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EXPOSURES FROM MINING AND MINE TAILINGS

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Abstract—The mining, milling and tailings management of uranium ores results in environmental radiation exposures. This paper describes the sources of radioactive emissions to the environment associated with these activities, reviews the basic approach used to estimate the resultant radiation exposures and presents examples of typical uranium mine and mill facilities. Similar concepts apply to radiation exposures associated with the mining of non-radioactive ores although the magnitudes of the exposures would normally be smaller than those associated with uranium mining.

INTRODUCTION

Since uranium is ubiquitous in nature, there is some environmental radiation exposure associated with the mining, milling and tailings management of all types of ores. However, as uranium levels are naturally greatest in uranium ores and since uranium mining, milling and tailings disposal has been the subject of much debate in recent years, the focus of this paper is the significance of environmental radiation exposures arising from the mining, milling and tailings management of uranium ores. The issues discussed in this paper however, also apply to the mining of other ores containing elevated levels of uranium, notably phosphate ores and various ores containing rare earth elements.

The mining and milling of uranium ores has been carried out for many years in many environmental settings. In the following sections, we discuss how local conditions influence the ways in which the mining, milling and tailings management activities are performed. Following this, the basic approach used to estimate radiation exposure from uranium mining, milling and tailings management activities is discussed. Finally, we present several examples which illustrate the way in which radiation exposures are estimated.

TYPICAL URANIUM MINE AND MILL FACILITIES

In this paper, uranium refers to natural unenriched uranium in which the uranium-238 decay chain is of principal radiological interest. Perhaps the most striking feature of the uranium decay chain, shown in Fig. 1, is the presence of radon-222 (radon), an inert radioactive gas formed through the decay of radium-226 (radium). Because radon is a gas, some of it can escape into the air from solid materials containing radium, such as uranium ore and uranium tailings. This gives rise to an exposure pathway somewhat different from that of other radionuclides in the uranium decay series. The sequence of decay products from radon-222 to polonium-214 (shown in the shaded area in Fig. 1) are commonly referred to as radon and its short-lived daughters. This is because the radioactive half-life of radon is relatively long compared to its first four daughters. Unlike their gaseous parent, the short-lived daughter isotopes of polonium, lead and bismuth are all solid elements. The other solid members of the uranium series include isotopes of uranium, thorium, radium and lead. These species are all chemically distinct and the potential for their release to the environment depends strongly on the nature of the ore and on the chemical processing method used in the mill. Also, while these species typically occur in radioactive equilibrium, or near equilibrium in the ore (that is the radioactivity of each radionuclide is equal), they are rapidly fractionated in the environment depending on their own particular chemical properties.

Historically, most operating mines have had a relatively low uranium concentration, typically in the range of 0.025–0.25% uranium. However, in some of the newer mines, the ore grade is considerably higher (0.5% and greater). The mineralogy is diverse with some ores containing substantial quantities of associated species such as arsenic, nickel and cobalt. The environmental concerns associated with the release of these associated non-radioactive species to the environment may outweigh the environmental significance of the radiation exposure. Many uranium ores contain iron pyrites, as do many base metal ores, which can result in the generation of acid mine water and acid tailings porewater. While acid generation and the effects of acid generation on the environment are not subjects of this paper, it should be noted that uncontrolled acid generation can lead to the dissolution of radionuclides and their subsequent dispersal into the environment. This can be of significance with regard to the long-term management of uranium tailings.

The major components of a uranium mine, mill and tailings management facility, as shown in Fig. 2, are briefly discussed below.

Uranium mining

The type of mining method used at any location is influenced by many factors, including the nature and

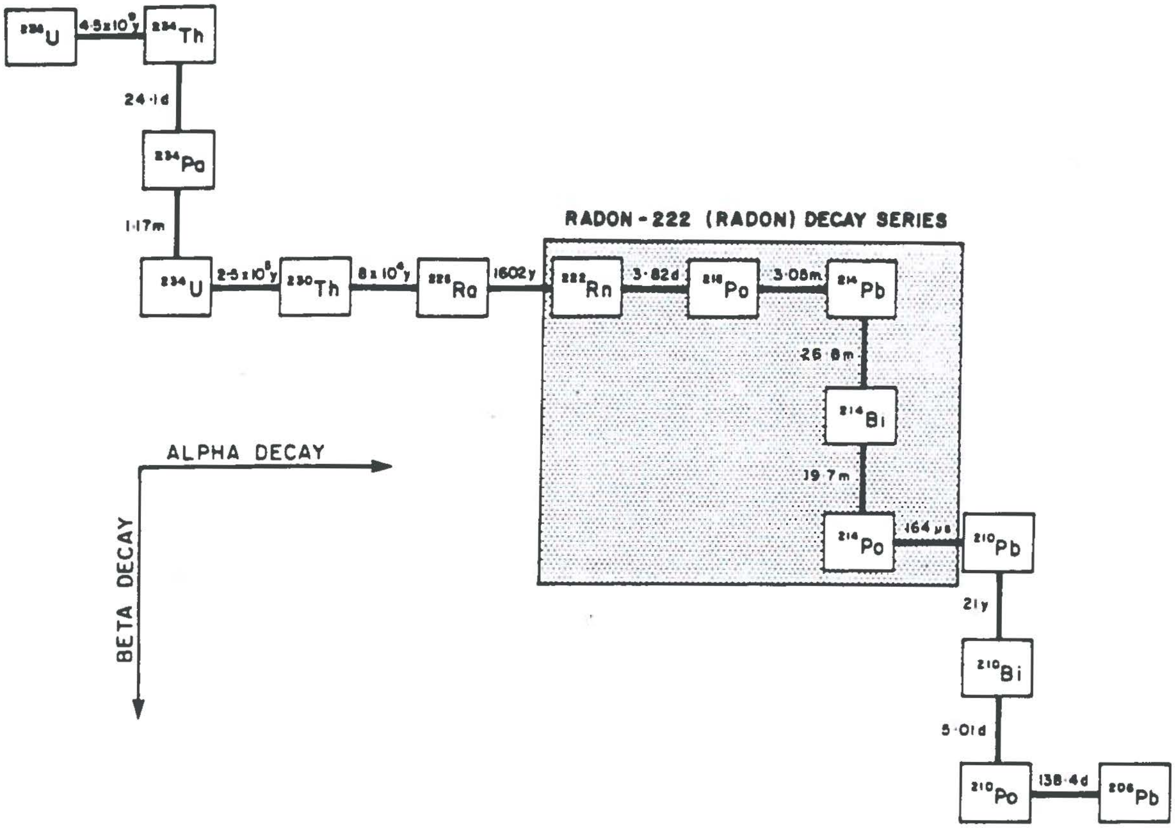

Fig. 1. The uranium-238 decay series.

grade of the ore body, its depth, the geological state of the surrounding rock, and the presence or absence of groundwater. Both underground and open pit mining methods are used to recover uranium. Each mining operation has its own unique environmental considerations that must be addressed. Many of these concerns, such as the storage of overburden from open pits and the control of minewater, are common to other types of mines.

Potential radiological concerns from uranium mining include:

—discharging minewater that contains radioactive contaminants:
—releasing radon and dust in the exhaust air from underground mines; and
—releasing radon and dust from open pit mines.

Contaminated minewaters are usually treated and, in many cases, used in the mill. Alternatively, the minewater is send directly to the tailings management area for evaporation or treatment. In most situations, the releases of dust and radon from mining opera-

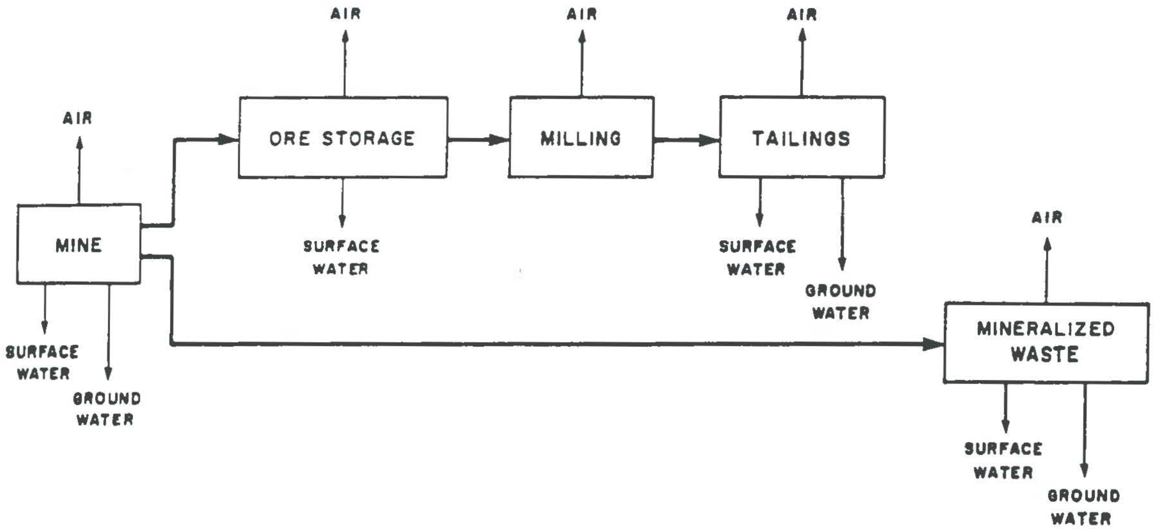

Fig. 2. Major mine/mill operations and associated emissions to air and water.

tions are smaller than releases from the associated tailings management area.

Milling

The first stage of milling typically involves grinding the ore to a very fine, flour-like consistency. The ground ore is then subjected to a leaching process in either highly acidic or alkaline solutions (depending upon the characteristics of the ore) which cause the uranium to dissolve. This separates the uranium from the solid rock particles. The uranium is then concentrated by ion exchange or solvent extraction and precipitated and dried into a relatively pure product called yellowcake (mixed uranium oxides).

Selection of optimal milling techniques requires extensive laboratory analysis to determine such matters as leachability of ore, uranium recovery rate, product specifications, the amount of water used, and the degree of recycle.

Because of the nature of the milling operation, the majority of the potential environmental radiological contaminants remain in the liquid phase and are sent to the tailings management area.

The amounts of radon and dust released from the milling operation are generally small in comparison to those released from the tailings management area.

Waste management

Two main types of wastes are produced by a typical uranium mine/mill facility: mineralized wastes (waste rock and overburden removed to permit access to the ore) and tailings.

Mineralized wastes contain levels of uranium that, while above background levels, are not economic to mill for uranium recovery. These are often set aside and managed separately or sometimes are incorporated into the tailings management system. In some instances, the weathering of these materials can release substantial quantities of radioactivity to the environment.

Tailings are the waste materials produced during the milling of the ore. Tailings consist of ground rock particles, water and various amounts of mill chemicals. All types of mills produce tailings of some form or other.

Tailings management areas often include one or more dams which help form a basin into which the material is placed. Modern dam design and construction techniques are quite sophisticated. Geological studies are used to locate and size the structures, and earthquake analyses are performed to ensure both static and dynamic stability. Hydrogeological studies are carried out to ensure that both core materials and foundations are sufficiently impermeable to control basin seepages. A typical modern dam includes a core trench and cutoff to bedrock, a grout curtain in bedrock, filter drains to control internal porewater pressures, shell materials for adequate stability, and rock riprap for long-term erosion protection.

If the operation of the tailings area requires a liquid discharge (as is the case, for example, at all Canadian uranium mines), then treatment facilities are provided. Treatment plants can include chemical addition equipment, a mixing area, and a solids separation facility.

Tailings management areas are designed to take into account local conditions but in general terms there are three basic types of tailings management areas, as illustrated in Fig. 3:

—dry land sites;
—land/shallow water combination sites; and
—underwater disposal sites.

Dry land containment sites are usually located in flat or gently sloping areas. Such sites can occupy large areas and require long dams or dykes around their borders to contain the tailings, accommodate storm run-off and direct water to treatment facilities.

The land/shallow water combination type of containment is often located in a valley, marsh or other low-lying area. In some cases, a dam across one end of the valley is required to produce a basin for the tailings. In many cases, a large storage volume can be created by the construction of a relatively short dam.

Underwater disposal refers to the placement of tailings below the water surface, such as at the bottom of a lake. On the lake bottom, the tailings are protected from the actions of wind, surface water and other environmental features that might disturb the tailings.

The selection of tailings management facilities and methods of operation evolves from the consideration of numerous factors including:

Location
—Climate.
—Local topography and geomorphology.
—Ore characteristics.

Economics
—Slurry versus filtered tailings.
—Distance from mill to tailings basis.
—Dam sizes.
—Close out (decommissioning).

Environment
—Liquid effluent treatment.
—Atmospheric emissions control.
—Seepage control.
—Public access restrictions.

At a specific site, local features and conditions determine which of these factors is most important.

Concern is often expressed over the possible effects of radionuclides that can be released from uranium tailings. Radon can be emitted as a gas, while other radionuclides can enter the environment as windborne dust particles or in liquid releases.

Radon is produced in tailings area through the decay of radium-226. Some of the radon will migrate to the tailings surface and then disperse in the atmosphere. Typically, only a small fraction of the

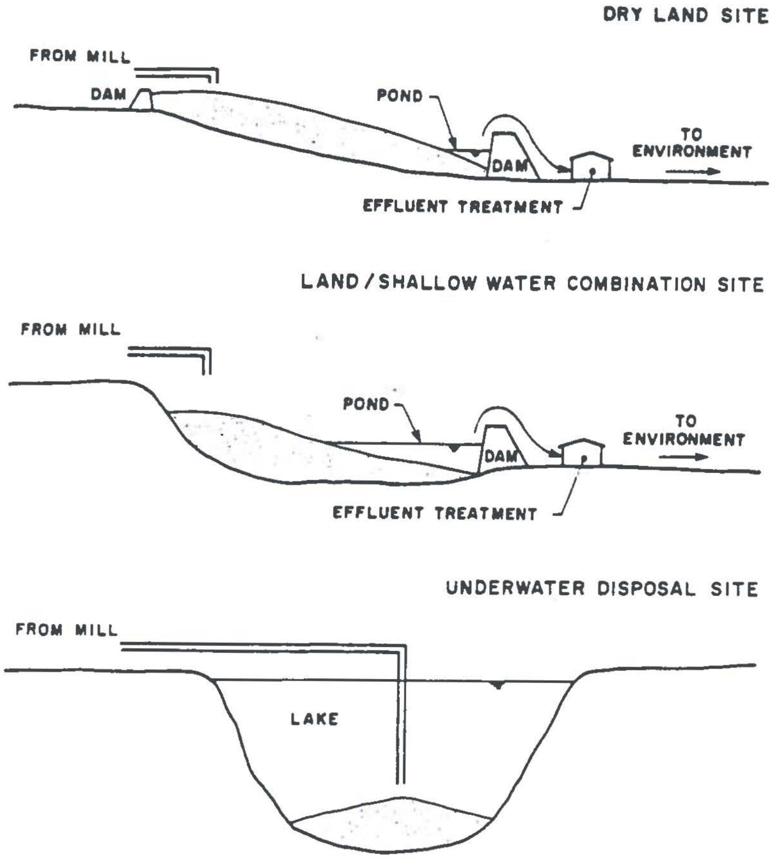

Fig. 3. Basic types of tailings management.

radon (that produced in the uppermost tailings) is released to the air. Radon emission rates from tailings areas have been established both by field measurements and model calculations in various studies (SENES Consultants Ltd. 1983, 1986; Shearer and Sill, 1969; U.S. Nuclear Regulatory Commission, 1980). Such studies indicate that incremental radon levels due to radon emissions from tailings areas decrease rapidly with increasing distance and typically are found to be indistinguishable from background levels within 1 or 2 km from a tailings areas.

Dust generation from tailings is not a problem where tailings are kept wet. Dusting from dry areas can be minimized using a surface cover such as vegetation or placement of a physical cover material such as asphalt or riprap.

The liquid portion of the tailings area is predominantly water with relatively high levels (when compared to background) of some dissolved constituents. At operations where the acidic milling process is used, and/or the ore contains pyrite, the tailings slurry is often treated chemically to make it alkaline prior to being discharged from the mill. This causes many elements including metals and some radionuclides such as thorium to precipitate from the liquid portion and to settle in the tailings area.

A mine/mill facility must meet government regulations for the effluents. These constraints on effluent quality necessitate the operation of treatment plants at the tailings basin outflow. The treatment plants typically provide for the removal of dissolved radium-226 via barium chloride addition and sedimentation. Adjustment of pH may also be required.

Table 1 presents a few examples of uranium tailings management practices in use throughout the world. These illustrate the effect of different site conditions, economics and local regulation on the development of tailings management practices.

Decommissioning

Decommissioning (close-out) options for a uranium tailings facility are dependent upon many site-specific factors. These include climate, geography, and demography of an area as well as the specific design features of the impoundment and the chemical, radiological and physical characteristics of the tailings.

The most common methods currently being considered for reclaiming tailings areas are direct vegetation, application of physical covers such as riprap, and water covers. The option selected will depend not only upon the site-specific conditions but also the technical and economic viability of the option.

Vegetation can be an effective approach to reclamation. Vegetation, however, may not be applicable in arid areas or regions of high population density where radon control may be a potential concern since vegetative cover alone does not reduce radon emissions. Some form of institutional land-use control may be required to prohibit either removal of tailings

Table 1. Examples of tailings management practices

Mining area	Containment method	Tailings form	Effluent treatment
Elliot Lake, Ontario	Land/water	Slurry	Yes
Beaverlodge, Saskatchewan	Underwater	Slurry	Yes
Rabbit Lake, Saskatchewan	Land/water	Slurry	Yes
Southwestern United States	Dry	Slurry	No
Le Bernardan, France	Dry	Filtered	Yes
Nabarlek, Australia	Underwater	Slurry	No
South Africa	Dry	Thickened slurry	No

material or construction of houses on tailings areas following close-out.

The application of physical covers on the tailings surface has been promoted by many regulatory bodies as an effective means for the control of radon, external gamma radiation, and tailings erosion. Covers tend to be expensive but may be applicable in certain instances. Some recent studies (Markos, 1982) have questioned the long-term benefit of covers in areas such as the mid-west United States because of various geochemical phenomena which lead to cover failure.

The method of water cover is applicable in some situations (Halbert *et al.*, 1982; SENES Consultants Ltd, 1983) provided that releases of radioactivity to surface and ground waters can be maintained within acceptable levels. This option has many benefits including tailings isolation, elimination of dusting potential and surface gamma radiation and a large reduction in radon releases.

For many installations, the close-out option selected may be far more dependent upon the nonradiological tailings constituents (Culver *et al.*, 1982). Components such as pyrite, which can lead to chronic acid production, and contaminants such as arsenic may represent far greater environmental concerns than do the radioactive constituents of the tailings.

PATHWAYS ANALYSIS

In most countries today, the approval to operate nuclear facilities requires that some form of environmental impact analysis be undertaken, regardless of whether these facilities are to be used for the production of power or for the management of wastes. A key objective of such analyses is the estimation of doses to individual members of the public arising from routine releases of radioactivity to the atmospheric and aquatic environments.

The potential dose associated with radioactivity released from a uranium mining facility is assessed by undertaking a pathways analysis. Such an analysis is used to estimate the exposure to dose that certain critical groups (those most likely to receive the highest exposures) could receive by all of the possible pathways of exposure. For optimization studies, collective population dose may also be calculated.

Radioactive materials released to the environment may result in exposure to man through various physical, chemical and biological processes. Such processes include the movement or transportation of radionuclides in the environment (usually via air or water), the uptake or bioaccumulation of radionuclides by local plants and animals, and the living conditions or lifestyle of the exposed individual (usually referred to as a receptor). The relative influences of these processes on predicted exposures vary from location to location and person to person. The results of these calculations can be compared with appropriate standards or other points of reference such as background radiation levels.

The assessment of doses received by the public due to releases of radioactive substances to the environment depends largely on the use of mathematical models to predict the behaviour and fate of radionuclides in the atmosphere, the hydrologic environment (surface and subsurface) and the biosphere. Many environmental models are in current use and have been reported in the literature by various national and international authorities including: the International Commission on Radiological Protection (ICRP) (1979), the U.K. National Radiological Protection Board (NRPB)/Commissariat à L'Energie Atomique (CEA), (1979), the International Atomic Energy Agency (IAEA) (1982), the U.S. Nuclear Regulatory Commission (Till and Meyer, 1983), the U.S. National Council on Radiation Protection and Measurements (NCRP) (1984) and Canada's National Uranium Tailings Program (SENES Consultants Ltd, 1987). A review of such models is beyond the scope of this paper and the reader interested in details of the models is referred to the original literature.

A typical pathways model developed for radiological assessment is composed of a number of submodels representing many different processes and mechanisms. The concept is shown in Fig. 4 which illustrates typical exposure pathways for a uranium mine, mill and tailings facility.

The most common type of model in current use is the "equilibrium" model, which is composed of parameter values which, more or less, represent conditions which approximate steady-state conditions between environmental compartments. In practice, the equilibrium model consists of multiplicative equations using a series of steady-state transfer factors (concentration factors). For some assessment questions, such as determining how dose varies with time, the equilibrium model may not be satisfactory and a dynamic model may be required (NCRP, 1984).

Model selection, modification and application re-

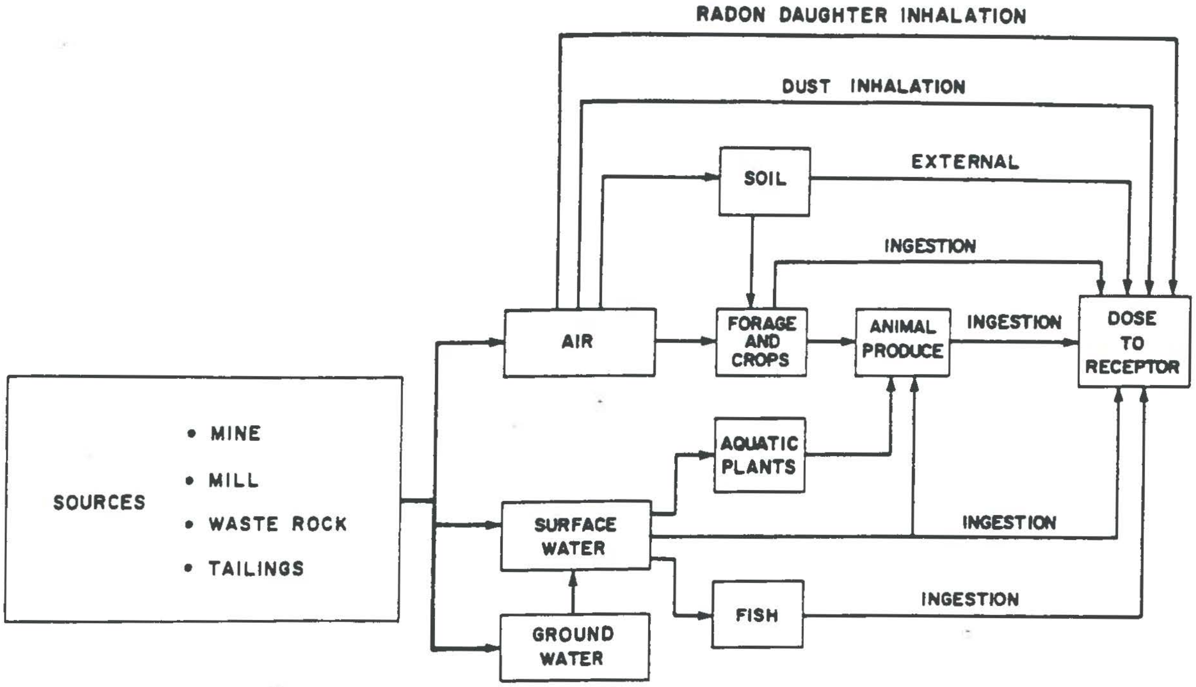

Fig. 4. Potential exposure pathways.

quires information about the type and nature of the source terms, the surrounding environment and the location and lifestyle of the individuals most likely to be exosed.

Models can be adapted to suit the situation being studied and the assessment question being asked. Pathways that are not appropriate for a specific situation can be eliminated from an analysis. Conversely, extra effort can be directed to those pathways known or suspected of being particularly relevant to a specific situation. For example, when it is known than an individual receptor hunts locally for meat, this pathway can be added to the model and information can be gathered about hunting habits.

Based on their information requirements, the models commonly used in radiological risk assessment for uranium mine/mill developments can be divided into four broad classes: source characteristics; environmental distribution (dispersion and uptake); receptor considerations; and dose calculations.

Source characteristics

Source term characterization typically is based on the following information:

—physical, chemical and radiological features of the ore and host environment;
—design of the mine;
—design of the mill;
—design of the tailings management area;
—chemical and biochemical reactions occurring in the tailings;
—scheduling information, operating procedures;
—emission controls;
—climate and meteorological conditions;
—laboratory feasibility studies;
—experience in other operating areas.

Environmental distribution and fate

These calculations involve the dispersal and distribution of radionuclide concentrations in the air, surface water and ground water and transfer to the relevant biosphere compartments (e.g. fish, vegetables). The following information is used to make a model site-specific:

—physical, chemical and radiological features of the surface water and ground water environment (e.g. pH, ion exchange capacity);
—climate and meteorological conditions (e.g. temperature, wind speed and direction, net precipitation);
—information on certain aspects of the sources (i.e. stack heights, exhaust flow rates);
—experience in other operating areas;
—chemical and physical features of the emissions
—the types and locations of potential receptors.

The information required to assess the incorporation of radionuclides into the terrestrial and aquatic environments at the receptor location, include:

—the media in which the uptake occurs;
—transfer and uptake factors from site-specific or other studies (i.e. literature values);
—local agricultural practices.

Receptor considerations

The dose associated with a facility is usually the principal consideration in assessing whether or not that facility presents a suitably low radiological hazard or risk. Moreover, by controlling the dose to the critical receptor (the individual(s) most likely to receive the largest exposure), it can normally be demonstrated that other more typical people will be subjected to a much smaller dose (risk).

Depending on site conditions and individual characteristics, the presence of a particular radionuclide in a critical pathway will result in varying doses to different members of the public. For dose estimation purposes, one or more groups of people are identified that are likely, on average, to receive higher doses than other groups of the public. The identification of such groups, called critical groups, requires consideration of lifestyle characteristics as well as releases to the environment, and local environmental conditions. Lifestyle characteristics include:

—recreational habits (e.g. time spent hunting at or near the site);
—diet, including local foods (e.g. gardens, livestock, fish, deer, wild fowl) and sources of drinking water or water for irrigation;
—fraction of time spent at home and time spent indoors versus outdoors;
—shielding factors (e.g. building construction, methods and materials);
—population density and distribution (where estimates of cumulative dose are needed).

Dose calculations

The final modelling component calculates external exposures (due to direct exposure from the site or levels of radionuclides in the air, water and soil) and internal exposure (due to intakes through inhalation and ingestion). This usually incorporates dose conversion factors (both external and internal) for one or more age groups as appropriate.

Estimated doses to members of the public can be compared to a maximum annual dose limit for members of the public of 5 mSv/y (ICRP, 1977; Moeller *et al.*, 1983; NCRP, 1971; U.S. Federal Radiation Council, 1965) or for chronic lifelong exposure conditions to a dose limit of 1 mSv/y (ICRP, 1977). Occupational dose limits are a factor of 10 higher or 50 mSv/y.

The latest ICRP recommendations (ICRP, 1977) express the dose limits in terms of "effective dose equivalent" limits which, for stochastic effects, are based on the total risk to all tissues irradiated. (Stochastic effects are those whose probability of occurrence is proportional to the dose received, e.g. cancer.) This ensures that the total risk from irradiation of parts of the body (for example, internal exposure) does not exceed that from uniform irradiation of the whole body.

Internal dose conversion factors. Since it is difficult, especially for internal exposure, to directly measure the doses described above, derived limits referring to quantities that can be measured are required. An ICRP report (1979–1981) provides a tabulation of Dose Conversion Factors (DCF) for inhalation and ingestion of selected radionuclides to facilitate the implementation of the latest ICRP recommendations. The calculation of the DCF considers several factors such as organ mass, fractional uptake of the radionuclide (i.e. soluble or insoluble), and radioactive decay energies.

Effective dose equivalent conversion factors based on the ICRP methodology have been calculated for both infants and adults by Johnson (Johnson, 1983; Johnson *et al.*, 1979). The solubility classifications for various radionuclide compounds must be taken into consideration. The Annual Limits of Intake (ALI's) for inhalation are based on a 1 μm particle size. The DCF's are based on the 50-yr committed dose equivalent, that is, the integral to 50 yr of the doses to all body organs following intake of radioactive material.

The limits of exposure for radon and its daughters require special consideration. As discussed in detail in ICRP (1981) Publication 32, it is the opinion of the ICRP that the same dose limit of 50 mSv/y or the corresponding level of risk should also be applied to individuals exposed to radon and its daughters. For adult radiation workers, the recommended annual limit of exposure to radon daughters is given in terms of the Working Level Month (WLM), and has a value of 4.8 WLM which, according to the ICRP (1981), is approximately equivalent on a risk basis, to exposure to 50 mSv/y. The corresponding annual limit for a member of the public is one-tenth of that for radiation workers (i.e. 0.48 WLM/y NCRP, 1979). Evans *et al.* (1981), in reviewing the estimates of risk from environmental exposure to radon and its daughters, discuss a number of factors which suggest that members of the public are at a lower risk per unit exposure than miners. Hence, the 0.48 WLM/y limit may be conservative.

External dose conversion factors. External dose conversion factors for the radionuclides of interest to uranium mining are given in Kocher and Sjorean, 1985) and U.S. NRC publications (USNRC, 1977, 1982). These factors are used to calculate the external dose (to the body) from radionuclides that are suspended in the air, deposited on the ground, in the water or in shoreline sediments. The results include electron dose-rate factors for skin calculated using a stochastic risk weighting factor of 0.01. The weighting factors for photon dose-rate factors for other organs are those given in ICRP Publication 26 (1977).

Uncertainty in dose predictions

As with any predictive assessment, an analysis of exposure pathways and dose due to a uranium mining facility involves the use of mathematical models. Information is provided to the model in the form of numerical values for the various input parameters and calculation produces the numerical values of one or more output variables. Unfortunately, the values of the input parameters are inherently uncertain. The uncertainty arises either from lack of knowledge because of inadequate measurements or from the actual variability in the real world (often referred to as "stochastic variability"). Where all of the variability in the model predictions is a result of known stochastic variations of the parameters, then the variability in the prediction is irreducible. Any variability that is a result of insufficient knowledge of a parameter can, in principle at least, be reduced by better knowledge.

The state of the art in environmental modelling is to explicitly account for uncertainty in the estimates of the input parameter(s) by describing the parameter(s) as a distribution(s) of values rather than as a single number. These uncertainties can be propagated through a model calculation analytically or numerically. For the former, variance propagation or moment matching are widely used.

In numerical error propagation (Monte Carlo methods), values of the input parameters are drawn at random from the appropriate distributions and the model is evaluated to produce a value of the output variable(s). (Simple random sampling or stratified sampling such as latin hypercube sampling is usually used.) The details of procedures to use in specifying uncertainty in input parameters, the propagation of uncertainty through the calculations and assessing the relative contributions of each parameter to the overall uncertainty in model predictions is beyond the scope of this paper. The reader interested in this topic is referred to the literature (such as that cited in Chapter 6 of U.S. NCRP Report No. 76, NCRP, 1984).

EXAMPLES OF DOSE ESTIMATION FOR URANIUM MINE AND MILL FACILITIES

Overview

In earlier sections of this paper, we discussed how pathways analysis can be performed to assess the radiation exposure to people arising from radioactivity released from uranium mining, milling and waste management activities. The pathways analysis technique either uses field data or makes assumptions about radionuclides along various environmental pathways (with appropriate transformations such as bioaccumulation, dilution and chemical complex formation), and finally exposes selected populations to these radionuclides by assuming that they have certain standardized aspects of behaviour such as eating habits. Data from environmental impact statements for various uranium mining operations (Canada Wide Mines Ltd, 1980; Key Lake Mining Corporation, 1979; MacLaren, 1978; Ranger Uranium Mine PTY Ltd, 1975; USNRC, 1980) were used to develop the annual dose estimates for maximally exposed individuals shown in Table 2. (It should be noted that the original articles were prepared at different times and different calculational procedures were used. As a consequence, it was necessary to make various assumptions in developing Table 2. Nevertheless, the comparisons in Table 2 are considered reasonable.)

All of the total annual doses are the order of 0.1 mSv/y (10 mrem/y) which is of the same order as natural variations in background radiation exposure levels. For comparison, a dose of 0.1 mSv/y is about equivalent to the radiation dose received during two cross-Canada flights and the difference in annual radiation dose one would receive in moving from a frame to a brick house.

In view of the relative ease of access by these authors to published data on Canadian facilities, three examples of dose estimations from Canada are used to illustrate the concepts discussed earlier in this paper. The information presented here is derived solely from published or readily accessible information on site-specific or theoretical dose assessments in Canada. Because the dose assessments were carried out at different times and for different reasons, there is some variation in the depth and scope of the information available. No further detailed analysis of the large amount of original data was attempted although some numbers have been converted to common units for ease of comparison.

The examples of radiological dose assessments include both a low grade ore deposit and a high grade ore deposit. In addition, because tailings are the largest source of environmental radioactivity, we provide a generic example of dose assessment for a low grade tailings facility. The first two examples are deterministic assessments while the tailings example illustrates an uncertainty analysis using probabilistic techniques.

Low grade ore facility

Site and facility. The Elliot Lake mining camp is used to illustrate the dose calculation for a low grade (0.1–0.2% U_3O_8) pyritic ore. Elliot Lake is located approx. 30 km north of Lake Huron, midway between Sault Ste Marie and Sudbury, Ontario. Currently, the population is approx. 20,000. The area experiences a total precipitation of about 96 cm per year with an average evapo-transpiration of about 50 cm. Winter lasts five or more months with temperatures of 0 to $-25°C$ being typical. The area is characterized by abundant lakes and streams with about 20–25% of the total area being covered by water. The region is sufficiently forested with mixed coniferous and deciduous species to support lumbering. The bulk of the population rely upon the two existing mining companies for their existence. There is some tourism involving camping, fishing and hunting. There is no farming or farming potential within the immediate vicinity. The Serpent River is the major drainage from the area and passes through a reservation occupied by native peoples who make use of some wild food such as game and fish in their diet.

The assessment took account of the cumulative effect of several mining, milling and tailings management activities.

Pathways analysis. In the 1970s, the Elliot Lake Mining company expanded their operations due to the increased demand for uranium. Much of the following information on radiation pathways analysis is taken from the Environmental Impact Assessment (E.I.A.) reports undertaken on behalf of the mining

Table 2. Maximum annual exposure for representative uranium mining areas

Exposure (mSv/y)[a]	Elliot Lake, Ontario	Northern Saskatchewan	U.S. model mill	Ranger mine, Australia
Total body[b]	0.26	0.06	0.1	0.01
Radon daughters	0.17	0.02	0.4	0.15

[a] Original units of estimated exposures were converted to SI units using 1 mSv = 100 mrem and 1 WLM = 10 mSv.

[b] All pathways exclusive of radon daughters.

companies during the expansion (MacLaren, 1978) and the subsequent review by the Ontario Environmental Assessment Board (1979).

These reports compared estimated exposures and intakes to maximum permissible intakes that were derived using the critical organ concept of radiation protection. Only radon, radium-226 and thorium-230 were considered in detail at the time of the E.I.A. (in 1977) since these were considered to be of prime concern in Elliot Lake.

The critical group consisted of people who lived close to a tailings area and who consumed fish, wildlife (moose, deer) and produce from the local area.

The exposure calculations were conservative in that they were based on maximum intake rates of air, food and water for exposed individuals who were assumed to reside continuously at the locations of highest predicted, off-site exposure with no allowance for factors such as possible protective shielding provided by residences and time spent elsewhere (MacLaren, 1978; USNRC, 1977).

The sources of radioactivity were the mines, mills and the tailings areas. Their strengths were determined by a sampling and field measurement program.

The radon and dust concentrations at each mine ventilation upcast were measured and converted to emission rates using the known ventilation rates. The radon and dust concentrations in the mill stacks were measured and converted to emission rates per ton of ore so that the effects of a change in the production rates could be calculated. The tailings (870 ha in area) were the largest sources of radionuclide emissions and underwent the most extensive measurement program. Radon emissions (9.0×10^7 Bq/s) estimated from exhalation measurements were much larger than the emissions from the mines and mills (1.3×10^7 Bq/s). The particulate emissions from the tailings area were estimated by using a saltation-suspension model, high volume air samplers and on-site micrometeorological measurements (MacLaren, 1978).

Gaussian plume air dispersion models, calibrated by using measured values of suspended particulate and dustfall at stations adjacent to the tailings areas, were used to estimate ambient concentrations of radon and dust at potential receptors. The model predicted both suspended and deposited particulate as a function of particle size. These were converted to radioactivity values by using the results of the analysis of tailings surface samples. Suspended tailings dust levels were predicted to fall below 10 μg/m^3 within 2–3 km from the tailings.

Elliot Lake is situated within an extensive interconnection of lakes and streams. Numerous measurements of radionuclide concentrations at points of discharge from the tailings areas and throughout the river system were used to evaluate the existing radiological effects of the water pathway. A simulation model of the Elliot Lake watershed was developed to look at future water quality (Halbert *et al.*, 1980).

Measurements of radioactivity in fish and wildlife were also performed. This enabled calculation of intakes by people consuming local species.

Dose assessment exposures. Based on the data generated from measurements and the dispersion models, the exposures of the critical groups were estimated (Table 3). The pathways considered were: (1) inhalation of radon and particulate matter; (2) ingestion of water, fish, wildlife and vegetation; and (3) external radiation. Food consumption data were based on studies done by Health and Welfare Canada and a survey of Elliot Lake residents (MacLaren, 1978). The dose estimates are considered higher than the doses actually received because of the conservative assumptions used to estimate environmental concentrations and to characterize the critical groups (MacLaren, 1978).

Internal radiation exposures were estimated by comparing the estimated annual intakes of the various radionuclides to the maximum permissible annual intakes (MAI). These MAI's were based on the maximum permissible concentrations (MPC) of the ICRP and would deliver the allowable maximum dose to the body organ of interest (IAEA, 1967). These data, converted to committed dose equivalents, are shown in Table 3.

The calculation of external radiation exposure considered immersion in suspended radioactivity and exposure from the air-deposited radioactivity. External exposures were generally insignificant, unless the receptor was assumed to cross the tailings area.

The results show that exposure to radon daughters is the most significant pathway, followed by the inhalation of thorium-230 and the ingestion of radium-226. (The incremental contribution of lead-210 is unknown.)

High grade ore facility

Site and facility. A proposed mining facility located in northern Saskatchewan (Canada Wide Mines Ltd,

Table 3. Estimated doses or exposures for the critical groups in the Elliot Lake area[a]

By inhalation (mSv/y)		
Radon[b]	Radium-226	Thorium-230
0.1	0.001	0.04

	By ingestion (mSv/y)		
	Radium-226	Thorium-230	Lead-210
Fish	0.001	NC[d]	NC
Produce	0.02	0.007	NC
Moose/deer[c]	0.004	<0.002	0.2

[a] Based on data presented in James F. MacLaren Ltd (1978) and ICRP-30 dose conversion factors (ICRP, 1979). Values rounded.

[b] Assumes NEA dose conversion factor of 5.5 mSv per WLM (NEA, 1983).

[c] Based on analysis of very few samples and includes background contributions (unknown).

[d] NC, not calculated, sufficient data unavailable.

1980) was selected to represent the high grade deposits.

The deposit is located in an isolated area near the eastern margin of the Athabasca basin in northern Saskatchewan about 30 km inland from the shore of a large lake (Wollaston Lake). The area is characterized by numerous lakes interspersed with low hills and boreal forest. Winter lasts six or more months with temperatures of 0 to −40°C being typical. The average rainfall is about 50 cm.

Approximately 70% of the local population is aboriginal. The economy of the community depends heavily on caribou hunting and the local commercial fishery.

The environmental assessment (Canada Wide Mines Ltd, 1980) and the pathways analysis discussed therein were based on a proposed development plan based on an open pit mine. Since it had been planned to stockpile ore during mining, the pathways analysis considered releases from the mine, ore stockpile, the mill and the tailings. The composite grade (mill feed) was expected to be about 2% U_3O_8 compared to between 0.1 and 0.2% for the low grade facility.

Pathways analysis. Source data and local weather conditions were used as input for the Uranium Dispersion and Dosimetry model (UDAD) (Momeni *et al.*, 1979) to estimate the average concentrations of airborne radioactive dust and radon, and the amount of radioactive dust that would accumulate on the ground over the lifetime of the facility.

Radionuclide concentrations in the environment were predicted at selected locations identified as being inhabited on a year-round or part-time basis. External exposures from immersion and groundshine were taken directly from the UDAD output. Airborne radon and suspended dust concentrations from the UDAD output were used to estimate exposures from the inhalation pathway. Ground depositions from UDAD were used in the food chain calculations to estimate exposure through ingestion of meat and vegetation. As in previous calculations, the predicted environmental level and intakes were used with dose conversion factors based on ICRP Methodology (Evans *et al.*, 1981; Kocher and Sjoreen, 1985; ICRP, 1979–1981, 1981) to estimate dose.

Radionuclides released from the proposed facility in liquid effluents would result in human exposure either directly through consumption of contaminated water or indirectly through fish consumption. The transfer of radionuclides in water through the aquatic food chain to terrestrial animals such as moose was also evaluated.

Dose assessment. The site is remote and permanent nearby settlements are few. The two settlements closest to the project site (58 km to the SW and 30 km to the SE), were considered as receptors in the dose assessment, as no impacts were expected at more distant locations.

Caribou has been a major diet item for the aboriginal peoples and was estimated to be 90% of the meat consumed. Most of it comes from hunting in the region north of the site. The assessment assumed that local moose, some game birds, fish and berries are also eaten. Currently, local residents do not grow their own vegetables, but there is some potential for small-scale gardening of hardy varieties. All other food was assumed to be flown in.

On the basis of the above information and predicted results of radionuclide concentrations in air and water, the most exposed person was an individual: living year-round in the community 55 km SW of the site; who consumes berries grown within 30 km of the project site, local fish, hardy vegetables grown locally, local caribou and moose; and who drinks water from nearby Wollaston Lake.

Consumption rates of caribou, fish, birds, plants and berries reported for aboriginal people were used in all cases (Jarvenpa, 1975). This food chain modelling resulted in conservative ingestion exposure estimates for persons who import much of their food.

Table 4 Summary of estimated annual exposures and doses to maximally exposed individuals due to high grade ore facility

	Internal			
Radionuclide	Ingestion (mSv/y)	Inhalation (mSv/y)	Radon daughter (mSv/y)	External whole body (mSv/y)
U-nat	3×10^{-3}	8×10^{-4}		
Th-230	5×10^{-4}	3×10^{-4}		4×10^{-4}
Ra-226	3×10^{-4}	$1 \times \cancel{10}^{-6}$	2.1×10^{-2}	
Pb-210	2.7×10^{-2}	4.5×10^{4}		
Po-210	2.6×10^{-2}	1×10^{-5}		
Total	5.7×10^{-2}	1.6×10^{-3}		

Table 4 summarizes the estimated exposures and doses for the Wollaston Lake resident, the most exposed individual. External body exposures resulting from standing in air containing radionuclides and on ground with surface contamination are presented, along with the internal doses from the inhalation and ingestion pathways. The results indicate that the ingestion pathway is a larger dose contributor than is the inhalation pathway.

The estimated ingestion doses at Elliot Lake include the contribution from background radionuclide levels (because of data availability) thus accounting for their relatively high values compared to those estimated for the high grade site. The values nonetheless fall well within the maximum dose limits permitted under Canadian regulations.

The comparatively high inhalation doses and radon daughter exposures at Elliot Lake are due to the large amount of tailings (and consequent increased radon emissions) produced over the relatively long operating period of the Elliot Lake mines and mills.

Uranium tailings assessment program

In Canada, the National Uranium Tailings Program completed a study to develop a program to evaluate the long-term effects of uranium mill tailings (SENES Consultants Ltd, 1987). The Uranium Tailings Assessment Program (UTAP) adopts a probabilistic approach in evaluating the mathematical models. The following is an illustration of how this approach was used to assess uncertainty in a specific application of the Uranium Tailings Assessment Program (UTAP) (Harrison *et al.*, 1985).

Pathways analyses. To simplify the analysis, a hypothetical reference site was chosen to reflect the major environmental pathways pertinent to uranium tailings management on the Canadian Precambrian Shield. Further, the radionuclide pathways considered were restricted to radon gas release from the tailings surface, radium dispersal with windblown particulates and transport of radium dissolved in water. (The analysis also provided estimates of physio-chemical parameter such as lake water pH.)

The basic characteristics of the hypothetical reference site are shown on Fig. 5. The tailings disposal site occupies a natural depression formed within the upper reach of a valley. The tailings are contained behind a conventional, slightly pervious dam constructed across the low point. Surface and ground water flows from the site are assumed to follow the valley feature with ultimate discharge to a river which flows into a lake. The reference tailings site has a surface area of $0.5\ \mathrm{km}^2$, while the drainage basin containing the tailings covers $1.5\ \mathrm{km}^2$ and the total area of the drainage basin at the outflow of the lake equals $20\ \mathrm{km}^2$. The tailings are assumed to have a (nominal) radium activity of 10 Bq/g.

The reference receptor was chosen to be an adult male living year-round in a cabin on the lake, shown on Fig. 5, some 2 km downwind of the tailings site. The receptor lives off the land, deriving 50% of his food supply from local sources: eating vegetables and berries grown or harvested near the residence, eating fish taken from the lake, and eating game hunted in the immediate area. All drinking water is taken from the lake and consumed directly without treatment for radium removal.

Assessment of the dose to the reference receptor from releases of radon and radium from the reference tailings site was undertaken by pathways analysis.

Dose assessment. Mathematical models were developed to predict radionuclide and chemical concentrations at various points in the environment and to predict the dose to the reference receptor. A time period of 500 yr was selected for this modelling exercise. Given the nature of the models used, and the fact that the consequences change with time, a wide variety of results were generated and examined. The results presented here are intended only to illustrate the results of a (time-dependent) probabilistic analysis.

Figure 6 is a histogram of total dose to the receptor in the first year of the simulation. The histogram represents the results of 500 random trials and illustrates the range of calculated doses. A number of summary statistics characterizing the results are also presented. The histogram has the skewed shape commonly encountered in environmental studies. Most of the dose estimates are clustered in a narrow range at the low end of the distribution with only a few found at much higher levels.

Figure 7 presents the time-varying contributions of each exposure pathway to total dose. The geometric mean value of receptor dose via each pathway was plotted at 50 yr intervals over the 500 yr simulation period. As indicated, the dose via the water related

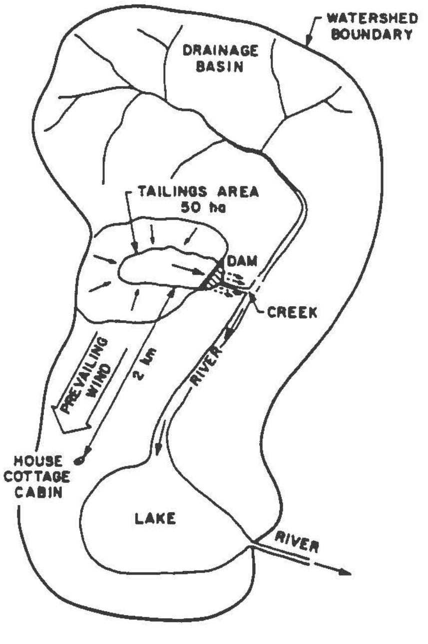

Fig. 5. Illustration of watershed setting for the reference tailings site.

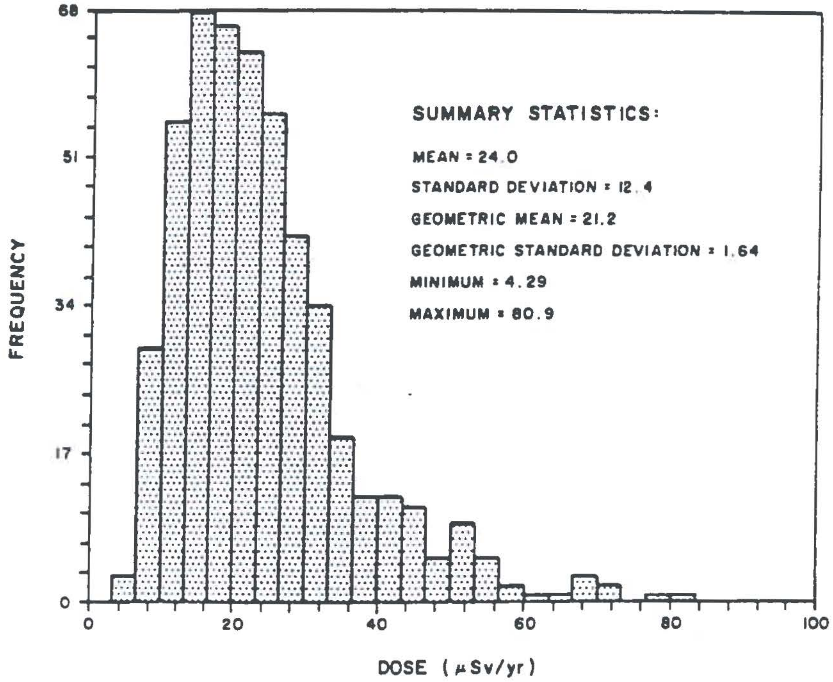

Fig. 6. Histogram of total dose.

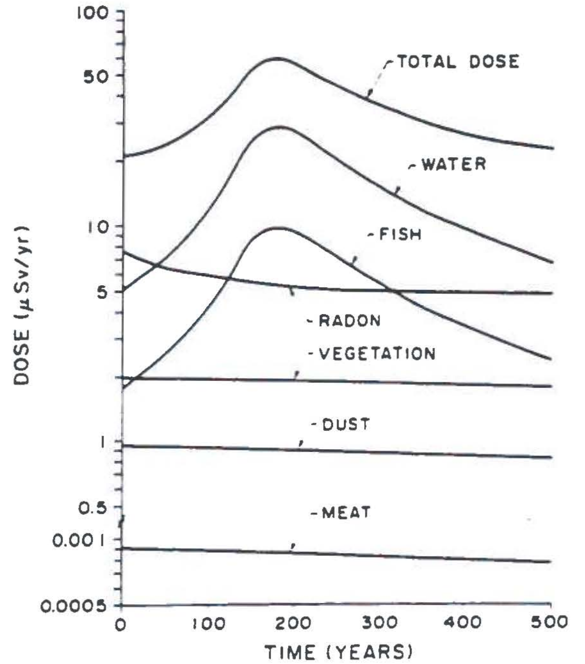

Fig. 7. Receptor dose vs time (geometric mean of 500 trials).

pathway (water and fish ingestion) increases for the first 180 years and decreases thereafter. Doses via the air related pathways decrease monotonically with time. Radon inhalation is initially the greatest contributor to total dose and will, in the long term, reassume that position.

The pattern of time behaviour is reasonable and can be explained by the gradual physical and chemical changes occurring in the upper layers of the tailings mass during the first 100–200 years. Much of the radium exists as a solid coprecipitate. Since the radium coprecipitate exists in equilibrium with the tailings porewater, the gradual dissolution of the compound also results in a gradual release of radium. After the readily soluble coprecipitate in the tailings mass is depleted (100–200 years), the primary source of radium is from the radioactive decay of thorium-230. This source of radium is hypothesized to be much less significant than that from dissolution. Radon, on the other hand, is derived from radium associated with both the host tailings material and coprecipitate solids in the upper layer of the tailings. Thus, as the radium is leached from this layer, the radon release will decrease. After coprecipitated radium is depleted from the upper layer, the source of radon is determined by the balance between the radioactive decay of radium-226, the ingrowth of radium-226 from thorium-230 and the gradual leaching of some of the radium-226 which ingrows to the thorium-230 matrix. This occurs as a slowly decreasing function of time.

Results of the type presented above are useful in comparing alternative methods of managing tailings areas. In addition, the probabilistic modelling framework may be used to determine which parameters are most important in the analysis and hence may provide direction for future research programs.

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