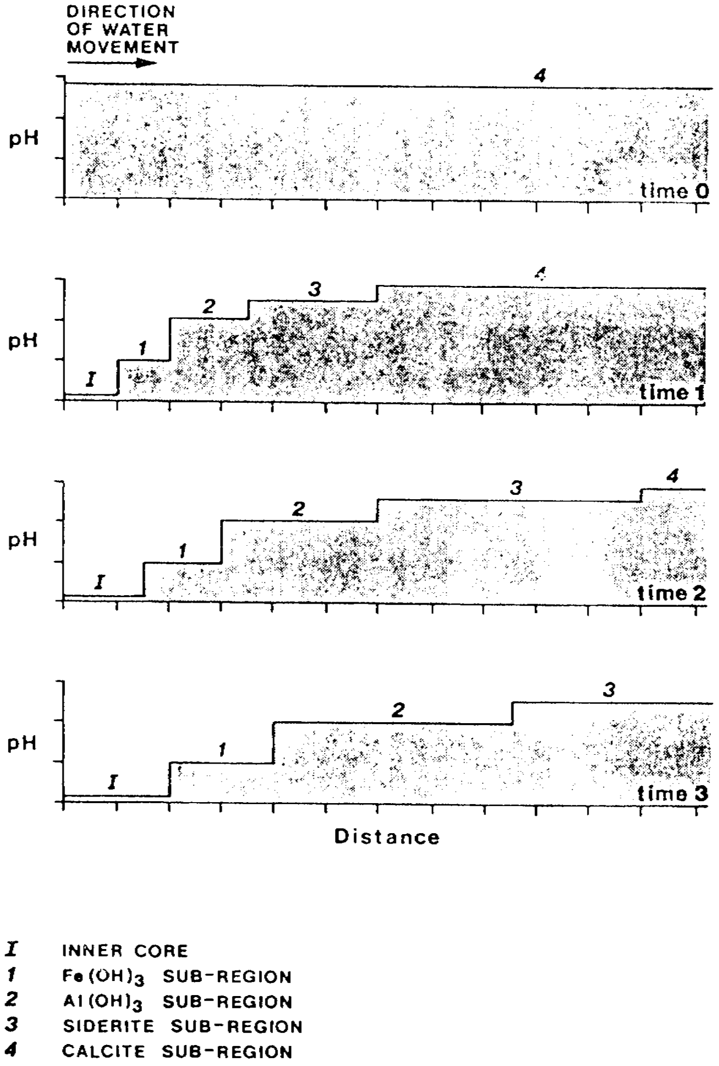

Figure 2. Schematic diagram of lateral migration of sub-regions and the inner core.

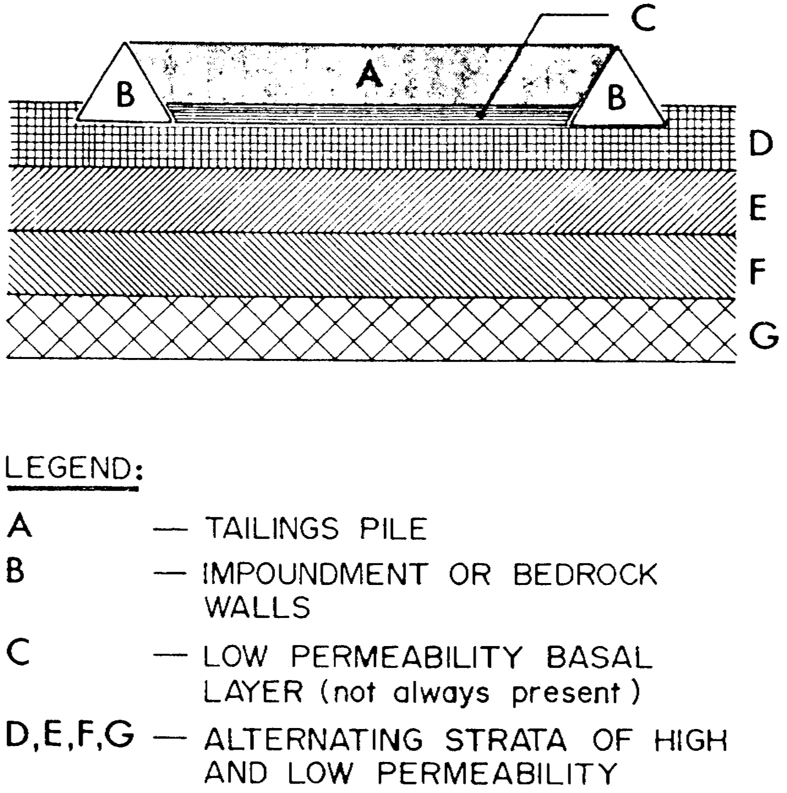

Figure 1. Schematic diagram of the physical conceptual model.

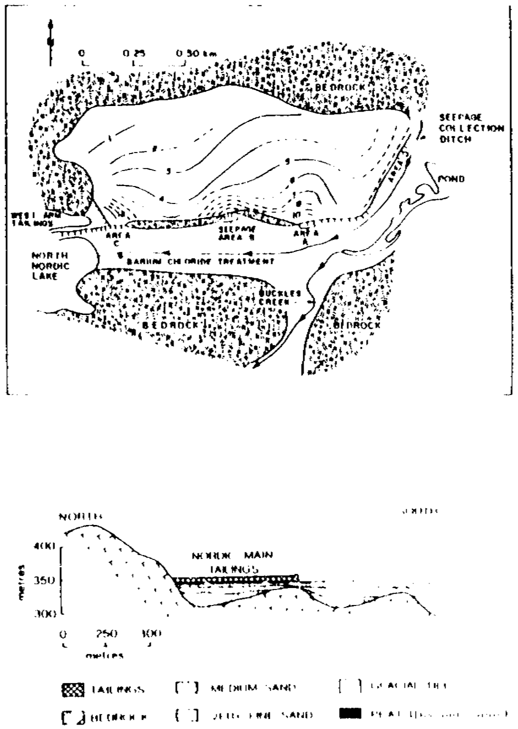

Figure 3. Map and depth-to-water-table (upper) and generalized cross-section (lower) at the Nordic Main site.

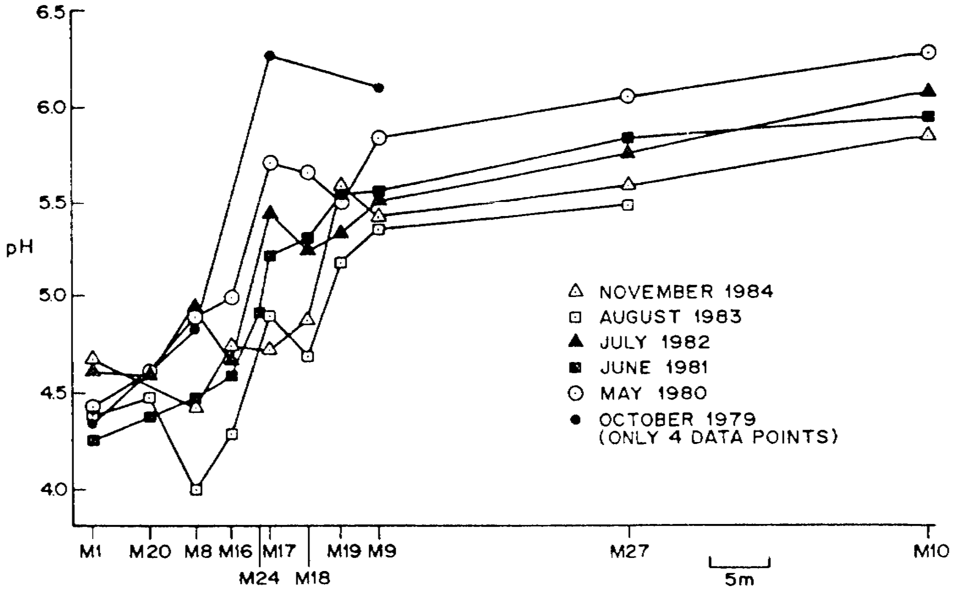

Figure 4 One-dimensional profile of pH through the center of the contaminant plume in Seepage Area A at the Nordic Main site.

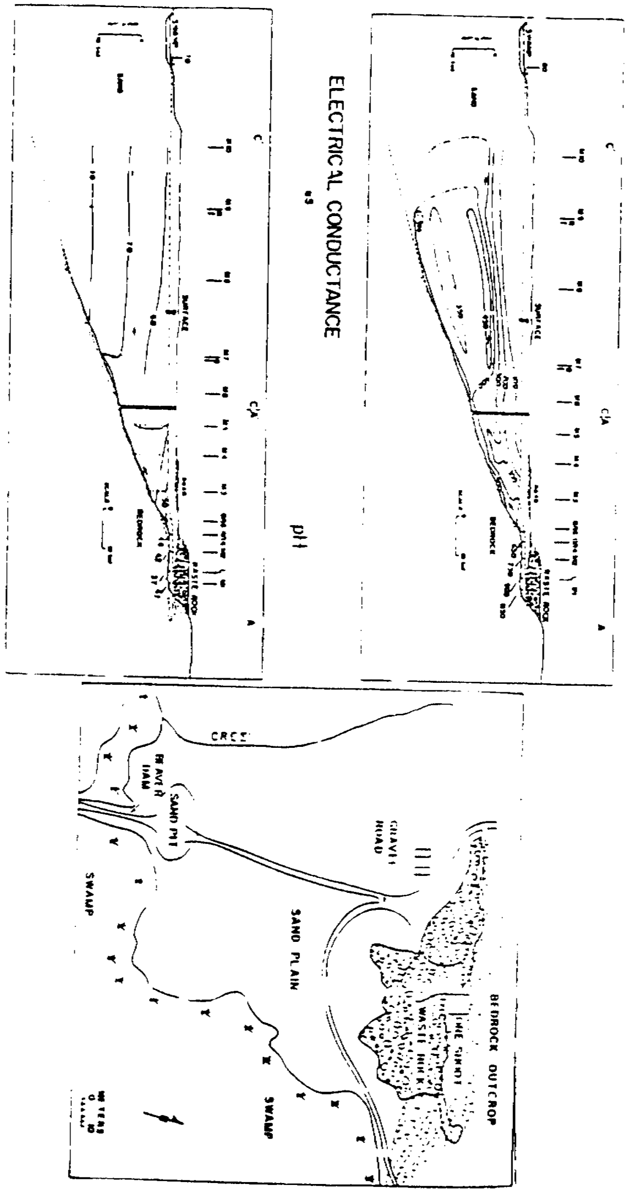

Figure 5. Map (right) and chemical profiles at the Greyhawk waste-rock dump (adapted from Veska, 1983).

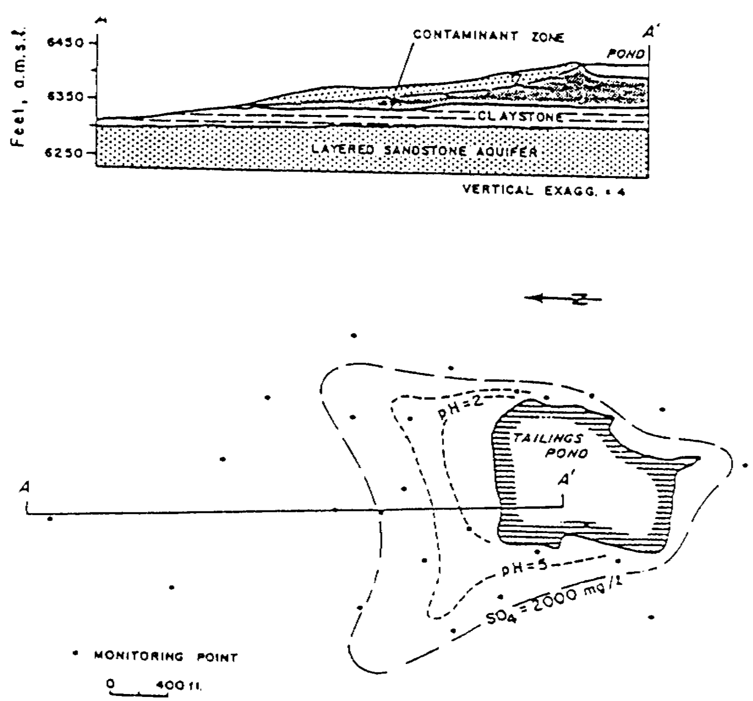

Figure 6. Cross-section and map of the Federal American Partners' tailings pond (adapted from Highland et al., 1981).

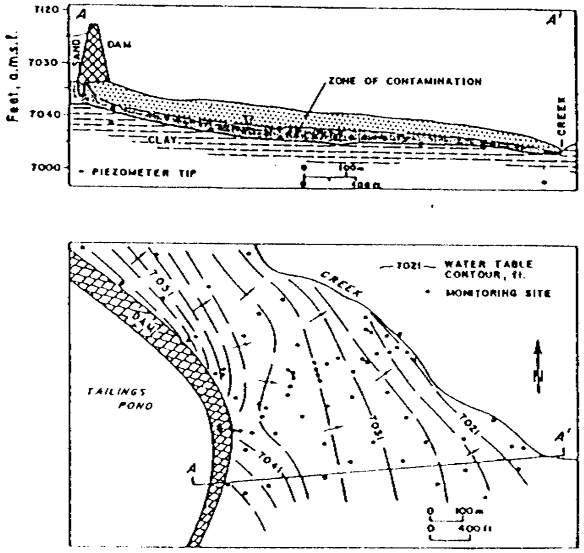

Figure 7. Cross-section and map of the site in the Shirley Basin Uranium District (adapted from Cherry et al., 1982).

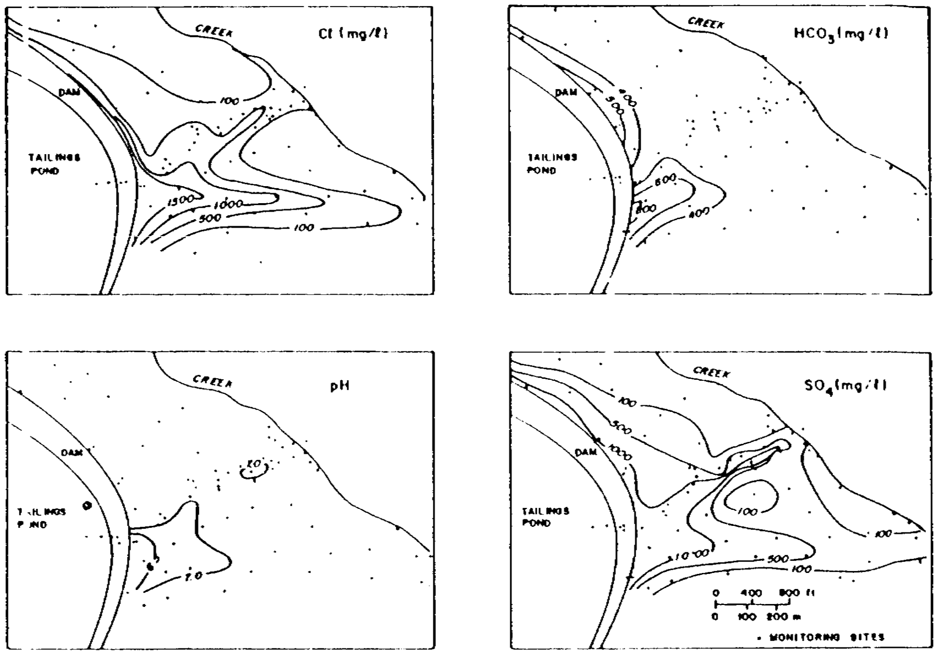

Figure 8. Chemical profiles for the site shown on Figure 7.

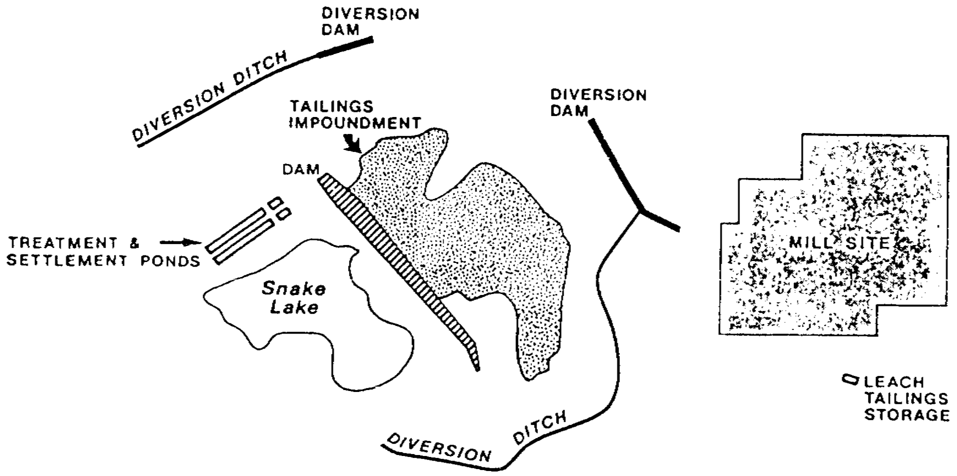

Figure 9. Map of the Amok Ltd./Cluff Mining site.

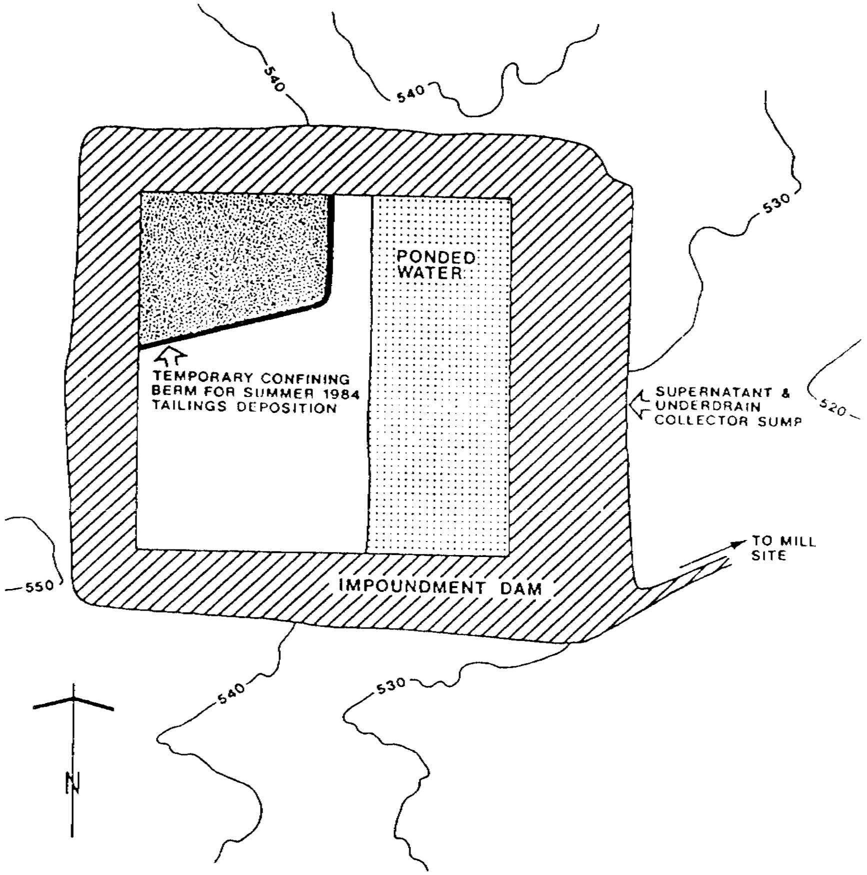

Figure 10 Map of the Key Lake Mine tailings impoundment (adapted from Knight and Piesold, 1985)