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Brief presented to

THE BRITISH COLUMBIA ROYAL COMMISSION OF INQUIRY HEALTH AND ENVIRONMENTAL PROTECTION URANIUM MINING

Phase VI
Appendicies

Department of Environment
Department of Fisheries and Oceans
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Brief presented to the British Columbia Royal Commission of Inquiry Health and Environmental Protection uranium mining, phase VI.

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BRIEF PRESENTED
TO
THE BRITISH COLUMBIA
ROYAL COMMISSION OF INQUIRY
HEALTH AND ENVIRONMENTAL PROTECTION
URANIUM MINING

PHASE VI
APPENDIX I

by

Department of Environment
Department of Fisheries and Oceans

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1 INTRODUCTION

This appendix (Phase VI, Appendix I) deals with uranium mining and milling operations, the major environmental problems generally associated with each operation and the mitigative measures employed to reduce or eliminate the problems. In discussing particular problems and the mitigative measures, there will be some reference made to the associated environmental impacts. However, it should be noted that the following appendix (Phase VI, Appendix II) deals with environmental impact considerations in detail.

This appendix is broken down into subsections addressing the various phases of operation in uranium mining. These phases are: prospecting, exploration, development, mining, milling and shutdown. We have addressed only the major environmental problems and mitigative measures associated with each particular phase of operation. It should be noted that the significance or degree of any particular environmental problem or concern will vary substantially from one site to another; e.g., acid mine water and acidic seepage from tailings ponds which present a problem at the Elliot Lake uranium mines have only occasionally been encountered at base metal mines in B.C. Just as there is no doubt that the significance of a particular environmental concern will vary from site to site, there is also no doubt that solutions to environmental problems have to be developed on a site specific basis.

The physical and aesthetic problems associated with uranium mines are very similar to those associated with base metal mine developments in B.C. and thus the mitigative measures employed and the experiences of the base metal mines in B.C. can be used to advantage in the resolution of these problems. In fact, as a working premise, with the exception of the radioactive components associated with uranium mining, the problems and solutions are similar in many ways to those associated with the base metal industry. Many of these concerns will, however, be addressed later in this Section.

Although the more significant environmental concerns are addressed on a phase-by-phase basis, it should be noted that: 1) all of the environmental concerns identified for a particular phase are not necessarily of the same environmental significance; 2) the significance of environmental concerns for one phase are not necessarily the same as those for another phase; e.g., the environmental concerns associated with the milling process are more significant than those for exploration. In the Brief, the uranium mining operations are not described in detail. The typical industry practices are well documented in texts, technical journals and reports and they will also be described in submissions to this Inquiry by companies proposing to develop uranium mines in B.C. As a result, in this submission the unit operations are only described in the detail necessary to provide the reader with sufficient background information to relate sources of the environmental concerns and mitigative measures to a specific phase of the operation. The operating phases chosen are standard.

Acid producing ore bodies such as those at Elliot Lake in Ontario are a very serious environmental concern. If an acid producing ore body exists at a particular site, the resultant environmental problems can be encountered in the exploration, development, mining, milling and shutdown phases. However, in the Brief, to avoid repetition, the problem and solutions to the problem will be discussed in detail in only one subsection, i.e., subsection 5.3.

The importance of an effective company monitoring program for effluents and emissions and the receiving environment cannot be overemphasized. Environmental monitoring will be discussed in detail in Appendix II. The Federal Metal Mining Liquid Effluent Regulations prescribe requirements for company monitoring of effluents and the reporting of the data obtained will be covered in Phase X. The monitoring and reporting requirements stipulated should be looked upon as the minimum acceptable requirement. The Federal government has not specified requirements for monitoring of air emissions from uranium mines. However, air emissions should be monitored and the requirements should be developed on a site specific basis.

2 PROSPECTING

Currently, mining and mine development companies utilize a combination of prospecting techniques. The predominant methods include airborne radiometric and geophysical surveys (over land areas measurable in hundreds or thousands of square miles) followed by "grass roots" prospecting which can include geological mapping, radiometric, geochemical, gravimetric and seismic survey programs. The objective of this activity is to determine "targets" for comprehensive exploratory work. There are no significant environmental concerns associated with this activity.

3 EXPLORATION

If the geophysical and geological evidence gathered during the prospecting stage is encouraging, exploration follows. Exploration activities include drilling, stripping, trenching, excavation of test pits, geochemical sampling, geophysical surveying and bulk rock sampling. These programs require the establishment of camps and a network of roads or trails connecting individual drill sites or test pits. The on-site activities carried out are very similar to those associated with exploration at potential base metal mines.

The actual drilling operations generally require a source of drilling water. Drill water can carry mineral particles and potential environmental contaminants in the form of dissolved and undissolved radionuclides and heavy metals into surface or groundwater systems. Moreover, if the deposit contains iron sulphide minerals, the drill water may also be acidic. In comparison to the amount of water used in milling operations, the volume of drill water used is extremely small (i.e., the make-up water ranges from 5 to 10 IGPM. per drill [1]). It is unlikely in most situations that drill water would pose a significant environmental threat. However, in order to ensure that the quality of surface water and groundwater is not altered, exploration permits issued for a particular site should address this subject and specify the necessary environmental safeguards (e.g., the monitoring of drill water quality, ponding or storage of drill water, drill water recycle, environmental monitoring). If at a particular site, drill water escapes to the groundwater system, instead of returning to the surface, then monitoring should be undertaken to determine whether the groundwater is being contaminated.

If the deposits are near the surface, trenching or stripping for the purposes of bulk sampling may be undertaken. The magnitude of these programs will vary from site to site, ranging from pick and shovel operations to those resembling a very small scale open pit mine. These operations can result in the release of contaminants in the forms of radioactive and non-radioactive dust particles and radon gas into the air. In addition, effluent streams and run-off from exposed mineralized work and ore storage piles could possibly contain dissolved and undissolved radioactive and non-radioactive minerals, heavy metals and/or be acidic. Because of the small scale of these operations, neither the airborne emissions nor the wastewater would be considered a significant environmental problem at most sites. However, the need for environmental controls should again be determined on a site specific basis and incorporated in exploration permits. It should also be noted that the combined effects of several exploration operations within a restricted geographic area, and/or drainage or groundwater system may lead to a situation requiring more stringent environmental protection practices at these exploration sites.

Upon the cessation of exploration activities and assuming the decision has been made not to develop the property, the site should be rehabilitated in a manner necessary to protect the environment. The rehabilitation activities would vary from site to site but would generally include the following:

1. backfilling of trenches and test pits,
2. sealing of drilling holes, exploratory shaft, adits, etc.,
3. covering mineralized waste piles with soil to reduce the release of chemical and radioactive contaminants,
4. leaving camp and work sites in an orderly condition,
5. removing oil drums from the site,
6. burying camp refuse.

4 MINE DEVELOPMENT

The development phase of a mining operation encompasses activities which are necessary to prepare a property for production, e.g., stripping, overburden removal, shaft sinking, dewatering of old workings, mill construction and waste management facility construction.

The most significant point sources of water and air pollution generally associated with the development phase are:

1. Untreated water removed from surface or underground mine workings. Depending upon the nature of the wall rock and ore, this water can contain variable quantities of dissolved uranium, thorium, radium and other radionuclides; heavy metals such as arsenic, copper, nickel, zinc, iron; sulphates; ammonia nitrates (from blasting agents); and suspended solids. In addition, these waters could be acidic.

2. Contaminated surface runoff from stock piles of ore and waste rock. This water can also contain dissolved and undissolved radionuclides, heavy metals, sulphates, and suspended solids. It also may be acidic.
3. Radioactive and non-radioactive dust particles and radon gas which can be released to the atmosphere from ore and waste rock handling facilities, storage piles and open pits.

In many cases one would expect the contaminants present and the concentration of these contaminants in untreated mine water and contaminated surface water generated during the development phase to be comparable to those in the wastewater streams from identical sources during the operating life of the mine. Accordingly, the pollution control technology employed to render these streams non-deleterious would be the same during the development and operating phases. This technology is discussed in detail in Section 5.1. The control of particulate and radon gas emissions is also discussed in Section 5.1.

The physical changes that take place during the development phase are similar to those that one would observe at a base metal mine. Many streams in British Columbia provide spawning, rearing and migrational habitat for both anadromous and resident fish species or lead to such waters. Some water courses are domestic drinking water supplies and others are sources of irrigation water. Every effort should be made by exploration and development companies to protect the integrity of streams from the effects of activities such as road construction, land clearing, etc., that take place during the development phase.

Exploration and development activities can also contribute to the visual deterioration of an area. However, assessing aesthetic damage is a difficult task. In most cases a combination of good planning and good housekeeping practices implemented by exploration and development companies will assist in alleviating aesthetic problems. Most certainly the requirements imposed in sensitive areas such as parks, other recreational areas and heavily populated areas would be very important and more restrictive than in remote areas. Regulatory agencies, in the review process, must ensure that aesthetic considerations are addressed.

5 MINING

5.1 Conventional Mining Practices

The conventional mining practices employed by the uranium industry in Canada are underground and open pit mining. In cases where an ore body is sufficiently close to surface, the ore can be extracted by open pit mining methods. The only uranium producers in Canada currently operating open pit mines are Gulf Minerals, which commenced operation at Rabbit Lake, Saskatchewan in 1975, and Eldorado Nuclear Ltd. which started mining in the Beaverlodge, Saskatchewan area in 1953. Gulf's open pit mine provides 100% of the 2000 TPD mill feed whereas Eldorado obtains the greatest proportion of its ore from its underground mines and only a minor but variable (5-10%) portion of its mill feed from two small open pits.

Although the largest volume of Canadian uranium ore is presently derived from underground mines, it is most probable that future production from uranium deposits in the Athabasca Basin of Northern Saskatchewan will be from open pit operations such as those of Amok Ltd. and Key Lake Mining Ltd. which are currently being developed at Cluff Lake and Key Lake respectively.

The underground mining operations of Denison Mines Ltd. and Rio Algom Ltd. in Elliot Lake, Madawaska Mines Ltd. at Bancroft and

Eldorado Nuclear Ltd. at Beaverlodge presently supply ore to mills having a total daily capacity in the order of 17,500 tons. Upon the completion of the expansion and mine re-activation program currently underway at Elliot Lake, the total mill capacity by the early 1980s will be in the order of 25,000 tons per day.

Due to the magnitude and history of underground uranium mining activity in Canada, and in view of the operating practices which in the early 1960s brought about increasingly stringent environmental monitoring and treatment requirements, an extensive body of technical data has been developed with respect to the sources, types, quantities, and controls of potential environmental contaminants associated with uranium mining and milling operations.

A discussion of the environmental concerns relative to open pit and underground mining practices and of mitigative measures currently employed to reduce their impacts follows. Generally speaking, many of the concerns and remedial measures are common to both underground and open pit mining.

1. Mine Water

   Depending on the mineralogy and hydrogeology of the ore body, the volumes of water involved and the duration of contact between the water and the mineralized rock, the mine water can contain variable concentrations of suspended solids, dissolved and undissolved radium, thorium and uranium, heavy metals such as copper, lead, zinc, cadmium, arsenic, nickel and iron, sulfates and ammonia, nitrates and nitrites from blasting agents. If pyrite or pyrrhotite are present in the ore in significant quantities, as may be the case in several areas of B.C., there is also the possibility of the mine water being very acidic (i.e., a pH of 2-4). For illustrative purposes untreated mine water effluent quality data for Gulf Minerals (2) is presented in Table 1. The average mine water effluent flow rate at this mine is approximately 300 IGPM. Peak flows of up to 960 IGPM are experienced during spring run-off and heavy rainfall periods.

Typical analyses of untreated mine water from the Denison (3), Rio Algom (3) and Eldorado Nuclear (4) underground mines are presented in Table 2.

TABLE 1 UNTREATED OPEN PIT MINE WATER CHARACTERIZATION - GULF MINERALS LTD.

pH	6.0 - 9.0
Ra-226 (D)	1 - 15 pCi/l
Ra-226 (T)	5 - 30 pCi/l
Suspended Solids	1 - 30 mg/l
Heavy Metals (T)*	0.1 mg/l
Kjeldahl Nitrogen (T)	1 - 2 mg/l
$NO_2 + NO_3$	1 - 2 mg/l

*The data presented is the sum of the total heavy metal concentrations of arsenic, copper, lead, nickel and zinc.

D - Dissolved values
T - Total values

TABLE 2 UNTREATED MINE WATER CHARACTERIZATION - UNDERGROUND MINES

Parameter	Denison Mines Ltd.	Rio Algom Ltd.	Eldorado Nuclear Ltd.
pH	2.7	3.0	8.0
Dissolved Solids (mg/l)	3100 - 3300	680 - 720	NA
Suspended Solids (mg/l)	NA	NA	750
SO_4 (mg/l)	1700 - 1900	370 - 390	455
NH_3 (mg/l)	70 - 80	60 - 70	NA
NO_3 (mg/l)	300 - 350	220 - 240	NA
Fe (mg/l)	150 - 250	40 - 70	NA
U_3O_8 (mg/l)	100 - 200	40 - 70	5 - 15
Ra-226 (D) (pCi/l)	150 - 300	500 - 550	150 - 210
Ra-226 (T) (pCi/l)	NA	750 - 800	190 - 390
Heavy Metals (T) (mg/l)	NA	NA	0.1*
Volume (Igpm)	420	485	300

*The data presented is the sum of the heavy metal concentrations of arsenic, copper, lead, nickel and zinc.

NA - Not Available
D - Dissolved values
T - Total values

The current practice at Gulf Minerals and at the underground Elliot Lake mines is to route mine water through the mill in order to extract the uranium and to provide a source of mill process water. Efforts are made at Gulf Minerals to control or reduce the volumes of water entering the pit by diverting uncontaminated surface water flows away from the pit. Ultimately, in all cases, the mine water reports to the tailings pond with the mill discharge for treatment.

The use of mine water in the mill at Eldorado Nuclear is precluded by the high chloride content of this water and its associated corrosive properties. At Eldorado Nuclear the mine water is treated separately and then discharged to the tailings impoundment system for additional treatment.

At any uranium mine, good housekeeping practices associated with blasting operations are important in minimizing the ammonia, nitrate and nitrite levels in the mine waters discharged.

If at a particular site, the inflow of groundwater into the pit is or is expected to be excessive, inflows from this source can be reduced by drawing down the groundwater table by utilizing a series of pumping wells around the perimeter of the pit. The quality of the water from the wells should be monitored.

2. Contaminated Surface Run-off and Seepage

Ore and waste rock storage piles are sources of contaminated surface water run-off and contaminated seepage water. The contaminants generally associated with these wastewater streams are the same as those associated with mine water and have been discussed previously. The most obvious pollution abatement practices that may be employed are: i) diverting surface runoff away from storage piles, ii) using contaminated runoff and seepage as mill process water, or iii) collecting and treating this effluent flow prior to discharge. If the latter is employed, this effluent in most cases would be combined with and treated with the mill tailings and mine water.

3. Radon Gas, Radioactive and Non-Radioactive Particulate Emissions

Mines, ore stock piles and waste rock storage areas are all sources of radon gas and radioactive and non-radioactive particulate emissions. A number of mitigative measures can be employed to reduce the level of discharge of these contaminants. It should be noted that the severity of the environmental problem associated with these emissions and the selection of mitigative measures to control the emissions are site specific and dependent on a number of factors including geology and mineralogy of the deposit, and the atmospheric conditions.

When open pit mining is employed, particulate emissions can be controlled by a number of means such as:

a) employing dust collectors on blast hole drills;
b) wet drilling;
c) limiting the blast size;
d) spraying water on haulage roads, exposed ore, and ore stock piles;
e) covering ore trucks.

Radon gas is emitted from open pits. When low grade uranium deposits are involved, mitigative measures are generally not required. However, extensive monitoring programs should be carried out to ensure that environmental problems are not developing. High grade deposits, such as those at Cluff Lake in Saskatchewan, require the use of special measures to control radon gas emissions for both worker and environmental protection. The solutions recommended are documented in the "Final Report - Cluff Lake Board of Inquiry" (5).

In underground mines, forced air ventilation is used to prevent radon gas from accumulating to levels hazardous to miners' health (i.e., to provide a safe work environment). The ventilation system is designed to minimize the radon residence time and to maintain a low radon concentration in the mine through dilution with clean air. The average residence time at Denison Mines is about 19 minutes and more than 19 short tons of fresh air are circulated through the mine for every ton of ore mined or 260 CFM/short ton mined (3). The radon release rates from mine ventilation exhaust ranges from 50 uCi/sec to 100 uCi/sec for the Eldorado Nuclear, Denison and Rio Algom mines (6). The emission of radon in the mine ventilation exhaust has not posed an environmental problem at operating Canadian uranium mines.

Within an underground mine, wet drilling and sprays during blasting are mandatory dust suppression requirements in work areas. Wetting is also practised during ore handling and dumping to prevent fine dust particles from becoming airborne. These techniques are used to protect worker health. The mine ventilation system is used to remove the airborne particulates from the work environment. In practice the volume of air required to meet the radiation and diesel exhaust health codes are sufficient to maintain low dust counts in the work areas. Particulate emissions from mine ventilation exhausts at Elliot Lake are approximately one gram per second (3). The ventilation exhaust particulates have not posed an environmental problem at the Elliot Lake uranium mines.

5.2 In-Situ Mining

Two *in-situ* mining techniques, solution mining and underground leaching, are currently utilized outside of Canada to extract uranium from ores as they occur naturally in the ground. The latter method is also practiced at one mine in Canada but recently it was announced that this mine is shutting down as a result of poor economics.

5.2.1 Solution mining - general

Solution mining is an operation in which the desired metals are recovered from essentially porous ore-bearing rocks, such as sandstones, without the conventional breaking of the ore and hoisting the ore to the surface. This is accomplished by drilling production wells and a cluster of injection wells into the ore bearing strata. The wells are cased throughout all but the ore bearing zone. Acid or alkali solutions are pumped down injection wells to dissolve the uranium and the pregnant leach solutions are extracted via production wells. Uranium is recovered from the pregnant solution by standard milling procedures as described in Section 6.1.

Upon the cessation of operations in a well field, fresh "restoration" water is pumped down the injection wells to flush residual leaching and pregnant solutions to the surface via the production wells.

Although uranium is not presently recovered by solution mining in Canada, it is being extracted from uraniferous zones in sandstone formations in the Wyoming Basin and the Texas Coastal Plain. Some uranium deposits in British Columbia however, may be amenable to solution mining.

5.2.2 Solution mining - environmental advantages

Solution mining has significant environmental advantages in that:

1. Ore and barren (leached out) rock remain beneath the surface thus eliminating the need for the long-term management of large tailings impoundment facilities and waste rock disposal facilities;
2. A large proportion of the barren solutions can be reconstituted and recycled to the injection wells;
3. Ore breaking, loading, crushing and grinding operations are eliminated, thus reducing the emission of radioactive particulates and radon.

5.2.3 Solution mining - environmental concerns

The porous rocks containing the uranium minerals which can be recovered by solution mining techniques commonly constitute a portion of an aquifer. Thus, although this type of mining may have limited effects on the surface environment, it can have significant impact on the groundwater regime. Accordingly, local geologic and hydrogeologic conditions in areas in which solution mining is contemplated must be thoroughly assessed and evaluated in order to minimize the impact on the groundwater resource.

Most commonly, an aquifer may be affected by:

1) Vertical or horizontal excursions of solutions (via highly permeable zones, faults or fractures) during injection and/or the natural migration of solutions after the cessation of mining. Consequently, excursion monitoring programs must be conducted to prevent the contamination of an aquifer outside of a well field (7).
2) The improper disposal of effluent produced during the extraction and restoration phases. The resultant effluent must be treated in waste-water treatment facilities and disposed of in a manner such that neither groundwater nor surface water systems are contaminated.

Although environmentally safe leach field waste disposal wells are in operation in Texas, geologic and hydrologic conditions may not be suitable for this purpose in all potential leach mining areas.

In addition to the foregoing, the following aspects should be considered in order to determine the potential impacts of any proposed solution mining operation on the groundwater resource:

1. Where yields from wells near a mine property are already limited, dewatering the mined zone during and after _in-situ_ leaching of uranium ores may further deplete the groundwater supply;
2. As a restoration activity, dewatering may have to be continued for

an extended period of time to protect other uses of the aquifer;

3. Treated or untreated process wastewater returned to the aquifer via disposal wells or wastewater treatment ponds may affect water in the aquifer such that it cannot be used for domestic, agricultural or industrial purposes;
4. Soil water passing through a former leach zone may mobilize Ra-226 and other potential contaminants.

5.2.4 Underground leaching

Underground leaching is a related production method, which differs from solution mining in that conventional mining techniques are used to provide access to the ore, which is then leached by introduced solutions percolating through the broken ore. Approximately 30% of the material has to be removed and leached on the surface because the volume of broken ore is greater than that of the ore "in place".

Until recently, Agnew Lake Mines used this method at a uranium deposit near Sudbury, Ontario. Uranium is leached from broken ore underground and on surface pads with sulphuric acid. Uranium is recovered from the solution using ion exchange, solvent extraction and uranium precipitation. Generally speaking this process has environmental advantages and concerns similar to those of solution mining. On-surface waste rock disposal is however an additional concern. This subject was discussed in Section 5.1.

5.3 Acid Generating Ore Bodies

Acid generation may occur in a mine or ore body if sufficient quantities of readily oxidizable iron sulphides, such as pyrrohitite, pyrite and marcasite are exposed to air, water and carbon dioxide in the absence of sufficient natural compensating buffering minerals. Sulphuric acid is produced as the minerals are oxidized and this acid may attack other minerals present releasing heavy metals such as, copper, zinc, lead, nickel, arsenic etc., and radionuclides into the mine water. Although the pyritic minerals are relatively stable in their natural environments, when these environments are changed, as is the case in a mining operation, they can become oxidized quite rapidly. The acid production can result from either chemical or bacteriological activities or a combination of both.

Within the Canadian uranium mining areas, the most significant acid producing ore bodies are those of the mines in Elliot Lake. These ores contain 5% to 10% pyrite with an average content of 6.5% (3). The pyrite content varies with the ore grade generally decreasing as the ore grade decreases. Due to the high pyrite content and the absence of carbonates and other buffering minerals (to act as buffering agents) in the ore, the pH of the water pumped from the mines in this area is in the range of 2.7 to 3.0. These waters are moreover reported to contain up to 200 mg/l U_3O_8, 800 pCi/l Ra-226 and 16300 pCi/l thorium (3,8). Even though the ore at Eldorado contains 1.5 to 2.0% pyrite by weight, it also contains a sufficient quantity of calcium carbonate and chlorides to act as a buffering agent. Consequently, the untreated mine water has a pH in the range of 7 to 8 (4).

The problems associated with acid mine water from operating uranium mines can be minimized by either:

1. Using the water in the milling process. The dissolved and undissolved uranium is recovered in the process and the release of other radionuclides and heavy metals is minimized by treating the mill effluent in the tailings impoundment facility.
2. Neutralizing the water with lime to a pH of between 8 and 10 to precipitate the dissolved metals prior to discharge to a tailings impoundment area. Barium chloride is then added to the decant in order to precipitate radium as a barium-radium sulphate co-precipitate. Treatment ponds with sufficient

retention times have to be used to allow adequate settling of the fine precipitate. Flocculants may be used to improve the rate of settling. This subject is discussed in more detail in Section 6.3.

With respect to item (1) above, the heavy metals and radionuclides will remain in solution during acid leaching (milling). However, these pollutants will be removed when the mill effluent is neutralized and treated in the tailings management system. The treatment of mill effluents is also discussed in detail in Section 6.3.

Once a sulphide bearing uranium deposit has been developed and mined, the potential to produce acidic water becomes an essentially permanent condition. Thus, even though a mine ceases to operate, the generation of acidic water will continue due to such factors as:

1. increased surface area of exposed sulphide mineralization and,
2. increased availability of channels in the form of man made openings and natural faults for water, oxygen and carbon dioxide to enter the workings.

Even during the shutdown phase, acid mine water discharges from underground or open pit mines are capable of contaminating surface and/or groundwater systems. Unless the sources of outflowing acid mine water can be permanently sealed, which is difficult, provisions may be necessary for its collection and treatment on an on-going basis in order to prevent the release of radionuclides and heavy metals into the environment.

6 MILLING

6.1 The Milling Process and Sources of Wastewater

The objective of the milling process is to recover uranium from its ores in a concentrated form. The content of uranium ore milled in Canada normally ranges from 0.1 - 0.2% uranium, but some of the newer deposits that will be mined during the next few years contain 1 to 3% with a portion of one known deposit (Amok Ltd., Cluff Lake) containing as much as 39% uranium. The end product of the milling process is commonly referred to as "Yellowcake" and contains approximately 80% U_3O_8.

During the milling process, uranium is extracted from the ore by a leaching (hydrometallurgical) process. Dictated by the chemical nature of the ore, more precisely its acidic or basic components, either an acidic (sulphuric acid) or basic (sodium carbonate) leaching process is employed. In Canada, as well as throughout the world, the former process is by far the more common. In Canada at the present time, six of the seven active uranium mills employ the acid leach process. Moreover, all of the proposed new mills including those considered in British Columbia plan to use the acid process.

The milling of uranium ore consists essentially of five major stages:

1. preparing the ore for leaching;
2. selective leaching of uranium from the ore;
3. separating the leach solution from the tailings solids;
4. purifying and concentrating the leach solution;
5. recovering uranium from the leach solution.

A flowsheet illustrating the basic steps is shown in Figure 1. A short general description of the two leach processes is presented to identify the effluent discharge sources. Detailed information of specific mill processes is available from numerous text books (9,10,11).

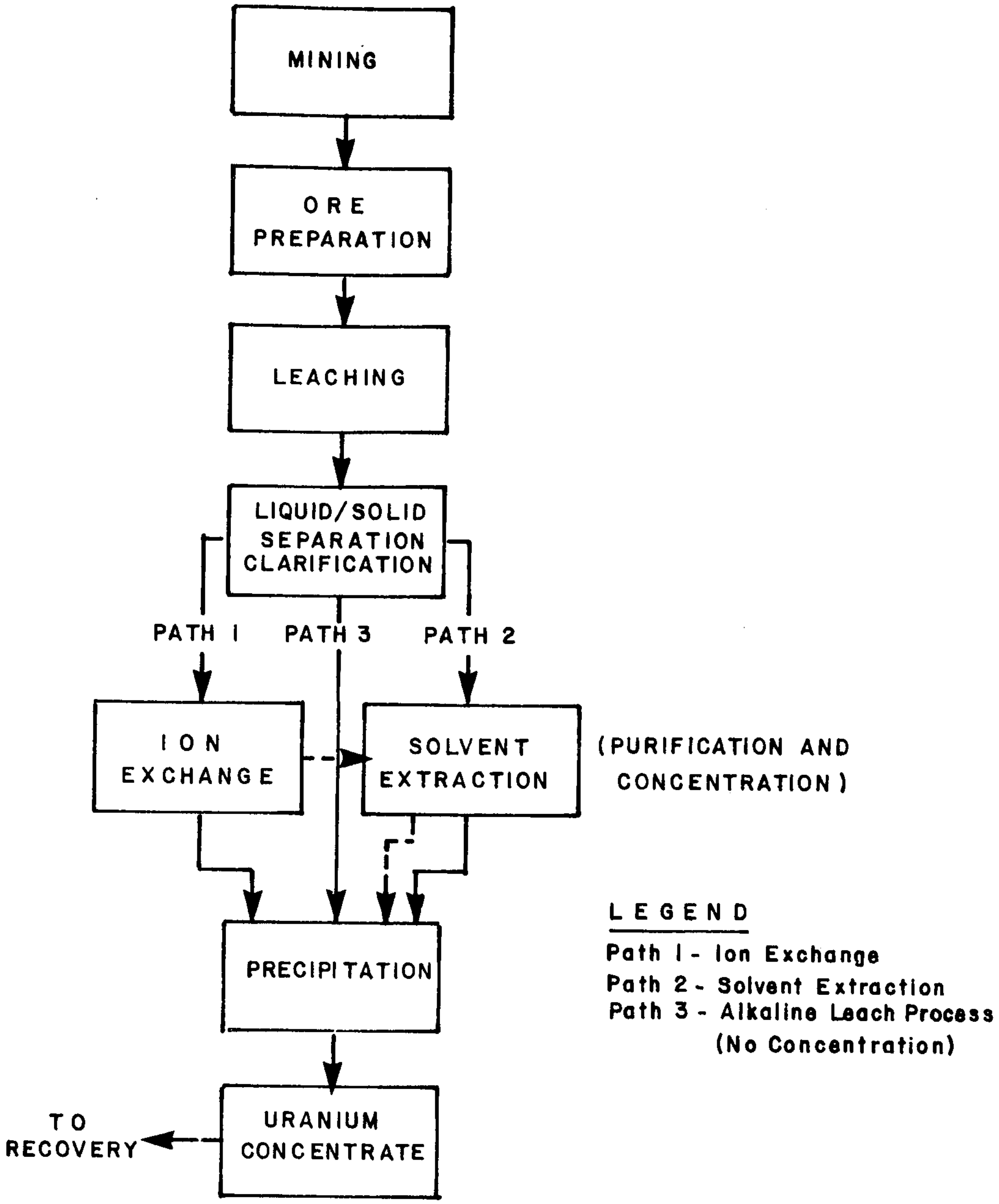

FIGURE 1 GENERALIZED FLOW DIAGRAM FOR MILLING OF URANIUM ORE

Ore preparation processes for the acidic and basic leaches are similar and involve crushing and wet grinding. Strict dust control from dry crushing operations is required to prevent the escape of dust and radon gas. The fine slurry from the grinding operation is thickened and leached.

In the acid treatment process, fine ore is leached with concentrated sulphuric acid and the spent solids are separated from the uranium bearing solutions. The spent solids are then washed with barren solution from either the ion exchange or solvent extraction processes in order to displace the entrained uranium solution. Subsequently, the solids are repulped with water and/or waste barren solution, neutralized with lime, and rejected to the tailings impoundment area.

The uranium bearing solution (pregnant solution) is relatively impure and is up-graded and concentrated by ion exchange or solvent extraction prior to uranium recovery. The principles of both processes are similar and involve the preferential absorption of uranium complexes, from solution, on an intermediate material via an ionic exchange process. The impure uranium bearing solution is contacted with the exchange medium which absorbs the uranium. A portion of the resulting uranium depleted barren solution is recycled for spent solids washing and the balance is rejected with the tailings. The conventional ion exchange process uses a solid, nitrate exchanging organic resin and the conventional solvent extraction process, a tertiary amine sulphate, organic liquid. Nitrate and sulphate ions are exchanged for the uranium complexes and discharged in the barren liquids, in the two processes respectively.

A concentrated and purified uranium solution is produced by contacting the exchange medium with a nitric acid-ammonium nitrate solution, or with ammonium sulfate solution, in the cases of conventional ion exchange and solvent extraction respectively. In this process uranium is stripped from the exchange material and the material is regenerated.

Residual impurities are removed from the concentrated solution by raising the pH to 3.5 with lime and ammonia. The pH is then raised to 7.0 and uranium is precipitated as a diuranate. Ammonia is the most commonly used precipitant and it produces ammonium diuranate ($[NH_4]_2 U_2 O_7$). The product is filtered, dried and packed in drums. The spent solution is recycled to the stripping circuit, although a portion is discarded to limit the accumulation of impurities (12). It should also be noted that the Madawaska Mine and the recently reopened Rio Algom Panel Mine recover uranium as magnesium diuranate ($MgU_2 O_7$) by magnesia precipitation.

In basic leaching process, a solution of sodium carbonate-sodium bicarbonate is used to dissolve uranium from the crushed ore. The process is more selective than the acid leach and solution upgrading is not required. The leach solution is separated from the waste solids and, following washing, the solids are rejected to a tailings impoundment. Uranium is recovered by adding sodium hydroxide and producing a sodium diuranate ($Na_2 U_2 O_7$) precipitate (12).

6.2 The Nature of Mill Tailings

The composition of tailings, as they are discharged from a mill, is dependent upon the mineralogy of the ore body, the processes and the chemicals used to extract the uranium. Typically, and regardless of the extraction method used, the mill tailings contain 25 to 40% solids, consisting of particles of the common rock forming minerals (gangue), heavy metal sulphides, pyrite, precipitated heavy metal hydroxides and radionuclides, such as Ra-226 and Th-230. Although the exact proportions are variable from one operation to another, roughly 85% of the radioactivity originally contained in the ore is discharged with the mill effluent. One to two percent of the radioactivity is in solution, and the remainder in the solid phase. In the solid form these radionuclides have the potential to dissolve under low pH or low sulfate conditions (3, 12). It should also be noted that approximately 75% of the radioactivity in the solid phase is associated with the slimes fraction. Therefore the fines must be effectively settled from the tailings effluents before these waters can be safely discharged to the environment.

The presence of long lived radionuclides in uranium ores dictates that special measures must be taken in the disposal of mill tailings to ensure that maximum protection is provided to man and his environment. Of the radionuclides, Ra-226 is of the most environmental significance. Over 98% of the Ra-226 is associated with the solid fractions and retained in the tailings impoundment and less than 2% is in solution and removed by chemical precipitation in both the tailings impoundment and the treatment pond. This subject is discussed in more detail in Section 6.3. In addition to Ra-226, radionuclides of significance and generally associated with tailings are Th-230, Pb-210 and Rn-222.

The most common heavy metals which may be present (usually in low concentrations) in the ore are: copper, zinc, manganese, iron, lead, nickel, and arsenic. In acid leach mills, lime or limestone or a combination of each is added to the effluent to bring the pH up to the 8-11 range prior to discharge into a tailings impoundment facility. In addition to reducing the effluent's acidity, this procedure results in the precipitation of the dissolved metals, Th-230, Pb-210 and the majority of the Ra-226 in the tailings impoundment.

The heavy metal hydroxides and thorium can be expected to re-enter solution if the acidity within a tailings impoundment facility increases. In the absence of buffering minerals, if pyrite or pyrrhotite are present in the tailings, the acid produced by the chemical and/or microbial oxidation of these minerals greatly accelerates the dissolution of thorium and the heavy metal hydroxides. Radium, on the other hand will dissolve slowly in low sulfate water even without an increase in acidity.

Mill tailings discharges may also contain variable proportions of process reagents such as ammonia, nitrates, nitrites, and sulphates which, other than being diluted, are not specifically treated nor affected within a tailings impoundment. Four of the Canadian acid leach mills presently produce yellowcake by the addition of ammonia. The milling of one tonne of ore in an acid leach circuit can require up to 0.5 kg of ammonia and 2.5 kg of nitric acid (12). Variable quantities of ammonia and nitrogen compounds contained in the mine water may also be included in the mill discharge. With the exception of the quantity of ammonia which is in the yellowcake, all of the chemicals used in the milling process are ultimately discharged to the tailings impoundment facility. The varieties and quantities of the major chemicals used per tonne of ore milled (12) are shown in Table 3.

TABLE 3 CHEMICALS USED IN MILLING OPERATIONS

Process	Amount of Reagent Used (Kg per tonne of ore milled)
Acid-Leach	
Sulphuric Acid	25 - 55
Sodium Chlorate	2.5
Nitric Acid (60%)	1.6 - 2.5
Ammonia	.1 - .5
Lime	10
Limestone	16
Alkaline-Leach	
Sodium Hydroxide	5.63
Lime	5.93
Xanthates	.115
Flocculants	.35

6.3 The Treatment of Mill Tailings

6.3.1 The impoundment of mill tailings

The mill tailings slurry consists of the leached solids, excess barren solution from ion exchange or solvent extraction and uranium precipitation and often some mine water. The treatment of mill tailings involves two steps: one of solids separation and retention and a second of solution treatment. Treatment begins in the mill where the tailings slurry is neutralized with lime to pH 10. The neutralized tailings slurry at 25-40% solids is pumped to the waste management system which consists of two separate sections. The first section, and by far the largest is the tailings impoundment area which is followed by the effluent treatment pond (precipitation pond). The areas occupied by the tailings impoundment facilities and effluent treatment ponds for some uranium mills (2,3,4) are shown in Table 4.

TABLE 4 AREA OF TAILINGS IMPOUNDMENT SYSTEMS

	Tailings Impoundment	Effluent Treatment Pond	
	(Acres)	(Acres)	(Retention Time) (days)
Denison	105	43	20
Eldorado Nuclear	135	13	2 - 7
Gulf Minerals	93	12	18
Madawaska	35	0.15	3
Rio Algom (Quirke)	400	9	2

Within the tailings impoundment, the solids are settled out of the slurry and are retained to produce a clear supernatant which overflows to the effluent treatment pond. With proper operation, the suspended solids content in the tailings pond overflow can readily be maintained below 25 mg/l, the requirement stipulated in the Federal Metal Mining Liquid Effluent Regulations. As a result of the alkaline pH of the water in the tailings impoundment, dissolved heavy metals, Th-230, Pb-210 and a very large proportion of the Ra-226 are precipitated from solution, settled and retained with the tailings solids. For illustrative purposes, analyses of the liquid portion of untreated mill tailings and tailings impoundment effluent for two mines (3) are presented in Table 5.

TABLE 5 WASTEWATER ANALYSES - LIQUID PHASE

	DENISON		RIO ALGOM	
	Mill Effluent	Tailings Pond Effluent	Mill Effluent	Tailings Pond Effluent
pH	9.5	8.0 - 9.5	10	8 - 10
Ra-226 pCi/l	4500	350 - 1000	4500	400 - 1000
Dissolved Solids (mg/l)	4500	3000	3500	2000 - 3000
SO_4 (mg/l)	2200	1500	2000	1200 - 1500
NH_3 (mg/l as N)	130	50	120	10 - 25
NO_3 (mg/l as N)	140	90	650	60 - 80
Heavy Metals* (mg/l)	0.1	0.1		

*The data presented is the sum of the heavy metal concentrations of copper, lead, nickel and zinc.

Noting the results in Table 5, it is apparent that over 80% of the dissolved Ra-226 in the mill tailings is removed in the tailings impoundment. Actually over 98% of the total radium and essentially 100% of the thorium in the original mill feed are retained with the tailings in the tailings impoundment.

6.3.2 Removal of radium from tailings impoundment supernatant

Since the effluents from tailings impoundments still contain sufficient amounts of dissolved Ra-226 to be of particular concern, further treatment for radium removal is essential. The radium removal process is essentially a two-stage process in which the dissolved radium is first converted to relatively insoluble particles that are then settled from solution. This is accomplished in the effluent treatment pond first by the addition of barium chloride to coprecipitate the radium with barium sulphate, i.e., produce a barium-radium-sulphate ($BaRaSO_4$) precipitate. This material is a fine, crystalline solid and requires a long settling time for effective solid-liquid separation. The long retention time is necessary to allow the fine barium-radium-sulphate crystals to grow or coalesce into larger particles which will settle. The precipitate which settles out is stored on the bottom of the ponds.

On an experimental basis, ferric chloride has been added as a flocculant to assist in the settling process. The addition of ferric chloride has the disadvantage of producing a more voluminous sludge on the bottom of the pond thereby reducing the retention time in the pond or necessitating a larger pond to provide additional sludge storage capacity. However, the advantage of improved settling of the solids is considered to outweigh the disadvantage of the larger sludge volume. (It should be noted that the Department of Environment and the Department of Fisheries and Oceans consider the storage of sludge in the pond as one of interim convenience and certainly an unacceptable long-term practice. This subject is pursued in more detail in more appropriate sections of this Brief, (i.e., Section 7.2 Shutdown Phase, Environmental Concerns, and Section 7.3 Shutdown Phase, Mitigative Measures).

It is generally considered, although it still remains to be verified, that a retention time of 5 days is sufficient in a closely controlled system to meet the 10 pCi/l dissolved Ra-226 requirement. In order to meet the stipulated requirement, careful control of reagent additions, maintenance of quiescent settling conditions and avoidance of both short-circuiting and surge flows to the system are essential. The analyses of typical effluents from the radium removal treatment ponds at various sites (2,3,4,) are presented in Table 6.

The retention times in various radium removal treatment ponds in Canada has been presented in Table 4. This table indicates that the retention time in treatment ponds varies widely from 2 to 20 days at the different mine sites. Noting Tables 4 and 6, in the ponds with longer retention times, the federal effluent requirement of 10 pCi/l dissolved Ra-226 is being met consistently on a year round basis. This is not the case when short retention treatment ponds are employed. For informational purposes it should be noted that Environment Canada's Wastewater Technology Centre research target level of 3 pCi/l dissolved Ra-226 is not being met consistently at any operating uranium mine in Canada (see Phase V).

6.4 Total vs. Dissolved Radium in Effluents

Although exemplary radium removal methods currently in practice have proven successful in meeting the federal requirement of 10 pCi/l dissolved Ra-226, the technology has resulted in total Ra-226 activities which appreciably exceed the dissolved values. In many instances total Ra-226 activities have exceeded dissolved levels by a factor of 10 or more due to the presence of Ra-226 in the form of

TABLE 6 FINAL EFFLUENT ANALYSES

	Eldorado Nuclear	Gulf Minerals	Rio Algom	Denison
pH	7.5 - 9.0	5.5 - 9.5	6.0 - 8.0	8.0 - 9.5
Ra-226 (D) (pCi/l)(range)	1 - 20	1 - 15	3 - 10	2 - 7
Ra-226 (D) (pCi/l)(mean)*	5.2	3.4	7.3	2.1
Ra-226 (T) (pCi/l)(range)	2 - 45	2 - 300**	27 - 200	10 - 42
Ra-226 (T) (pCi/l)(mean)*	16.5	29.9	83.0	23.0
Dissolved Solids (mg/l)			850 - 2700	2000 - 3000
Suspended Solids (mg/l)	2 - 45	2 - 25	3 - 7	1 - 12
Fe (mg/l)	.02 - 0.4	.05 - 1.0	0.05 - 1.5	0.05 - 0.25
SO_4 (mg/l)	100 - 400	2000 - 8000	600 - 1500	1200 - 2000
NH_3 (mg/l)	0.10 - 0.25	100 - 400	9 - 25	35 - 70
NO_3 (mg/l)	1 - 5	2 - 6	30 - 90	1 - 100
Heavy Metals (T)*** (mg/l)	0.2	0.5 - 1	0.16	0.1

* Unpublished data submitted by operators to Environment Canada Regional Offices.

** Four out of 52 samples collected in 1978 were above 100 pCi/l; the rest were lower than 50 pCi/l. Sixty percent of all samples were less than 10 pCi/l.

*** The data presented is the sum of the heavy metal concentrations of arsenic, copper, lead, nickel and zinc.

D - Dissolved values
T - Total values

unsettled $BaRaSO_4$ particles. This is a matter of concern since the $BaRaSO_4$ precipitate is soluble at the lower sulphate concentrations encountered in the receiving waters and ultimately results in the release of Ra-226 into the aquatic environment. This suggests a need to regulate the total Ra-226 levels in uranium mine effluents as well as the dissolved Ra-226 levels. An example of the correlation of total versus dissolved Ra-226 activities in the effluent from Rio Algom's Quirke operation during 1977 (13) is given in Figure 2.

The Department of Environment and the Department of Fisheries and Oceans believe that an effluent requirement based on total Ra-226 activity, as recommended by the Radioactivity Sub-group of the Mining Effluent Task Force, is more appropriate to safeguard the receiving environment. In order to determine the levels of both total and dissolved Ra-226 in their final effluents, the uranium mining companies have been required for over a year to report both of these figures to the Atomic Energy Control Board. A comparison of the total and dissolved Ra-226 activities in the final effluents of four Canadian uranium mines in 1978 (14) is presented in Table 7.

TABLE 7 DISSOLVED VS. TOTAL Ra-226 IN TREATED MINE EFFLUENTS - 1978 AVERAGE

Dissolved Ra-226 (pCi/l)	Total Ra-226 (pCi/l)
25.3	168
3.4	26
4.8	20
1.3	12

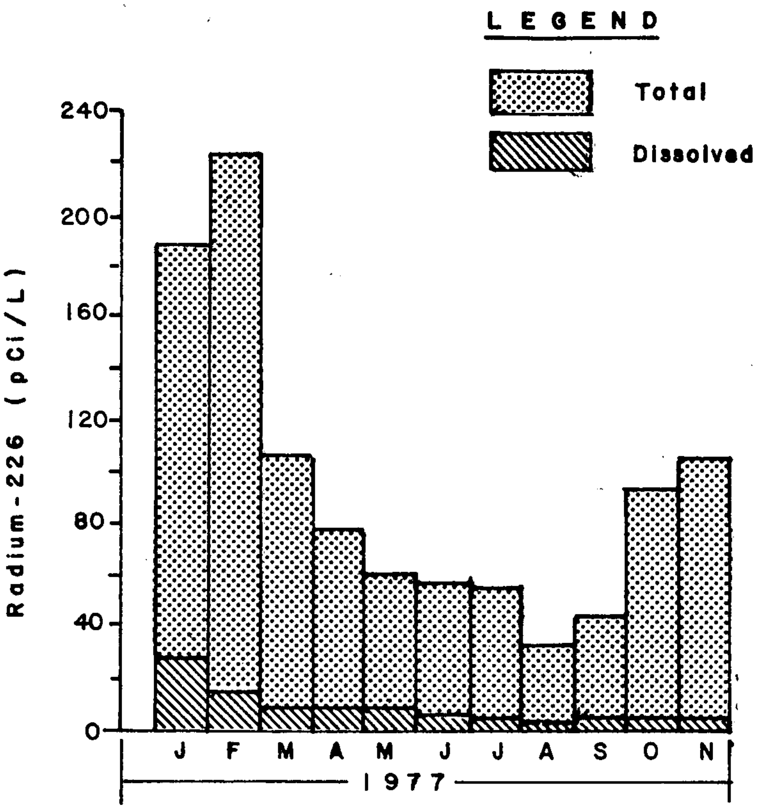

FIGURE 2 RADIUM-226 ACTIVITIES IN FINAL EFFLUENT FROM OPERATING QUIRKE MINE/MILL

The above figures represent the average of 30-50 samples from each mine. On occasion, total Ra-226 activities exceeded dissolved values by greater than tenfold. However, it is also noteworthy that over a recent 10 month period (July 1978 - April 1979) one company discharged an effluent with a monthly average of less than 10 pCi/l total Ra-226.

Since January 1978, the Department of Environment, the Department of Energy, Mines and Resources, and several uranium producers have been involved in a jointly funded and managed pilot plant program to investigate the total and dissolved Ra-226 activities which can be achieved by physical-chemical treatment. One process consists of barium-radium precipitation in agitated tanks, flocculation in mechanical flocculators and solid-liquid separation in a clarifier. A second method which is also being investigated employs granular media filtration instead of clarification in the solid-liquid separation phase. The work to date, although still requiring a longer period of demonstration, gives every indication that the project effluent target levels of 10 pCi/l total Ra-226 and 3 pCi/l dissolved Ra-226 can be achieved by both these methods. This project has been described in detail in Phase V.

6.5 Seepage Water

Tailings impoundment areas have to be properly engineered and constructed to ensure structural integrity and to prevent the escape of contaminated water via seepage to the adjacent surroundings. Serious problems may arise if the tailings contain significant amounts of acid producing minerals. Oxidation processes may generate acidic solutions and cause heavy metals and radionuclides to dissolve from the tailings. The problems are especially severe if the ore has been treated in an acid leach process. A process which results in the removal of the natural buffering constituents in the ore.

Table 8 illustrates the range of concentrations of different constituents found in seepage discharges from the Elliot Lake area (3).

TABLE 8 SEEPAGE WATER CHARACTERISTICS

Parameter	Measure Range	
pH	1.8 - 3.8	
Dissolved Ra-226	5 - 42	pCi/l
Total Thorium	1000 - 10000	pCi/l
Dissolved Pb-210	30 - 1000	pCi/l
Fe	1.8 - 3760	mg/l
Dissolved Solids	630 - 21500	mg/l
SO_4	360 - 11550	mg/l
NH_3	0.12 - 35	mg/l
NO_3	0.01 - 0.6	mg/l
Ni	0.32 - 5	mg/l
Zn	0.06 - 11.5	mg/l

In order to protect the downstream receiving water environment by minimizing seepage through impoundment structures, the Atomic Energy Control Board in its guidelines recommends that these structures be built such that their permeability is less than 1×10^{-6} cm/sec.

Measures taken to minimize seepage include the use of impermeable clay cores or synthetic liners in retaining dams, extending impermeable cement grout or interlocking sheet steel curtains down to the bedrock, grouting fractured bed rock with cement and compacting the overburden to reduce the permeability. Even when proper engineering practices are employed the total elimination of seepage is very difficult to achieve. The seepage water produced should be collected and recycled to the tailings impoundment facility for treatment. It should be noted that seepage problems can persist long after mining operations have ceased.

6.6 Recirculation of Treated Effluent

The environmental advantages of recycling and reusing effluent from the tailings management facility are well documented. The mining industry, in general, has adopted the widespread use of this practice.

Only one uranium mine in Canada, Madawaska Mines, recycles supernatant water from the tailings pond for reuse in the mill. At this mine, about 25% of the water from the mill discharged to the tailings pond is recirculated back to the mill. Madawaska is able to recycle this water since it employs sulphuric acid - sodium chloride elution in the ion exchange stage rather than ammonium nitrate - nitric acid elution as practiced in most acid leach mills. If ammonium nitrate - nitric acid elution is used nitrates are discharged to the tailings impoundment facility in the waste barren solution from ion exchange. Because a portion of the barren solution is also normally recycled in the mill, however, some of the nitrates which it contains can enter the pregnant solution. According to the industry, the concentration of nitrates in the pregnant solution must be less than 600 mg/l to avoid reduced uranium recovery during the loading stage of ion exchange. In order to avoid exceeding the permissible limit for nitrates in the pregnant solution, tailings decant water is not recycled to the mill.

It is recommended that uranium mills employ extraction processes which permit high degrees of solution recycle and thereby reduce fresh water requirements and final effluent discharges.

6.7 Ammonia and Nitrate Substitution

Ammonia and nitrate discharges from mills using the conventional acid leach process are of concern because of the adverse effects of these pollutants on the aquatic environment and the practical difficulty of removing them from a wastewater stream. The most practical solution to minimize their concentrations is to avoid their use whenever possible. This can be achieved by:

1. avoiding the use of ammonia as a neutralizing agent;
2. employing ion exchange processes which use alternate reagents to ammonium nitrate and nitric acid for elution. Examples include the use of sulphuric acid and acidified sodium chloride solutions;
3. employing sodium chloride stripping of the organic solvent instead of ammonium sulfate stripping in the solvent extraction process;
4. using sodium hydroxide or magnesia as the uranium precipitating agent.

The Elliot Lake uranium producers have considered a number of alternatives to minimize the discharge of these chemicals. One alternative of interest is the LAMIX (Limestone-Acid-Magnesia-Ion Exchange) process, which eliminates the use of both ammonia and nitrates. Rio Algom are using this process in their recently re-opened Panel Mill.

6.8 Air Pollution Control

The various operations of the milling process produce two principle types of airborne contaminants - particulates (radioactive and non-radioactive) and radon gas.

The main sources of particulate releases are the ore crushing and grinding circuits, the screening and transfer points and the yellowcake drying and packaging operations. Particulates entrained in the air from the crushing and grinding circuits and the screening and transfer points are usually exhausted through fabric filters where outlet emissions have been reported to be in the range from 0.03 - 0.7 gram/sec at the Elliot Lake mills (3). Assuming the uranium content of the ore is 0.2%, the corresponding activity releases are 2×10^{-5} uCi/sec to 5×10^{-4} uCi/sec of U-238 and each of its daughter products (secular equilibrium). Depending on the moisture content of the ore, the particulate emissions reported for U.S. mills vary from 1×10^{-4}% to 5×10^{-4}% of the ore processed (15). These releases correspond to 0.1 - 0.5 gram/sec for a mill with a capacity of 7000 tonnes per day.

Emissions from yellowcake drying and packaging operations consist mostly of uranium without its daughters. As part of the drying operation, which is carried out at temperatures of up to 800°C to yield a product of 80% U_3O_8 with 20% moisture content, high energy venturi scrubbers are usually used to remove the particulates from the emissions prior to discharging the treated flue gas to the environment. For the packaging operation, fabric filters are used to minimize particulate emissions. The typical controlled release rate from the above operations is in the order of 0.05 gram/sec to 0.25 gram/sec at the Elliot Lake mills (3,6). These concentrations correspond to uranium activity releases of from 0.02 uCi/sec to 0.10 uCi/sec, each of U-238 and U-234.

The ore crushing and grinding circuits and the leaching tanks, are the two major sources of radon gas emissions. In the ore crushing and grinding and the leaching operations, which are carried out in enclosed systems, the radon gas generated is usually exhausted through fabric filters and venturi scrubbers respectively. It should be noted however that the fabric filters and venturi scrubbers are installed primarily to remove entrained particulates.

The radon emissions from the Denison and Rio Algom Quirke mills have been reported to range from 5 - 10 uCi/sec (3).

The tailings impoundment facility can, under certain circumstances, be a source of both particulate and radon gas emissions. This subject is addressed in detail in Sections 7.2 and 7.3

7 SHUTDOWN

7.1 General

Although at times a tailings impoundment facility may be shutdown while a mine continues to operate, generally speaking, the shutdown phase begins when mining and milling operations cease. Within the mining industry, the need for the implementation and continuation of environmental protection measures does not stop when an operating mine ceases to produce or discontinues the use of a particular tailings impoundment facility. This is particularly significant with respect to the uranium mining industry. Because each ton of uranium ore commonly contains only a few pounds of uranium, virtually all of its other constituents are waste products which must be disposed of in an environmentally acceptable manner over both the short-term and the long-term.

Even though the quantities, physical/chemical characteristics and ultimate disposition of these wastes will vary from one mine to another due to site specific differences in geology, mineralogy, ore grade, mining methods, climate and topography, it is apparent that uranium mill tailings constitute a significant waste management problem, not only in terms of sheer volume, but especially in view of their contained radionuclides. The shutdown practices of uranium mining companies in the Elliot Lake area in the late 50's and early 60's resulted in the creation of significant long-term environmental problems (16). The companies and the government regulatory agencies must accept the responsibility for the results of past practices which today would not be acceptable.

The major problems in the shutdown phase result from the deactivating of the two major pollution abatement facilities, i.e., the tailings impoundment and the radium treatment pond. Efforts must be made to ensure that the radionuclides and heavy metals contained in the tailings impoundment and in the treatment pond do not cause environmental problems. It is apparent that the environmental considerations of the shutdown phase must be addressed as early in the overall planning as the development phase. An erroneous decision during early planning may make it essentially impossible or impractical to shutdown the mine waste disposal facilities in an environmentally acceptable manner.

7.2 Environmental Concerns

The major environmental concerns associated with the shutdown of waste management facilities include:

1. contamination of surface water or groundwater systems with contaminated seepage or leachate;
2. redissolution of radium from $BaRaSO_4$ sludges in treatment ponds;
3. tailings impoundment dam failures;
4. emissions of radon gas in particular from dried out tailings pond surfaces but also from moist surfaces;
5. the contamination of soil, water and vegetation from windblown radioactive dust particles from dried out tailings impoundments.

With respect to No. 1 above, this problem is aggravated when the tailings contain significant concentrations of pyrite or pyrrhotite and have the potential to produce acid. The composition of seepages from pyritic tailings at Elliot Lake was presented in Table 8.

With respect to No. 2 above, the $BaRaSO_4$ sludges remain stable under the high sulphate solution conditions which exist in an active treatment pond. However, investigations have shown (12,17) that radium leaches from the sludge when in contact with water low in sulphates. Such would be the case when a pond is no longer in active use since natural precipitation or surface runoff would reduce the sulphate content of the water sufficiently to cause redissolution of the radium and thus allow the escape of radium from its storage location. More isolated and permanent disposal sites or techniques have yet to be determined and this is presently a matter of considerable study by both government and industry. As a potential solution, the disposal of the material underground in special sections of the mine appears to be obtaining the greatest amount of attention and study.

Tailings impoundment dam failures (Item 3) have occurred in the past at a number of B.C. and Yukon base metal mines and at uranium mines in Ontario (3). The structural integrity of tailings management facilities is a serious concern during both the operating and shutdown phases of the mine. This concern would be enhanced in seismically sensitive areas of B.C. and in areas of the province subject to high rainfall and high runoff.

When tailings areas dry out, the tailings become a source of radioactive airborne particulates and radon gas (Items 4 and 5). The quantity of particulates released is dependent upon the moisture content of the tailings, the particle size distribution and the wind speed. The volume of radon emanation from tailings is primarily dependent upon the radium content, since radon is a daughter product of radium. However, the moisture content, particle size distribution and weather conditions also have a strong influence on the rate of radon release.

7.3 Mitigative Measures

Prior to a discussion on mitigative measures, the following points should be noted:

1. The Department of Environment and the Department of Fisheries and Oceans consider the environmental concerns associated with mine shutdown to be the most significant of the concerns associated with the various phases of uranium mining.
2. The radioactivity contained in tailings impoundments and treatment pond structures will exist for hundreds of thousands of years. While a great deal of information is available and substantial experience has been gained in the development and implementation of so called short-term or "interim" storage of this radioactivity, long-term solutions to the containment have not yet been demonstrated.
3. Government and industry have undertaken studies designed to provide both short-term and long-term answers to the environmental concerns associated with shutdown; however, most of these studies are currently at relatively early stages of development.

In the discussion on mitigative measures that follows it should be noted that the solutions discussed would be considered <u>short-term</u> only.

With respect to contaminated seepage or leachate, efforts should be made to minimize the volumes produced. This can be accomplished by ensuring that all surface water runoff originating outside the tailings disposal site by-passes the site. Other steps that should be considered at particular sites include:

a) revegetation of the tailings pond surface;
b) chemical fixation of the tailings;
c) upon closure, encapsulating the tailings in an impermeably lined pond by covering the tailings with clays topped by earthen fill and/or topsoil and revegetating the topsoil;

d) during the milling stage, physically separating the acid producing constituents from the bulk of the tailings (rock forming minerals) and storing the acid producing constituents in smaller and impermeable storage sites.

A study, jointly funded by the federal government and several uranium producers, to determine the effectiveness of a number of approaches in reducing Ra-226 levels in tailings impoundment leachates is currently on-going. This study has been discussed in detail in Phase V.

Steps should be taken to ensure that $BaRaSO_4$ sludges in treatment ponds be stored in an environmentally acceptable manner. In some cases it may be necessary to physically move the sludge to underground storage areas. The underground storage areas may be either natural or man made or a combination thereof, but regardless must be capable of isolating the sludge from the environment. At the Madawaska mine in Bancroft, Ontario, the treatment pond is actually a concrete tank excavated into the ground (13). Upon cessation of operation, consideration is being given to covering the tank with an impermeable cover (e.g. clay) and topsoil sufficiently thick to inhibit the entry of surface water and the release of radon gas. The effectiveness of this method of isolation still has to be proven.

Many papers and texts have been published on the proper design and operation of tailings pond structures (18,19,20) and this information will not be repeated here. The siting of the pond and diversion of surface water streams away from the pond are obviously important considerations. Because natural geomorphic processes degrade the landscape, elevated, above ground tailings impoundment structures are subject to erosion over the long term. Whenever possible therefore, a tailings disposal facility should be sited, constructed and reclaimed in a manner that will minimize the degrading effects of erosional processes. Consequently the construction of a tailings management facility below the surrounding natural ground level, i.e., in a natural or man made depression, rather than above the surface should be considered provided that surface water flows can be diverted away from the tailings storage area and groundwater can be protected from contamination.

Radon gas and particulate matter become a problem when part or all of the tailings in a shutdown impoundment are exposed to the atmosphere. The most appropriate preventative measure will depend upon the specific site. A water cover will prevent radon and particulate problems but may be difficult to maintain. It would also be necessary to ensure that no leachate or seepage problems resulted. Covering the tailings with compacted earth and vegetation will eliminate most of both the radon and particulate problems. The vegetation will assist in preventing wind erosion. However, it should be noted that although this widely accepted approach appears to be effective, it has yet to be demonstrated on a long-term basis at uranium mines.

8 CONCLUSIONS

1. Prospecting activities do not produce any significant environmental concerns.

2. The volumes and concentration levels of radiological and non-radiological contaminants which could be released to the environment from individual exploration sites are generally minimal. The combined releases from several exploration operations within a restricted geographic area and/or drainage or groundwater system, however, may have significant detrimental effects on the receiving environment.

3. Mine development activities can physically disturb surface and groundwater systems and create sources from which radiological and non-radiological contaminants, comparable in nature to those which would be released during actual mining operations, can be released to the environment. The effects of these releases on the receiving environment can be minimized through the use of the control technologies applicable.

4. Ammonia based explosives are sources of ammonia, nitrates and nitrites in mine water. Good housekeeping practices are imporportant in minimizing the amounts of these contaminants in the mine water produced.

5. _In situ_ mining has proven to be environmentally acceptable at a number of sites in the U.S.A. The overall environmental acceptability of _in situ_ mining can only be assessed on a site specific basis.

6. Mill tailings discharges contain a variety of pollutants including radionuclides, heavy metals and process reagents. The current technology for treating these wastes consists of a tailings impoundment facility followed by a radium removal treatment pond. The federal effluent regulations for Ra-226, heavy metals, suspended solids and pH can be met by the diligent application of current technologies.

7. The structural integrity of tailings impoundment facilities and radium removal treatment ponds is influenced by site specific factors such as seismic activity, rainfall and runoff patterns, and topography.

8. Current federal requirements for Ra-226 in uranium mine effluents are prescribed in terms of dissolved Ra-226 and do not apply to the discharge of total Ra-226 which can exceed the dissolved values by considerable amounts.

9. Milling processes are available which do not necessitate the use of ammonia or nitrate compounds, both of which are of environmental concern, in the recovery of uranium, e.g. LAMIX.

10. Radon gas, radioactive and non-radioactive particulate matter are generated during various phases of uranium mining and milling. Pollution control technologies exist to minimize these emissions at their source.

11. On a short-term basis environmentally acceptable technology for the control of tailings and $BaRaSO_4$ sludge does exist. However, the lack of satisfactory long-term disposal methods, methods which would not necessitate human intervention, is a matter of serious environmental concern.

12. A comprehensive effluent and emission monitoring program is essential to ensure that permitted effluent and emission concentrations are being met.

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BRIEF PRESENTED
TO
THE BRITISH COLUMBIA
ROYAL COMMISSION OF INQUIRY
HEALTH AND ENVIRONMENTAL PROTECTION
URANIUM MINING

PHASE VI
APPENDIX II

by

Department of Environment
Department of Fisheries and Oceans

Environmental Protection Service
Department of Environment
Pacific Region

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1 INTRODUCTION

Many of the contaminants which result from the mining and milling process (see Phase VI, Appendix I) are derived from the ore itself. These include radioactive substances, heavy metals, pyritic sulfur, suspended solids and other trace elements. Process reagents, nitrates and ammonia, for example, which are discharged with the effluent are added in the milling process. Unlike most base metal mining operations in British Columbia, which recycle essentially all their wastewater, uranium mines in Canada generally discharge the majority of their wastewater to the receiving environment. Atmospheric contamination results primarily from emissions of particulate matter and radon gas.

Once present in the environment the effects of these contaminants on the various environmental processes at work are dependent upon their radiological, chemical and biological properties. The discussion that follows provides an overview of both the physical and biological transport mechanisms and ecological sinks that the biosphere provides. This Section also provides a description of the effects that contaminants have on the physical and biological components of the environment. A complete understanding of these factors is necessary to effectively assess and interpret the expected environmental impact of a proposed uranium mining operation.

A comprehensive environmental impact assessment is essential in providing the information upon which to base the decision of whether or not to develop a particular uranium mine and, if so, under what conditions. If a mine is allowed to proceed, a totally integrated monitoring program of the physical, chemical, biological and radiological receiving environment is essential.

This Appendix provides a discussion on the elements of a generic, receiving environment monitoring program for the Commission's consideration.

2 THE IMPACT OF POLLUTANTS ON THE ENVIRONMENT

2.1 Radioactive Components of Effluents and Emissions

2.1.1 Interaction of radiation with matter

Radioactive materials are characterized by the types of radiation they emit while undergoing transformation or disintegration to stable elements. In this manner, alpha, beta or gamma-emitters are identified. Radiation is often referred to as "ionizing radiation" because of its effect on atoms or molecules of material, both biological and non-biological, with which it interacts. The radiation causes atoms to lose electrons in their orbital shells and results in "ions" being produced. The ionization of a large number of atoms or molecules in a living tissue or organ can have a disrupting effect on the normal chemical activity of the organism. The resultant effects are of two major types: acute effects, or effects that are evident shortly after exposure to moderate or high levels of irradiation (e.g., reddening of the human skin), and chronic or late effects that become evident only after a period of "latency", following exposure to low level radiation. Because uranium mining wastes result in low level radiation, only the chronic or late impacts will be discussed.

The late effects of radiation manifest themselves some time after the dose has been received and result from the radiation interference with the biological information the cells transmit during the natural process of cell (mitotic or meiotic) division. When this interference affects the cells of a tissue then the effect is termed "somatic". Somatic effects include cancers and leukemia. When the interference occurs among the cells responsible for sperm or egg production, then the effect is usually manifested in future generations and the phenomenon is called a "genetic" effect.

The somatic and genetic effects discussed above are not specific to radiation and may be induced by other environmental factors (carcinogens and mutagens in addition to "natural" incidences). Most members of a population exposed to low levels of radiation will not suffer any effect but a small fraction of that population might develop cancer or might pass on genetic damage to their offspring. It is not possible to predict which individuals of a population will be affected and therefore the late effects of radiation are termed "stochastic" in order to reflect this statistical nature of possible effects.

It is important to note that life has evolved in an environment of natural radiation exposure that varies in both time and space. The mining of uranium increases this exposure particularly from radium and radon.

Risk estimates have been derived for the stochastic effects of exposure to ionizing radiation in human populations. For somatic effects, these risk estimates are based, to a large extent, on epidemiological studies of groups exposed to reasonably quantifiable levels of radiation (e.g., personnel in nuclear facilities). While data on the natural incidence of genetic diseases in humans are of some use, the genetic risk estimates are not based on the epidemiological studies of irradiated human populations. Instead these genetic risk estimates are based mainly on the observation of radiation effects in laboratory animals such as mice.

Risk estimates for stochastic effects in biological systems other than man have not been as well quantified, partly because little is known of the natural incidence of malignancies in key species of the ecosystem, but mainly because the study of stochastic effects has been of more importance in public health considerations than in ecological protection. It is often suggested that man is one of the most radiosensitive species; however, this is difficult to substantiate because of this lack of data on stochastic effects for other species. It is also often claimed that radiation standards set to protect man will also ensure protection of the environment. This is so only if secondary or derived release standards take into account the complexities of the ecosystem, the potential for bioaccumulation, possible radiosensitive species and/or radiosensitive stages of certain species, combined impact of a number of effluent sources in one region and the long-term effect of persistent radionuclides such as radium.

There is a good deal of disagreement over the seriousness of late effects at low doses, especially when the low doses are received by large populations over long periods of time. Much of the disagreement is focused on two alternative possibilities with respect to the dose-effect relationship for the delayed consequences of low level exposure: <u>threshold</u> and <u>linearity</u>. Most scientists will agree with the notion that all radiation has the potential of resulting in an adverse effect no matter how little the dose. They therefore reject the idea that, for late effects, there is a threshold of dose below which no effect will result even though no experiment can be devised which is sensitive enough to demonstrate the presence or absence of an effect at the very lowest doses. Consequently, it is believed that rejection of the threshold concept is a prudent step.

Linearity refers to the straight line or linear relationship between low-level radiation and effect. The theory of linearity has been supported by laboratory research. However, epidemiologic studies on exposed human populations are subject to various, often contradictory, interpretation. Much of the present controversy on low-level radiation effects stems from an interpretation of the linear extrapolation: some critics argue that it under-estimates the effects at low doses whereas others claim it actually over-estimates them.

2.1.2 Environmental pathways - general

The aquatic, terrestrial and atmospheric ecosystems provide transport pathways which result in the dispersion, dilution and, in some instances, the accumulation of radioactive compounds in a variety of biotic/abiotic environmental compartments (sinks). Figure 1 illustrates generalized environmental pathways in a uranium mining area which may result in human exposure to contaminants (1).

An ecosystem is a complex interrelationship of the biotic, chemical and physical components of the environment with functional interchanges of water, minerals and energy between the various compartments. Site specific data is required to evaluate the relative importance of the various pathways operating in a given ecosystem and, therefore, in identifying the "critical pathways" which lead to the exposure of man or animals. These pathways indicate the most important transport mechanisms resulting in environmental impact or human exposure for a given contaminant.

The results from a well conceived environmental baseline study are directly applicable to pathway analysis and provide the only means of monitoring the environmental changes resulting from uranium mining and milling. Therefore a comprehensive baseline study should be undertaken on a site specific basis before any development proceeds. This subject is pursued in detail in Sections 3 and 4 of this Appendix.

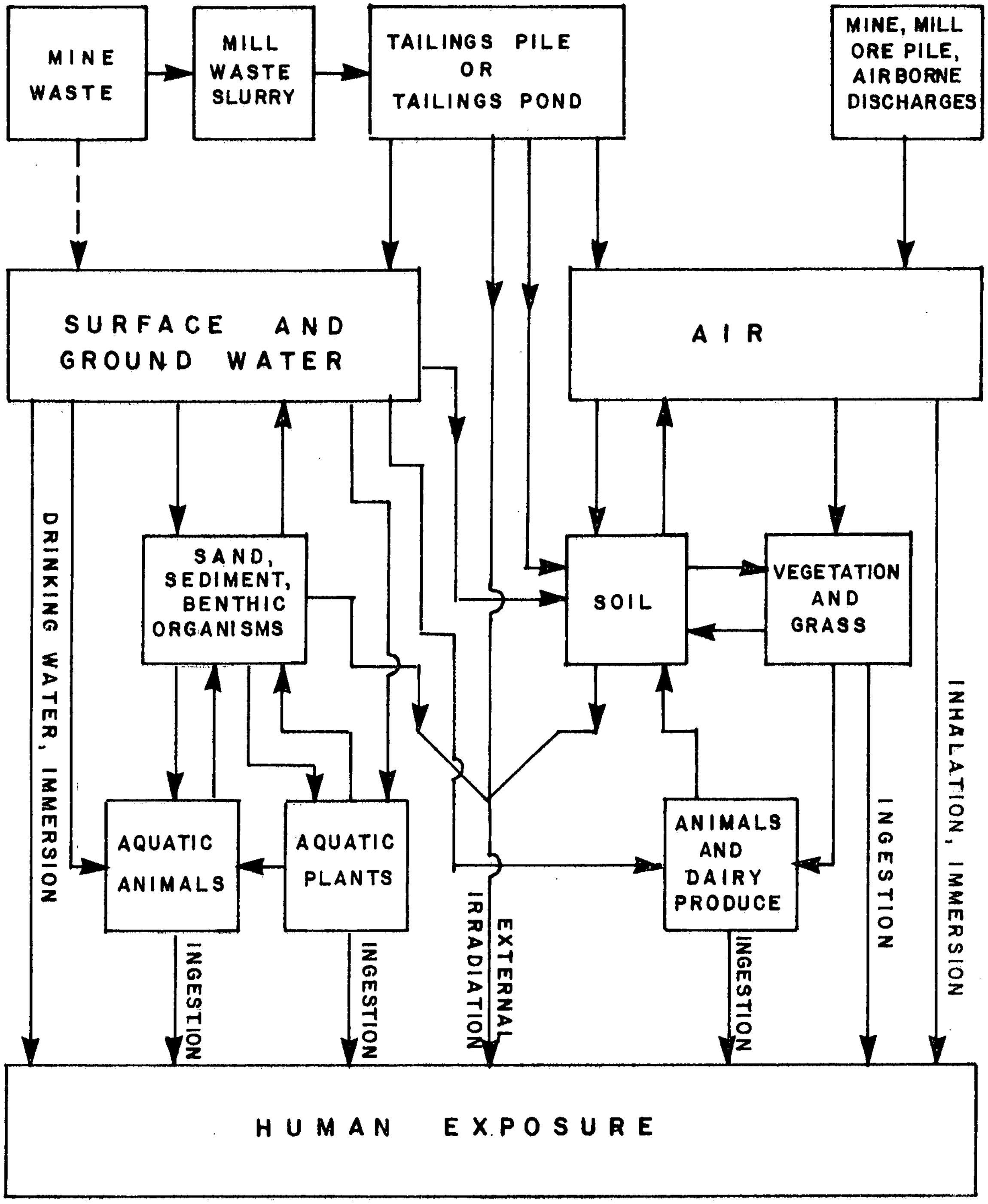

FIGURE I ENVIRONMENTAL PATHWAYS IN URANIUM MINING LOCATIONS

2.1.3 Releases to the aquatic environment

Radionuclides of significance in the aquatic environment are the isotopes of uranium and thorium, Ra-226, Pb-210, and Po-210. U-238, U-235, Th-230, Th-232 and Ra-226 are alpha-emitters with long half-lives. Pb-210 is a beta-emitter with a relatively short half-life of 22 years. Polonium-210 is a alpha-emitter with a half-life of .4 years. Alpha-radiation is relatively more effective than beta- and gamma-radiation in inducing biological changes.

The primary impact of radioactive liquid discharges is manifested by an impairment of the quality of local and regional receiving water bodies. Some of the experience documented in Ontario and Saskatchewan is reviewed below.

Uranium mining and milling activities in the Elliot Lake area in Ontario have resulted in increased Ra-226 levels in the Serpent River basin (2). Although radioactivity levels decreased significantly between 1970 and 1975, elevated levels still persist (3). Radium-226 concentrations near the mouth of the Serpent River, some 40 miles downstream from the mining areas, averaged 4 pCi/l in 1975, a level still above the Ontario drinking water standard of 3 pCi/l. It should be noted that the observed elevated concentrations have occurred as a result of a number of factors including the higher release rates of past mining activities, past tailings dam failures, dispersion of tailings solid, their settlement into bottom sediments, and the subsequent redissolution of Ra-226. Substantial accumulation of Ra-226 from the mining and milling of uranium at Beaverlodge, Saskatchewan has also been found in the sediments of Beaverlodge Lake near the mouth of Ace and Tailings creeks (4). Levels of 10 - 910 pCi/g dry weight have been observed. Also, fish collected in this area have exhibited elevated levels of Ra-226.

Certain aquatic plants (particularly algae) take up or accumulate specific radionuclides from water and sediments. The transfer of radionuclides from water to plants provides an important pathway, and is influenced by the chemical form of the radionuclides, and by such things as sediment and plant characteristics.

The uptake of radioactivity by aquatic biota tends to be much higher in fresh water than in oceans because mineral constituents in the fresh water are usually present in much lower concentrations than in sea water. Due to the complexity of the processes involved in the uptake of radioactivity, the degree of uptake is highly site specific.

Radiation effects in aquatic organisms were recently reviewed and the report (5) notes that fish, particularly their fry and egg stages, are the most radiosensitive of aquatic organisms. A discussion prepared by the Department of Fisheries and Oceans on these and other implications of radionuclides in effluents from uranium mines on fish and aquatic biota is provided in Section 2.1.4 which follows.

The presence of radionuclides within the body of an organism will result in exposure to radiation from within the body and consequently in internal radiation doses. Radionuclide uptake by organisms can occur by inhalation of air and by ingestion of water and food containing radionuclides. The magnitude of the internal dose rate depends on the quantity of the radionuclide internally deposited and its distribution within an organism.

The presence of radionuclides in water, air, sediments and soil will also result in exposure to radiation sources external to the body of an organism. External doses are directly related to the concentration of radionuclides in an environmental medium in which a specific organism exists. Also, external exposure depends on the size, form, and habits of the organisms exposed.

Internal doses to aquatic biota were calculated for activity levels for various radionuclides and reviewed in reference 1. The results which are probably upper estimates are summarized in Table 1 (1). These doses result from an uranium mining operation for a "model" mine and are presented to show the relationship between levels of radioactivity in water and resulting doses to aquatic organisms. Invertebrates and aquatic plants receive higher doses than fish. Po-210 and Ra-226 are the radionuclides delivering the highest doses.

Bottom invertebrates and aquatic plants show very high bioaccumulation factors for radium, thorium, lead and polonium. Although these organisms are part of the complex aquatic food-chain, they are not usually (except in the case of marine invertebrates) a direct exposure pathway to man. However, they are significant as indicators of radioactivity levels in the aquatic environment.

The principal means by which radioactivity from liquid effluents may reach humans is through ingestion. Ingestion may occur by drinking water and by eating foodstuffs containing radioactivity. The significance of fish consumption may be evaluated as follows. If it is assumed that the average daily fish consumption for a member of the "critical group"* is 50 gm (40 lb/year) and that the average daily water intake is 2000 ml, then the fish intake pathway will be the major one if the bioaccumulation factor exceeds 40. Based on the values shown in Table 2 this will be the case for radium, lead and polonium, particularly if whole fish is consumed.

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* defined as those members of a population receiving the highest dose as a result of their physical location and/or their age and lifestyles, including eating habits.

TABLE 1 ESTIMATED DOSES TO AQUATIC BIOTA

Radionuclides	Water Concentration (pCi/litre)	Dose (rad/year)		
		Fish	Invertebrates	Aquatic Plants
U-234	5.3	0.049	0.49	4.9
U-235	5.3	0.046	0.46	4.6
U-238	5.3	0.043	0.43	4.3
Ra-226	7.4	0.76	3.8	38
Th-230	1.3	0.039	0.58	1.8
Pb-210	0.33	0.019	0.006	0.012
Po-210	4.7	0.24	97	9.7
	Total:	1.2	103	63

TABLE 2 BIOACCUMULATION FACTORS IN AQUATIC BIOTA

$$\left(\frac{\text{pCi/kg biota}}{\text{pCi/litre water}}\right)$$

	Fish Flesh	Whole Fish	Invertebrates	Aquatic Plants	Remarks
Ra	3 - 44	100 (Skeleton)	500 - 1000	500 - 1000	Animas River, Colorado
	1 - 14	2 - 11	200 - 10000	1000 - 10000 (algae)	Elliot Lake Basin
	100 - 600	500 - 5000			Downstream of a uranium mine in France
	50		250	2500	Data tabulated by the U.S. Nuclear Regulatory Commision and Oak Ridge National Lab.
Th	30		500	1500	
U	2		60	0.5	
	10		100	1000	
Pb	100		100	200	
	300				
Po	500				
	50		20000	2000	

It should be noted that conditions affecting the potential exposure of human populations to radiation in British Columbia are substantially different than conditions existing in the Elliot Lake region of Ontario. Notably, surface water bodies in southern B.C. are significantly less abundant, the population density is higher and land utilization is different and more intense than in northern Ontario. Under these conditions, releases of equivalent amounts of radioactive substances are expected to result in comparatively higher exposures of radiation to man.

For illustrative purposes the results of a (draft) generic environmental impact statement (GEIS) by the U.S. Nuclear Regulatory Commission (6) are of interest, since some of the conditions encountered in uranium mining regions covered by the GEIS, i.e., the western and northwestern United States, are similar to those in southern B.C. This study indicated that radionuclides released from an operating "model" uranium mill may contribute from 10 to about 80 millirems per year to the critical population group (children) by the ingestion pathway at a distance of 0.6 to 2 km downstream from the mill.

2.1.4 Detailed review of the impacts on fisheries and aquatic biota

The introduction of radionuclides into the aquatic environment from uranium mines and mills may have direct deleterious effects on fish and other aquatic organisms, and radionuclides may accumulate to such an extent in fish, shellfish and other aquatic resources to render them unsuitable for human consumption.

Information is available on the concentrations or activities of some radionuclides in the water, sediments and aquatic biota downstream of some uranium mines and mills (7,8,9,10,11), on the results of an experimental addition of Ra-226 to a small lake (12), on the accumulation and some effects of uranium, thorium, and Ra-226 on aquatic organisms in laboratory studies (13,14,15), and on the general effects of radiation on aquatic organisms (5).

Most of this information is of limited use in predicting the effects of new uranium mines and mills on the aquatic environment. Although providing information on the distribution and accumulation of some radionuclides in the aquatic environment, the studies at uranium mines and mills generally fail to relate adequately this information to 1) the total release and release rate of radionuclides, 2) the mechanisms responsible for their distribution in the aquatic environment, 3) the exposure of aquatic organisms to the radiation, and 4) the effects of such exposure; also most studies provided information on uranium and Ra-226 but not on thorium isotopes, Pb-210 and Po-210. The major shortcoming of information derived from most laboratory studies in predicting effects is that they fail to take into account the complexity of the aquatic environment especially in relation to the behaviour of radionuclides.

A. Effects of Radiation on Aquatic Organisms

The International Atomic Energy Agency (5) recently published an excellent review of information on concentrations and activities of radionuclides in the aquatic environment and resultant radiation doses received by aquatic organisms, the acute and chronic somatic effects and genetic effects of ionizing radiation on aquatic organisms, and effects of ionizing radiation on aquatic populations and ecosystems. Much of the information in this section is based on this review.

Most studies have examined the effects of acute exposure to radiation on aquatic organisms in the laboratory; less than 10% of the studies dealt with chronic exposure and even fewer studies assessed the effects of radiation on populations or actual aquatic ecosystems (5). Consequently there is a problem in predicting effects on aquatic ecosystems because 1) there is a lack of data on the radiosensitivity of aquatic populations, communities and ecosystems, 2) experimental dose rates usually were orders of magnitude greater than those experienced by natural populations even in areas where radioactive waste disposal occurs, and 3) the linear dose-response relationship is an assumption although this relationship fits the data best (5).

1. Acute Lethality

The acute lethal radiation dose varies among taxa and with age. Generally primitive organisms are more resistant than vertebrates and older organisms are more resistant than younger (16). Bacteria and blue green algae are the most resistant organisms with LD90s (dose lethal to 90% of individuals) of 4.5 - 735 and 400 - 1200 krad respectively (5). The most sensitive group of aquatic organisms now known are teleost fish whose adults have an LD50/30 (dose lethal to 50% individuals after 30 days) of 1.1 - 5.6 krad (5). Their developing eggs and young are even more sensitive; the most radiation sensitive stage of the coho salmon (Oncorhynchus kisutch) was one stage during mitosis of the single cell which had an LD50/150 of 16 R (R = Roentgen, 1 R is approximately = 1 Rad) (17).

As with many other environmental contaminants, radiation sensitivity is described better by dose response curves than by LD50/30s etc. since mortality, and often relative sensitivity, varies with exposure time. For instance the oyster (Crassostrea virginica) had an LD50/20 of about 190 krad and a LD50/40 of about 20 krad, and was more resistant than the clam (Mercenaria mercenaria) for 30 days but less resistant after 30 days (18).

The effect of radiation on aquatic organisms is influenced by temperature, salinity, their interaction, and other environmental or biological factors. Normally increased temperature during or after exposure results in increased radiosensitivity (16). Some estuarine species are more resistant at lower salinities (5). The mummichog (Fundulus heteroclitus) was more resistant in low salinity at higher temperature whereas at lower temperature the tolerance was reversed (19). Also, organisms that can survive in varying environmental conditions generally are less radiosensitive than those that require a stable environment (5).

2. Sublethal and Chronic Effects

Sublethal and chronic effects of radiation include larval mortality, changes in metabolic activity and the rate of development, reduced life spans, behavioural changes, altered sexual development, and increased numbers of malformations, mutations and chromosomal breakages, with some of these effects occurring at dose rates of 1 rad/d (5).

The damage caused by irradiation at low dose rates may be either repairable or irreversible. Reversibility of damage depends on the stage of development at which irradiation occurs and the magnitude of the dose (5). Consequently if organisms are irradiated continuously at low dose rates, a higher total dose is required to produce a particular injury than if irradiation was from a single large dose (20), and at very low dose rates repair processes may keep pace with the injury so that no detrimental effects are observed.

Egg and embryos of marine and freshwater fish have been shown to have a wide range of sensitivities to irradiation. Some studies with eggs of marine and freshwater fish have shown reduced hatching of larvae and increased early mortality at activities of 10^{-7} Ci/l and greater from radionuclides in water and more larval abnormalities at 10^{-10} Ci/l and greater (5). In contrast no significant effects were found by other researchers in similar experiments with eggs of brown trout (*Salmo trutta*) and plaice (*Pleuronectes platessa*) at activities of 10^{-10} to 10^{-4} Ci/l (21,22). Hatching in carp (*Cyprinus carpio*) and fathead minnow (*Pimephales promelas*) embryos was affected by 1.3×10^4 and 2.7×10^3 rads from U-232 respectively and more abnormal larvae occurred at 3.2×10^3 and 2.7×10^2 rads respectively (15).

Low level radiation increased metabolic activity of Atlantic salmon (Salmo salar) at 1 uCi/l (83), caused hyperactivity in fish (16), increased the rate of growth in fish embryos at 3 x 10^{-6} to 3 x 10^{-9} Ci/l and of algae, periphyton, crabs, brine shrimp (Artemia salina), rainbow trout (S. gairdneri) and salmon (5). However, photosynthetic oxygen production from four species of algae was reduced sharply by 24 hour exposure to 3 x 10^{-8} Ci/l Ra-226 (14).

Some other sublethal effects of radiation are: 1) x-rays affect the ATPase activity in chinook salmon (O. tshawytscha) smolt gills which could result in mortality during their transition from freshwater to saltwater (23); 2) behaviour is altered, some aquatic organisms can detect radiation; for instance, x-rays affected the withdrawal of antennae of molluscs at 1.5 R/s for 5-15 s, and contractions of the mantle cavity (5); (3) the reduced ability of rainbow trout to produce antibodies against disease organisms (24); 4) formation of ovotestes in medaka, Oryzias latipes (25); and 5) a greater percentage of male guppies, Poecilia reticulata (26).

In addition to such somatic effects, irradiation can result in genetic and chromosomal damage. Such damage, if not repaired, may accumulate in populations to cause significant effects in future generations. The chironomid, Chironomus riparius, developed chromosomal aberrations at 1.25 x 10^{-1} Ci/l and higher of tritiated water but no aberrations were detected at 1 x 10^{-4} Ci/l or lower (27). Dose rates greater than 1 rad/d may increase chromosomal aberrations in fish embryos (28). Rainbow trout sperm exposed to doses of 100 - 400 rad produce significantly more deformed embryos (29). Sperm of medaka were more sensitive to radiation than ova (30).

3. Effects on Populations

The reproductive characteristics of laboratory and wild populations of aquatic organisms have been altered by chronic exposure to radiation. Laboratory populations of parthenogenic *Daphnia pulex* exposed to 25 - 75 R/h showed a decrease in the intrinsic rate of increase as a non-linear function of dose, attributed to the direct effects of radiation on the ovaries (31). Populations with limited food and space showed lower tolerance than unlimited populations (32) and exploited populations (33). Reproduction of the aquatic snail, *Physa heterostropha*, was eliminated by a dose rate of 25 rad/h during their 24 week life span (34). The population would have become extinct at 10 rad/h and there was some decrease in fecundity, although not significant, at 1 rad/h. At the two higher doses the size of adults increased and their life span was shortened.

Several significant effects were observed when chinook salmon embryos were irradiated from shortly after fertilization until feeding commenced (35,36,37,38,39). At 10 R/d and above measurable radiation damage was evident; growth rates of fingerlings were significantly less and mortality was more than that of controls, gonadal development was retarded, decreased numbers of adults returned to spawn, age of return increased, and there was apparent sterility in adult males. Dose rates of 0.5 - 5.0 R/d did not reduce the reproductive capability of the stock over several generations, and the low-dose irradiated stock returned in greater numbers and produced more viable eggs than the control stock. Abnormalities in young fish increased at all doses.

Chronic exposure to radiation from contaminated bottom sediments has affected several populations of aquatic organisms, but the observed effects, although affecting individuals, probably do not have any deleterious effects on the populations. Populations of mosquito fish (Gambusia affinis) exposed to 10.9 rad/d for many generations had larger brood sizes with some dead embryos and more abnormalities than control populations (40). A population of P. heterostropha receiving 0.65 rad/d had reduced capsule production but increased numbers of eggs per capsule than a control population (41). Populations of Chironomus tentans absorbed 0.65 rad/d for 130 generations over 22 y and had an increased frequency of new chromosomal aberrations but these were eliminated by natural selection (42).

B. Radionuclides from Uranium Mines and Mills

Uranium mining and milling operations introduce radionuclides into the aquatic environment mainly through the disposal of liquid effluent, the contamination of groundwater, and the deposition of airborne particulates. Once present in the aquatic environment, the distribution of radionuclides is dependent upon their chemical and biological properties and various environmental processes, and their effects are dependent upon their distribution, their chemical, biological and radiological properties, and the biological characteristics of the environment. An understanding of all these factors is necessary to assess the effects of uranium mines and mills on the aquatic environment. Many of these factors, such as the relative importance of various processes affecting the distribution of radionuclides and the biological characteristics of the environment, are site-specific so that only generalizations can be made without site-specific information.

1. Distribution

The activities or concentrations of Ra-226 and uranium are higher downstream of uranium mines and mills than in upstream areas (7,9,11). However the actual activities or concentrations in different compartments of the aquatic ecosystems vary among areas and among sites within areas.

The most important factors affecting the distribution of radionuclides in the aquatic environment are the movement of water, the dispersal of dissolved and suspended matter in the water, the sorption of substances by natural materials, sedimentation, resuspension of sediment, leaching and re-dissolution, accumulation by aquatic organisms, and the presence of stable isotopes of the introduced radionuclides or of chemically similar elements (43,1).

The radionuclides of different elements behave differently in the aquatic environment as a result of their different chemical and biological properties. For instance Ra-226 is not necessarily correlated with Pb-210 in the biosphere, since Ra-226 decays to the gas Rn-222 which is easily translocated and Pb-210 is metabolized independently of radium; however both Ra-226 and Pb-210 tend to accumulate in bone. Similarly Po-210 is not necessarily correlated with Pb-210 because of their different chemical and metabolic properties (44). Another example is that high acidity (>1000 mg/l) groundwater contained elevated concentrations or activities of uranium, thorium isotopes and Pb-210 whereas low acidity groundwater contained elevated activities of Ra-226 (45).

The sediment has been shown to be the major sink for Ra-226. Of the total Ra-226 activity in a reservoir downstream of a uranium mine, 83.75% was in the bottom sediments, 14.09% in the aquatic vegetation, 1.33% bound in water, 0.83% as insoluble compounds and 0.0004% in fish (8).

The importance of the sediment as a sink for Ra-226 was confirmed by the experimental addition of soluble Ra-226 to a small lake in August (12). The Ra-226 was deposited initially in the littoral zone primarily through its adsorption by the epilithophyton. Although remaining adsorbed it became redistributed in the lake during the fall, probably as a result of sediment redistribution during the fall turnover; by the summer of the following year most of the activity was in surface sediment below 8 m.

Several factors affect the accumulation of radionuclides in the sediment including the form of the radionuclides in the water, their sorption to organic and inorganic materials and deposition processes. Radium from uranium mines and mills mostly enters streams and lakes bound to suspended material which is deposited in deposition areas (see 13). At some stream sites the Ra-226 content of the sediment was related to the radium and calcium concentrations of the water and not to the organic content of the sediment; in contrast the uranium content in the sediment was related to the uranium content of the water and was also higher in sediments with higher organic content (9).

Once present in the sediments the radionuclides may recontaminate the water if the sediments are resuspended or if they become redissolved. The redissolution of uranium, Ra-226 and other radionuclides is affected by pH, the chemical composition of the overlying water, temperature and dissolved gasses (1). The methylation of lead intake in lake sediment (46) may increase the availability of Pb-210 to aquatic organisms.

Although the sediment is the major sink for accumulating some radionuclides, aquatic organisms may accumulate higher concentrations or activities of radium and uranium. In the Animas River aquatic insects and algae contained higher concentrations of radium than did, in order of decreasing concentrations, sediment, water and fish. Relative concentrations of radium in the San Miguel River were similar except that algae had higher concentrations than aquatic insects and fish had higher concentrations than water (10). Similarly, in some streams, filamentous algae, phytoplankton, aquatic bryophytes and macrophytes accumulated higher activities of Ra-226 and higher concentrations of uranium than the upper 2 cm of bottom sediments except for a few localities which had higher concentrations of uranium in the sediments; uranium was accumulated most by macrophytes and least by algae whereas Ra-226 was accumulated most by algae and least by bryophytes (9). In the Serpent River basin, clam (Unionidae) flesh contained higher activities of Ra-226 than, in order of decreasing activities, filamentous algae, caddisfly larvae and fish (11).

The uptake of Ra-226 by algae in the laboratory was dependent upon the species of algae, Ra-226 concentration in water, growth rate and physiological condition of the algae, and length of exposure; the factors responsible for radium accumulation were adsorption, absorption and incorporation in that order of importance (13).

The distribution of radionuclides within fish and other aquatic organisms varies. Thorium, radium and lead accumulate most in bones and in shells of molluscs whereas uranium and polonium accumulate most in organs such as the kidney and spleen and in the hepatopancreas of Crustacea. In the laboratory the snail, Limnaea stagnalis, absorbed Ra-226 by an active transport mechanism similar to that for calcium; the resultant activity was greater in the new shell border than in the older shell and viscera, and least in the blood (47).

The accumulation of Ra-226 and uranium in fish varied among species and among localities affected by uranium mines and mills (8,10,11) with the activity and concentration varying with the environmental contamination (8). The uranium content of brown trout (Salmo trutta) was positively correlated with age (8). In a contaminated area viscera of brown trout contained 42.0 ug uranium/g dry weight with 3.5 and 5.5 ug/g in the muscles and skeleton respectively; in contrast Ra-226 activities were greatest in skeleton (9.2 pCi/g) with 0.98 pCi/g in the muscle and 2.0 pCi/g in the viscera (8).

2. Exposure and Effects

Aquatic organisms are exposed to radioactivity released by uranium mines and mills from radionuclides dissolved or suspended in the water, adsorbed to sediments and adsorbed to outer surfaces of organisms (external sources), and from radionuclides in the gastrointestinal tract and incorporated into body tissues (internal sources). Generally alpha-emitters, such as U-238, U-234, Th-230, Ra-226, Po-210, Th-232 and Th-228, are biologically ineffective unless deposited within an organism whereas beta-emitters, such as Pb-210 and gamma-emitters, which includes many alpha- and beta-emitters, may be biologically effective outside of an organism. Alpha-emitting radionuclides adsorbed to outer surfaces are not significant to organisms with large surface to volume ratios.

Absorbed dose rates from incorporated radionuclides increase with increasing body size because less radiation leaves the organism. About 30% of emitted alpha-particle energy is absorbed by phytoplankton and most is absorbed by zooplankton and large organisms, varying with the size of organism. A major fraction of beta-particle energy is deposited outside of phytoplankton and zooplankton whereas most is absorbed by molluscs, crustaceans and fish. Deposition of gamma-ray energy is negligible in phytoplankton but some energy is deposited in larger organisms with about 10% being deposited in fish.

Evaluation of exposure pathways suggests that incorporated radionuclides are the most important source of radioactivity for plankton and pelagic fish, that beta- and gamma-radiation from radionuclides in the sediment is equally important as incorporated radionuclides for benthos and demersal fish, and that the dose from radionuclides in water is less important (5). The exposure pathway from radionuclides in the sediment is important in British Columbia since the eggs and alevins of Pacific salmon are closely associated with stream and lake bottoms for up to a half a year.

Internal radiation doses received by aquatic biota have been calculated from assumed radionuclide activities in liquid effluents from average United States uranium mines and mills using the higher bioaccumulation factors in the literature and calculated for 30 cm diameter organisms (48). The average uranium mine occupied about 1200 ha, produced about 1600 tonnes of ore per day, pumped 5700 litres per minute of drainage water into a settling basin and 10% of this was discharged as runoff into a small stream. At the average uranium mine the estimated internal dose from U-238, U-235, U-234, Th-230, Ra-226, Pb-210, and Po-210 was 100 rad/y to invertebrates, 63 rad/y to aquatic plants and 1.2 rad/y to fish. Most of these doses were contributed by Ra-226 and Po-210; Ra-226 contributed 4% of the dose for invertebrates, 60% for aquatic plants and 63% for fish, and Po-210 contributed 97% for invertebrates, 15% for aquatic plants and 20% for fish. The assumed activities of Ra-226 and Po-210 in the mine water were 7.4 pCi/l and 4.7 pCi/l respectively.

The average uranium mill was located near a uranium mine, processed 600,000 tonnes of ore per year, released 2,500 tonnes of liquid waste per day into a tailings-retention-pond system which permitted the evaporation of most liquid but permitted seepage of 300 litres per minute into a stream with a flow rate of 3400 litres per second. At the average uranium mills the estimated internal dose from U-238, U-235, U-234, Th-230 and Ra-226 in tailings pond seepage was 1200 rad/y to aquatic plants, 350 rad/y to invertebrates and 22 rad/y to fish (48). Th-230 contributed over 90% of these doses and Ra-226 contributed most of the remainder.

These calculated dose rates for an average uranium mine and mill are less than those known to have significant adverse effects on the populations of fish and other aquatic organisms.

Although the above calculated dose rates probably are a good general estimate of the typical internal dose rates received by aquatic organisms exposed to radionuclides from uranium mines and mills, they do not necessarily reflect the conditions at all proposed uranium mines in B.C. Activities of radionuclides in receiving waters and effluents from uranium mines and mills have been shown in some cases to be higher than those used in the calculations (see 11,1). Dose rates at specific locations may also differ significantly from those calculated dose rates because the calculations did not consider the intricacies of radionuclide distribution at specific localities and the subsequent exposure of aquatic organisms. In particular, external dose rates from sediment, which may be as important as dose rates from incorporated radionuclides for benthos and some fish (5), were not included in the calculation of total dose rates. Consequently calculations of expected internal and external dose rates to aquatic organisms (such as Pacific salmon) are required for any proposed British Columbia uranium development especially because, in many areas economically important stocks of Pacific salmon (<u>Oncorhynchus</u> spp.), whose eggs and alevins spend up to half a year associated with gravel beds in streams and lakes, could be affected adversely by exposure to radionuclides.

The federal requirement for dissolved Ra-226 in the effluent from uranium mines and mills is that it should not exceed 10 pCi/l as the monthly average activity, 20 pCi/l in a composite sample and 30 pCi/l in a grab sample (49). However the total Ra-226 activity may be ten times that of the dissolved Ra-226 (62). The target suggested by the Atomic Energy Control Board for total Ra-226 in the effluent is 10 pCi/l (62). Exposure to an effluent of that quality should not cause any direct adverse effects on aquatic organisms since the resultant dose to aquatic organisms would be low even though small amounts of other radionuclides would be present; for instance exposure to 10 pCi/l total Ra-226 would result in phytoplankton receiving a dose of 0.07 urad/h (5).

The final consideration is that radionuclides may accumulate to such an extent in fish and other aquatic resources so as to render them unfit for human consumption. In Czechoslovakia brown trout accumulated sufficient uranium and Ra-226 (1.14 pCi/g wet weight) so that, at the maximum possible legal catch, a fisherman could consume about 4.6% of the safe annual uranium intake and about 152% of the safe annual Ra-226 intake as specified by Czechoslovakian standards (8). Even higher activities of Ra-226 can accumulate in fish and shellfish; in the Serpent River basin, walleye (Stizostedion vitreum) accumulated 1.3 pCi/g wet weight, bass (Micropterus sp.) accumulated 9.1 pCi/g wet weight, and the flesh of shellfish accumulated 419 pCi/g dry weight (11). Hence fish or shellfish exposed to radionuclides from uranium mines and mills may accumulate sufficient radionuclides to be unsuitable for human consumption.

2.1.5 Releases to the atmospheric environment

The radiological impacts resulting from the operation of a uranium mining and milling complex is generally assessed in terms of radiation doses to the individuals who are occupationally exposed and to the members of the general public who are exposed to radioactivity released to the environment. There would also be potential impacts on species other than man living within the region. Exposure pathways would result in some species receiving significantly higher doses than those calculated for man. In view of the widely accepted recommendation on environmental radiation protection standards based on human exposure (discussed in Section 2.1.3) and on the lack of pertinent data on the effects of low level radiation on the ecosystem, this discussion on radiological impacts due to atmospheric emissions is limited to the dose effects on human populations.

The main airborne radiological hazards of the uranium mining industry are those associated with the release of radon-222 and fugitive dust during the mining and milling process, and from dry tailings. These atmospheric releases may result in the direct exposure through inhalation of radon progeny and particulates, and the indirect exposure through ingestion of contaminated vegetation resulting from foliar deposition and uptake of radioactivity from soils. Radioactivity released to the atmosphere is normally dispersed and diluted such that its concentration in air generally decreases as the distance from the source increases. For example, it is shown (50) from the data obtained in the southwest U.S.A. that the radon concentration falls off rapidly with distance and the concentrations are virtually indistinguishable from the background levels beyond 1 to 2 km. The resultant dose due to inhalation is therefore strongly dependent on distance. This general rule may be completely inappropriate for hilly terrain where stagnation in valleys under stable atmospheric conditions may reverse known trends.

Radon gas and radon progeny

The major impact associated with the release of radon is from the inhalation and retention of its daughter products within the lungs. However, radon daughters in air are rarely in secular equilibrium with radon at outdoor locations. For instance, from the limited monitoring data obtained in the Elliot Lake area, it was shown (51) that equilibrium factors* ranged from 0.01 to 0.02 in close proximity to mill tailings. This low range of equilibrium is indicative of significantly higher radon levels than its daughter products in the vicinity of mill tailings impoundment.

A number of generic radiological assessments for "model" uranium mill sites have shown (49,53,54) that radon released by tailings constitute the principal radiological hazard. For a typical tailings area of several hundred meters in width and typical wind speed of a few meters per second, the transit time over the tailings is no more than a few minutes (52). The concentration of radon daughters in the immediate vicinity, therefore, rarely exceeds 10% of its equilibrium value or 0.001 WL per pCi/l of radon. The maximum concentration of radon daughters would occur just beyond the edge of the tailings impoundment in the direction of the prevailing wind.

These "models" however are based on "typical" areas with good ventilation consistent with flat terrain and light to moderate winds. The microclimate of valleys, the location of most habitations in mountainous regions, is by contrast liable to stagnation and accumulation of pollutants.

$$\text{*Equilibrium Factor} = \frac{\text{Working Level} \times 100}{\text{Conc. of Radon (pCi/l)}}$$

Under stagnant air conditions, short lived daughter products have time to approach secular equilibrium with the radon which may itself be slightly diluted following releases at the tailings area. Consequently, even though the radon concentration may be slightly reduced under stable air conditions, the daughters constitute the major health hazard. These become associated with aerosol particles and may even reach concentrations significantly higher than at the tailings areas. If the tailings disposal area were in a deep valley these factors would be aggravated since the source emissions remain about the same but reduced ventilation would result, over a few days, in concentration well above background, for reasons essentially similar in nature to those resulting in the high radioactivity levels in the basements of houses in Port Hope, Ontario.

Enclosed structures located adjacent to tailings will contain concentrations of radon levels essentially equal to that of the tailings area. The critical factor in determining the indoor radon daughter concentration (expressed in terms of working level) and hence the exposure to individuals is the mean residence time of radon in the indoor atmosphere because the longer the residence time, the higher the concentration of radon daughters becomes.

Tailings management depends, to a great extent, on local factors such as terrain, hydrology and demography. In Ontario and Saskatchewan, where the major Canadian mining operations are currently located, it is typically a "wet" environment and the usual practice is to use small lakes or depressions for the disposal of the tailings material. The tailings areas can become quite dry in summer and radon concentration at that time may reach levels which restrict human habitation in the immediate area. In the United States, where many mine/mill sites are located in dry areas, the dose from radon in the tailings is considered to be the largest contributor to radiation exposure to the public from the entire nuclear fuel cycle.

Radon releases can be reduced by covering (stabilizing) the tailings piles with earth and rock or by revegetation of the surface. However, even if the tailings area is covered with two to three feet of soil the tailings will provide a constant source of radon gas and its daughters. Schiager (52) has estimated that approximately 20 ft of earth cover is required to reduce the radon flux to a level equivalent to the normal background.

Radioactive particulate matter

A potential radiological health hazard to humans is ingestion of long-lived radon daughter products (Pb-210, Bi-210 and Po-210) via the food chain pathway. These radionuclides as well as Th-230 and Ra-226 from airborne dust materials contaminate the ground or edible foliage as a result of dry deposition or washout. It is difficult to accurately assess the impacts associated with Pb-210 and Po-210 due to the lack of available information on the levels of these radionuclides in food produced and vegetation grown in the province of British Columbia. Detailed studies of transport mechanisms on these important radionuclides is obviously needed.

During the crushing and grinding operations of uranium ore, and the drying and packaging of yellowcake, radioactive particulate materials are discharged to the atmosphere. The major radionuclides in airborne particulates are Th-230, Ra-226, U-238 and U-234. It has been shown that ore dust releases from crushing and grinding operations in Elliot Lake have negligible radiological impact on the atmospheric environment (51). The impact from mill discharges into the atmosphere has been shown to be negligible in terms of the estimated long-term concentration of U-238 and U-234 radionuclides (1).

The majority of the radionuclides, other than uranium, are discharged with mill effluents to the tailings ponds. Wind erosion of a dry tailings pond causes suspension of tailings particles. The quantity of the suspended material is affected by the topography and physical properties of the tailings surface, the extent of surface contamination, and the local micrometeorology. The suspended particulates that are mixed into the passing air stream and subsequently transported by wind creates a potential radiation hazard. Earth covering or otherwise stabilizing the tailings serves to prevent resuspension of tailings particles and decreases the radiation dose to individuals living close to tailings impoundments. A more detailed discussion of the stabilization of tailings impoundments has been provided in Phase VI, Appendix I.

The effect of airborne dust emissions from the tailings areas in Elliot Lake is considered to be acceptable in terms of estimated radiological impact to the local population (51). It is estimated that the average exposure rate from airborne radium, thorium and uranium particulates to the lungs of individuals living within 1 km of the tailings is about one-third or less of that from radon released from the tailings (50). The exposure from suspended particulates is usually less indoors than outdoors.

2.2 Non Radiological Components of Effluents and Emissions

2.2.1 Releases to the aquatic environment

Contaminants originating from both the ore and from the addition of process reagents are discharged following treatment to the receiving environment. These contaminants are then diluted and dispersed by the receiving waters and may accumulate in biota and downstream sediments.

(i) pH Value

The pH of several Elliot Lake area lakes has been gradually decreasing although the pH of the inflow to the lakes was neutral. The pH depression observed in these lakes is likely due to the continuous oxidation of large quantities of sulphides present in nearby abandoned tailings sites and low pH seepage from waste rock dumps, particularly since pH of current discharge is above 8.

The effect of pH on aquatic organisms and water quality has been thoroughly studied (55). The toxicity of many compounds (e.g., ammonia, hydrogen sulfide, hydrogen cyanide) can be increased by pH changes. For example, cyanide toxicity to fish increases as pH is lowered because the chemical equilibrium is shifted towards an increased concentration of HCN, the more toxic form (56). Conversely, ammonia toxicity increases as pH is raised because of an increase in the concentration of un-ionized ammonia. At high pH levels many metals form insoluble hydroxides or carbonates. For example, acid mine drainage often contains high levels of dissolved iron which is converted to particulate ferric hydroxide and insoluble ferric species when pH is elevated and oxygenation occurs (57). The toxicity of copper to rainbow trout was found to vary considerably in laboratory experiments at different water hardness/pH combinations (58). Decreasing the pH resulted in a decrease, then an increase, and subsequently, a decrease in copper toxicity, illustrating the complexity of the relationship between pH and metal toxicity.

The pH of a solution can be directly toxic to fish and other aquatic organisms. Lower and upper lethal limits of pH for a number of organisms are presented in Katz _et al_ (55). Sublethal effects of pH on fish have also been documented and include reproductive impairment, reduced egg viability, and tissue and cellular degeneration.

To ensure that the deleterious effects of pH are minimized, effluents from uranium mining and milling operations should be treated such that the pH is not less than 6.0. The maximum allowable pH should be determined on a site-specific basis.

(ii) Ammonia and Nitrogen-based Compounds

The use of ammonia in various milling operations results in its presence in tailing effluents and in receiving waters. Observed ammonia levels in affected water bodies are up to 20 times background.

Ammonia is highly soluble in water and readily dissociates into ammonium (NH^+4) and hydroxyl (OH^-) ions. Some toxic effects of ammonia have been attributed to these ionized species (59,60). However, the greatest toxicity of aqueous ammonia solutions is generally related to the un-ionized NH_3 concentrations. This level is a function of pH and temperature. For example, a pH increase from 7.0 to 8.0 within the range 0 to 30°C results in a nearly ten fold increase in the concentrations of NH_3; a temperature increase of 5°C, between 0 to 30° at pH 7.0 results in an NH_3 concentration increase of 40 to 50% (61).

Ammonia (as N) levels originating from untreated minewaters and final settling pond overflow at Elliot Lake uranium mills are 60 to 80 mg/l and 9 to 70 mg/l respectively (62). Using the final effluent ammonia levels, the pH range stipulated in the present B.C. Provincial Mining Objectives (i.e., pH 6.5-8.5) and water of typical temperatures for British Colubmia (i.e., 5-20°C), the percentage un-ionized ammonia in the effluent could range from 0.04% (5°C and pH 6.5) to 11% (20°C and pH 8.5). These values correspond to a range of 0.0036 mg/l to 7.7 mg/l of un-ionized ammonia in the final settling pond overflow in the Elliot Lake example.

Levels of un-ionized ammonia above 0.20 mg/l have been shown to be toxic to some species of freshwater aquatic life. In order to provide a safety factor for those life forms not examined, 1/10th of the lower value of this toxic effect range resulted in the United States Environmental Protection Agency criteria of 0.02 mg/l of un-ionized ammonia (63).

The addition of ammonia and nitrates from uranium mine wastewaters also contributes to the total nitrogen load to the receiving environment. Such waters, where nitrogen is the growth limiting factor for algae, may result in accelerated eutrophication (64).

In order to protect the fisheries resources, consideration should be given to establishing a maximum allowable level of un-ionized and total ammonia (as N) in uranium mine wastewater discharges in the order of 0.02 mg/l and 0.5 mg/l respectively.

(iii) Heavy Metals

Heavy metals associated with uranium ores may result in toxic and sublethal effects on aquatic organisms. The form and effect of these metals is dependent on a number of factors including water hardness, pH, temperature, and dissolved oxygen. Some of the major effects of heavy metals on aquatic organisms include the following:

1. Acute Toxicity

   Heavy metals in effluent discharges can be directly toxic to fish, invertebrates and other organisms. Several good reviews of metal toxicity are available (65,66,67), and indicate that many metals are toxic at low concentrations. For example, dissolved copper concentrations of 0.015 to 3.0 mg/l, a lead concentration of 0.1 mg/l and zinc concentrations of 0.2 to 1.0

mg/l are reported lethal to fish (65). Studies have also shown that combinations of metals may have synergistic or antagonistic effects. For example, zinc, cadmium, and copper in combination have more than an additive effect on toxicity (68,69) while calcium and magnesium salts reduce zinc toxicity (70).

Test animals for toxicity testing have often been limited to certain species and life stages (e.g., juvenile salmonids) (49). However it is becoming more evident that the embryonic stages of animals and food organisms are usually more sensitive to metals (71,72). Thus, concentrations of metals which do not kill mature fish species may kill egg and larvae stages and food organisms resulting in a decline in fish stocks.

2. Bioaccumulation

Various aquatic organisms are known to bioaccumulate certain metals. This can result in reduced resource utilization through human consumption because of metal levels which exceed food and drug standards. For example, evidence of mercury contamination of marine fishes, invertebrates and sediments in upper Howe Sound, British Columbia in 1970, resulted in the area being closed to the taking of shellfish, crustaceans and all fishes except salmon, trout and herring (73). In addition, elevated zinc, copper and cadmium concentrations were evident in oysters collected in the vicinity of pulp and paper mills in British Columbia. Oysters concentrated zinc by a factor of greater than 150,000 over levels present in ambient water (74), resulting in tissue levels which far exceeded acceptable Canadian food and drug levels (75). Additional effects of bioaccumulation of metals includes unappealing color (e.g., "green" oysters from high copper levels) and unpleasant metallic taste (71).

3. Sublethal Effects

Heavy metals may also have subtle but important effects on organisms at levels below those at which toxic effects appear (76). Effects which have been attributed to the presence of unnatural levels of metals include effects on enzyme activity, increased susceptibility to parasites and disease, avoidance reactions and reduced reproductive ability (71). For example, chronic exposures of yearling coho salmon to sublethal concentrations of copper (5 to 30 ug/l) in freshwaters resulted in a reduced ATPase activity. This was probably a factor leading to loss of osmoregulatory ability and increased mortality when fish transferred to seawater (77). In addition, rainbow trout have shown strong avoidance reactions to sublethal concentrations of zinc sulphate. In laboratory experiments the threshold avoidance levels was as low as 5.6 ug/l of zinc, a level which was 0.01 of the lethal threshold concentration (78).

(iv) Suspended Solids

Suspended solids can be considered as a very broad spectrum pollutant with the capability of affecting (directly and indirectly) all life forms from primary producers to adult fish. Additions of sediment to a stream can increase turbidity, cause scouring, smother periphyton and cover available substrate for periphytic attachment. Any of these conditions will have an adverse impact on primary production thereby reducing or eliminating the conversion of solar radiation into forms of energy usable by the next trophic level.

Increased sediments also affect stream invertebrates by abrasion of gill membranes, dislodgement, clogging of feeding apparatus, and clogging of interstitial habitat. Since these lower trophic levels produce most of the food required for salmonid production, any decrease in their quantity or quality will affect fish growth and survival.

Sediment causes the greatest reduction of salmonid production by causing mortality at the egg and alevin stages of development. For example, Langer (79) found that small increases in suspended solids (12%) resulting from a known sediment release, increased gravel sediment levels which caused a very disproportionate (55%) decrease in fish egg survival in downstream areas of a river. The abrasive quality of sediments also lowers the disease resistance of fish but has its greatest effect on the sensitive gill tissues. The gill tissue responds by secreting a mucus covering for protection. If the sediment levels are high, the sediment particles will stick to the mucus covering the gill tissue and will cause the fish to suffocate (79). Stream turbidity can also have chronic effects on fish life. Most salmonids lead a predacious mode of life and depend on sight for capturing prey and consequently reduction in water clarity causes fish to stop feeding.

Removal of suspended solids from mill effluents is important to avoid pollution of streams, and to prevent damage to fish habitat. The Federal Metal Mining Liquid Effluent Regulations limit the discharge of total suspended matter to 25 mg/l, while the EPA "Effluent Guidelines and Standards for Ore Mining and Dressing" specify a limit of 20 mg/l and the Ministry of Environment (Ontario) prescribe a limit of 15 mg/l.

(v) Total Dissolved Solids

Dissolved solids are present in all natural waters to some extent and are due to inputs of water soluble materials, such as sulfates. Practically all discharges of effluents into fresh water will increase the dissolved solids content. Since dissolved solids are not specific to any one source or even type of source, they can only be used as a general indication of water quality.

Fish food fauna (in fresh water) is generally found to live within a range of 70 mg/l to 440 mg/l. Upper limits for dissolved solids tolerance can be as high as 10,000 mg/l but in general, the limit should not exceed 2000 mg/l (81).

Water with low dissolved solids may cause heavy metals and organic compounds to have a more toxic effect. Zinc, copper, chromates, cyanides, detergents, phenolic compounds, and several other compounds are more toxic in water with very low dissolved solids content. Dissolved solids in water used for irrigation may be deleterious to plants directly, or indirectly through their effects on the soil as a result of high salinity (81). They may also be beneficial in the case of dissolved nutrients such as fertilizers.

2.2.2 Releases to the atmospheric environment

The various phases of uranium mining and milling result in discharges of both non-radioactive (dust) and gaseous emissions from the mill processes (e.g., SO_2, NO_x, acid vapours).

Existing and predicted data on the air quality for uranium mining localities in Canada show that the impact to the environment from atmospheric emissions is insignificant. For instance, the Elliot Lake uranium mine expansion study (51) showed that the effect, on the air quality from the proposed expansion is minimal.

The level of average dust fall and suspended particulate matter observed in a three-month study in the Beaverlodge area also indicate that the effect of atmospheric emissions on the air quality is likely to be of no consequence. Predicted short-term and long-term impacts for the proposed Key Lake operations have also arrived at similar conclusions (81). These results, however, cannot directly be related to the British Columbia scenario because of the differing climatology, complex terrain and meteorological situations. Nevertheless the data tends to illustrate that the impact on air quality of the non-radioactive air pollutants is minimal at currently operating mines. Site-specific information on emissions and mesolclimatic conditions for proposed mining locations in British Columbia is essential if appropriate assessment of the potential impact on the ambient air quality is to be properly evaluated.

3 ENVIRONMENTAL IMPACT ASSESSMENT

The unique climatic, topographic and hydrological features and biological resources of British Columbia, in association with the distinct problems associated with uranium mining and milling, highlight the need for a comprehensive evaluation of the potential environmental impacts associated with the development, operation, and shutdown phases of uranium mines and mills. The mountainous terrain and high rainfall which typify a large proportion of the British Columbia land mass and the important fishery resource which depends on high quality water of sufficient quantity will impose constraints on the types of mining and milling operation possible and limit the waste disposal options available to mining companies if environmental and resource protection requirements are to be met. For example, the environmental protection requirements for an acceptable uranium mining and milling operation in the semi-arid regions of south-central British Columbia could well differ from those in the high rainfall coastal areas.

In order to determine if, and under what conditions, uranium mining and milling should proceed, detailed environmental impact assessments of each proposed mining and milling operation should be conducted. These assessments should be carried out by proponent companies under the direction of regulatory authorities, and should examine in detail the site selection, construction, operation, maintenance and shutdown phases of proposed mine/mill complexes. Existing environmental features of the proposed mine/mill sites such as proximity to population centres, climate, terrain, water quality and quantity, fish and wildlife, land and resource use values should be examined. The potential short and long-term environmental impacts on the environment should be identified, along with options available to minimize or mitigate them. Data gaps which prohibit the identification of specific impacts should also be identified.

The decision of whether or not a proposed uranium mine and mill should proceed and how it would be operated should depend upon the nature of the environmental impacts identified in the assessment, the degree of risk associated with all phases of the proposed development, and the mitigative measures available. Any proposed mining and milling operation which is allowed to proceed, should also be required to carry out a comprehensive environmental monitoring program.

4 ENVIRONMENTAL MONITORING REQUIREMENTS

4.1 Objectives

An adequate program must accomplish the following objective:

To provide an assessment of the adequacy of the control measures to reduce contaminant discharges and to protect the environment by:

1) establishing that individual members of the population are not, as result of the operation of a mine/mill, exposed to environmental radioactivity at levels in excess of those stipulated by the appropriate national regulations,
2) demonstrating compliance with regulatory standards on water quality and air quality, and

3) assist in the validation or refinement of environmental models developed, at times, in the absence of environmental data.

This objective inherently prescribes the necessity of documenting: pre-operational environmental conditions against which operational monitoring data may be evaluated; an operational environmental program to provide surveillance of possible trends in environmental degradation; and a post-operational program designed to provide continued assurance that shutdown measures are adequate to protect public health and the environment on a long-term basis.

4.2 Monitoring Program Design Considerations

Generic radiological program design considerations are discussed fully in reference 1 and non-radiological monitoring considerations for the mining industry are provided in reference 82. The purpose for environmental monitoring is to assess the impact of a given mining operation at a given location based on the monitoring data collected and to use that data as a basis for future course of action regarding the operation of that facility. The monitoring program should therefore be carried out with the understanding of the potential impacts as well as the existing physical environment around the facility.

The design of an environmental monitoring program to respond to the objectives stated earlier requires considerations of a number of factors: identification of critical pathways by which potentially significant radionuclides may ultimately deliver radiation dose to man and other organisms; potential build-up of radioactivity in the environment and its long term impact; sampling and analytical procedures to accurately evaluate the levels of radioactivity in various pathways; and a flexible program able to adapt to a changing environment.

All uranium mining operations result in emissions and liquid effluents; however, the nature and amount of pollutants (radioactive and non-radioactive materials) in the discharges vary greatly from one operation to another. The sampling media analysis and the necessary analytical sensitivity requirements will largely depend upon the nature and the quantities of contaminants in the effluents.

The potential exposure pathways dictate the sampling media. In this regard the various reservoirs of the environment, i.e., air, water, soil, food, and sediments should be considered as the appropriate media for monitoring purposes. The locations of the sample collection are to be selected such that the results of the monitoring are representative of the actual concentration of the contaminants in the sample medium. The frequency of sampling is determined by the importance of the pathway concerned, the half-lives of the radionuclides and the variability of contamination levels with time. In general, continuous monitoring is required when there may be wide or rapid variations in the concentration or nature of the radioactivity discharged. The type of analysis and measurement methods should be designed to cover at least the radionuclides that are significant from the radiation protection point of view and, in any case, the specific radionuclides known to be present in the ore and subsequent effluent discharges. Gross radioactivity measurements are acceptable when the activities released are so low that a comprehensive analysis of the specific radionuclides is not feasible or not necessary; but some confirmation is needed that the levels are low. These gross activity measurements are simple to perform but the results are difficult to interpret in a quantitative manner.

4.3 A Recommended Generic Environmental Monitoring Program

In order to identify and quantify any changes in environmental quality that might occur as a result of a uranium mining and milling operation, an environmental monitoring program should be mandatory for each uranium mine and mill scheduled for operation.

The monitoring programs for any nuclear facility is designed and carried out in three major phases, i.e., pre-operational, operational and post-operational phases. Detailed discussions on the essential components of these different phases for uranium mining/milling facility is included in reference 1. The basic considerations are summarized as follows:

(a) Pre-operational Monitoring Programs

The pre-operational monitoring program should commence at least two years prior to major site construction and should be designed to provide complete baseline data on the site and its environmental components and their variability over time. This is not to be confused with an "Environmental Impact Assessment" although it may be carried out coincidently and become part of any pre-startup "Environmental Impact Assessment". Particular emphasis should be placed on the physical parameters governing contaminant transport in atmospheric and aquatic systems and provide statistically significant measures of how air and water quality can be affected by effluents and emissions from an operation. Common aquatic parameters examined include dissolved and total radionuclides, suspended and total solids, dissolved oxygen, temperature, pH, conductivity, turbidity, alkalinity, concentrations of specific toxicants such as heavy metals, ammonia or process reagents, and biological nutrients such as phosphates and nitrates. Atmospheric monitoring should provide pre-production documentation of such parameters as annual rainfall and evaporation, snow depths, background levels of aerial particulates, radon gas and sulfur dioxide. Soil and sediment monitoring should include background measurements on particle size, pH, and radionuclides and heavy metal levels. Aquatic flora and fauna (i.e., algae, benthos, fish, macrophytes) and terrestrial flora and fauna (i.e., crops, grasses, wildlife) monitoring may require full documentation of their abundance, species diversity, habitat requirements, as well as background levels of radionuclides and heavy metals in their tissue.

(b) Operational Monitoring Program

The operational monitoring program should be a logical extension of the pre-operational program and should contain generally the same basic elements as those indicated in the pre-operational phase, but with increased emphasis on certain sampling media. The program must be tailored to each specific site and should continue until the tailings are eventually stabilized. A generic monitoring program designed to meet the basic considerations discussed earlier and to act as a guide for site-specific monitoring is presented in Table 3 (1).

The monitoring program implemented at a particular site should be reviewed periodically, every two or three years, and modified in terms of scope and intensity (i.e., sampling locations and frequency) based on the observed levels and actual or potential impact on public health and the environment. The program should be maintained to verify or refute assumptions upon which some of the program itself is based, to verify the analysis of the critical pathways for the appropriate radionuclides and to demonstrate compliance with the applicable regulations.

(c) Post-operational Monitoring Program

The post-operational monitoring which follows upon the termination of mill operation is aimed at following trends and evaluating on a continuing basis, public health and environmental effects. In the aquatic environment, continued leaching of radioactive materials from tailings is potentially a long-term problem. The migration of radioactivity in groundwater is yet another concern on a long-term basis. The level of monitoring required over the long-term will depend upon the practice of tailings waste management and the degree of stability achieved. The primary mode of isolating the tailings will continue to be physical barriers, and the post-operational monitoring represents an additional means whereby any violation of isolation could be detected in time to implement appropriate

TABLE 3

OPERATIONAL ENVIRONMENTAL MONITORING PROGRAM FOR URANIUM MINE/MILL SITES

Sample Media	Sample Collection				Sample Measurement		Comments
	Location	Method	Frequency	Number	Frequency	Analysis	
AIR							
Particulates	At or near the site boundaries and in different sectors predicted to have the highest concentration of airborne particulate	Continuous	Weekly filter change or as required by dust loading	Two to four	Quarterly composite of weekly samples	wt. per unit volume of air U(nat), Ra-226 Pb-210, Th-230 Metals	Site boundary locations to be chosen along the direction of prevailing wind. If the content of the ore is high, analysis for Th-232, Th-228, Ra-228 should be carried out. Metals dependent upon their appearance in the ore or as reagents.
	At or close to the nearest residence(s) or occupied structure(s) within 5 km	Continuous	As above	One or more	As above	As above	
	Control location(s) remote from site at approx. 15 km from site	Continuous	As above	One	As above	As above	Measurements of samples at a control location should be representative of background levels of radioactivity in air in the area.
Radon	Same locations as for air particulates	Continuous for at least 1 wk	One week per calendar month	Four or more	Monthly	Ra-222	
SO_2	Same locations as for air particulates	Continuous	24 hour	One	Monthly	SO_2	If sulfur contained in dryer fuel or use of acid leach

TABLE 3 (continued)

OPERATIONAL ENVIRONMENTAL MONITORING PROGRAM FOR URANIUM MINE/MILL SITES

Sample Media	Sample Collection				Sample Measurement		Comments
	Location	Method	Frequency	Number	Frequency	Analysis	
WATER							
Ground Water	Wells located around tailings disposal area. At least three locations hydrologically downgradient	Grab	Monthly	Six or more	Monthly (for the first year of operation) Quarterly thereafter	U(Nat), Ra-226 Pb-210, Th-230, Also Radon-222 pH, SO_4, NO_2 NO_3, Heavy Metals, process reagents	Metals dependent upon their appearance in the ore or used in mill process.
	Wells used for drinking water supplies, watering of livestock or crops	Grab	Monthly	One from each well	Quarterly composite	U(Nat), Ra-226 Pb-210, Th-230	Both suspended and dissolved concentrations should be determined.
	Control location hydrologically upgradient (i.e. not influenced by seepage from tailings	Grab	Monthly	One	Quarterly composite	as above	
Surface Water	Lakes, pond and streams which are close to the site and subject to surface drainage from potentially contaminated areas or which could be influenced by seepage from tailings disposal area.	Grab	Monthly	One from each location	Monthly	Suspended solids, total dissolved solids, D.O., temp., pH, conductivity, turbidity, alkalinity, Heavy Metals, NH_3, NO_2, NO_3 PO_4, SO_4, U(nat), Ra-226, Pb-210, Th-230, and process reagents.	Suspended and dissolved concentrations. In general for river sites, samples should be taken at one upstream and several downstream locations at approx. 0.1, 0.5, 1, 5 km. If discharge to a lake, surface, hypolimnion, epilimnion and bottom, on a grid pattern should be sampled.

TABLE 3 (continued)

OPERATIONAL ENVIRONMENTAL MONITORING PROGRAM FOR URANIUM MINE/MILL SITES

Sample Media	Sample Collection				Sample Measurement		Comments
	Location	Method	Frequency	Number	Frequency	Analysis	
Drinking Water	At drinking water intakes stations known or judged to be affected by site operation, after water treatment. Tap water is satisfactory if source of tap water is identified.	Grab (or 5 litres)	Weekly	One per station	Monthly composite	As above plus gross alpha	The information will permit prompt corrective action if Ra-226 or total radioactivity unexpectedly increases significantly. Dissolved and suspended activity should be measured.
Tailings Pond Discharge	Overflow from final settling pond.	Grab. 1-2 litres	Weekly	One per location	Weekly	Ra-226, gross alpha	This may be considered as effluent rather than environmental monitoring. Sampling problem to be considered are: a) size of filter for filtering, b) grab vs continuous sampling, c) reporting of total vs dissolved content.
					Monthly	As per surface water	Provides accurate comparisons for surface water quality degredation and contaminant source identification.

TABLE 3 (continued)

OPERATIONAL ENVIRONMENTAL MONITORING PROGRAM FOR URANIUM MINE/MILL SITES

Sample Media	Sample Collection				Sample Measurement		Comments
	Location	Method	Frequency	Number	Frequency	Analysis	
Vegetation	From animal grazing areas near the site operation	Grab	Quarterly during spring	Three to six	Quarterly	U(nat), Ra-226, Pb-210 and selected heavy metals	Sampling need to be carried out only if dose calculations indicate that the ingestion pathway from grazing animals is a potentially signficant exposure pathway.
	As above	Transects	Annually	Six	Annually	Volume, abundance, species diversity	Provides annual assessment on impact on ground cover.
Algae	Collected from lakes, rivers & streams in the site environs. At or near surface water sample locations	Grab, Stockner, artificial substrate, etc.	Annually	Two at each site	Annually	Dryash wt. Chlorophyll-a, species diversity, evenness, Ra-226	For river sites periphytic algae of importance Discharges to lakes detailed sampling of phytoplankton to depth of photic zone.
Benthic invertebrates	As above	Grab, surber, Hess, dredge, artificial substrate, etc.	Annually	Six at each site	Annually	Abundance, evenness, Species diversity, pollution tolerance groupings, Cu, Pb, Zn, Ra-226	
Fish	Collected from lakes, rivers and streams in the site environs	Grab, electro shoking, nets, or weirs	Annually	five to ten samples of predators and bottom feeders (resident)	Annually	U(nat), Ra-226, Pb-210, Th-230, Cu, Pb, Zn, Hg, As, Species, age, sex	Fish flesh is generally analysed unless habit survey shows that whole fish is consumed.

ABLE 3 (continued)

OPERATIONAL ENVIRONMENTAL MONITORING PROGRAM FOR URANIUM MINE/MILL SITES

Sample Media	Sample Collection				Sample Measurement		Comments
	Location	Method	Frequency	Number	Frequency	Analysis	
Food	Crops, livestock etc. raised at 3-4 locations within 5 km of the site.	Grab	Annually at harvest time	Three of each category	Annually	U(nat), Ra-226 Pb-210, Po-210 Th-230	
External radiation	Same as for air particulates	Passive integrating device (TLD) or radiation survey meter	Quarterly	ten or more	Quarterly	Integrated gamma-ray exposure	
Sediment	From contaminated lakes and surface streams at locations which favour sedimentation	Grab	Annually	Two from each location	Annually	U(nat), Ra-226, Pb-210, Th-230 Heavy Metals	Metals dependent upon their appearance in the ore.

environmental protection measures. The monitoring program, however, is not intended to replace physical barriers as the primary means of tailings isolation and environmental protection.

5 CONCLUSIONS

1. The irradiation of living organisms from the radioactive substances contained in uranium mine/mill discharges can cause chronic or late effects of the genetic and somatic type. These effects are difficult to observe and to discern from the natural occurrences of such effects.

2. Risk estimates for stochastic effects are better understood in man than in other living systems mainly because the study of stochastic effects is of more relevance to public health concerns than to ecological protection. Environmental radiation protection standards set to protect human populations will also protect other species in the environment but only if secondary standards take into account the short and long term complexities of the ecosystem.

3. Scientists are not in agreement as to whether or not a threshold of dose of radiation below which there is no effect can be established for late effects. We believe that rejection of the threshold concept is prudent since the lack of experimental evidence cannot rule this out.

4. The aquatic, terrestrial and atmospheric ecosystems provide transport pathways which can result in the bioaccumulation of radioactive compounds and may in turn result in appreciable doses of radiation to man or other species.

5. Although most of the radionuclides released to the aquatic environment from mining and milling operations are of potential biological significance, it is radium-226 that is of greatest concern. This is because the dose that will ultimately be delivered to humans via the consumption of fish and the drinking of water will be more significant than for other radionuclides. Because the uptake of radium by fish is not inconsequential and because salmon are of such importance in British Columbia, radium-226 is of potential concern to salmon, especially egg, alevin and fry stages.

6. In areas of limited water resources, higher population densities and mountainous terrain such as those encountered in parts of British Columbia, aquatic releases of radioactivity and other pollutants may result in comparatively higher environmental impacts than have been measured in Ontario and Saskatchawan.

7. The radionuclides of primary concern in atmospheric emissions are radon and radioactive particulate matter. The important pathways of consequence are direct external exposure and inhalation to the lungs where the radon decay products release their alpha energy to tissues of the respiratory system. In British Columbia, where population centers are often close to potential mine sites and where mountainous terrain can prevent rapid dispersal and dilution of radon, these concerns may be of greater significance than in other areas of Canada.

8. Radiosensitivity of aquatic organisms varies among taxa and with age, with teleosts being the most sensitive known taxa of aquatic organisms and younger organisms being more sensitive than older.

9. The effects of radiation on aquatic organisms is influenced by environmental factors such as temperature and salinity, and by the combined effects of these factors.

10. Internal dose rates calculated for fish, aquatic plants and invertebrates exposed to radionuclides from model uranium mines and mills are less than those known to cause adverse effects on populations of aquatic organisms. However, these calculations may not be good estimates of dose rates at specific locations in B.C. since they obviously have not considered the intricacies of the distribution of radionuclides in a specific environment such as found in B.C. and the subsequent exposure of aquatic organisms which depend upon the local physical, chemical, hydrological and biological conditions.

11. The distribution of radionuclides in the aquatic environment is affected by many factors including movement of water, sorption by natural materials, sedimentation, resuspension of sediments, leaching from sediments, accumulation by aquatic organisms and the presence of chemically similar isotopes or elements.

12. The sediment is the major sink for Ra-226 and probably for other radionuclides; however, aquatic plants and benthic invertebrates frequently contain higher concentrations or activities of uranium and Ra-226 than sediments but water and fish frequently contain lower concentrations or activities than sediments.

13. Internal dose from incorporated radionuclides are suggested to be the most important source of irradiation for plankton and fish. Beta- and gamma-radiation from radionuclides in the sediment is equally important as incorporated radionuclides with respect to benthos and demersal fish; the dose from radionuclides in water being least important.

14. Fish and shellfish exposed to effluents from uranium mines and mills may accumulate sufficient radionuclides to render them unsuitable for human consumption.

15. The non-radiological components of uranium mine/mill effluents can cause serious environmental degradation such as heavy metal contamination, pH depression, ammonia toxicity, habitat destruction, or eutrophication.

16. Heavy metals may be present in untreated uranium mine/mill wastes at levels which are toxic to aquatic organisms, metals can also bioaccumulate in aquatic organisms to unacceptable levels.

17. The pH of uranium mine/mill effluents can be directly toxic to aquatic organisms and can act synergistically by increasing the toxicity of other components in effluents.

18. Ammonia and other nitrogenous compounds in uranium mine/mill effluents can be toxic to aquatic organisms and may contribute to the increased eutrophication of receiving waters.

19. Detailed site-specific information is necessary to predict the impact on the environment of individual prospective uranium mining proposals.

20. A totally integrated monitoring program of the physical, chemical, biological and radiological receiving environment is essential.

21. The development of pre-operational, operational and post-operational environmental monitoring programs are highly site specific but design criteria necessitates the identification and adequate sampling (frequency and number) of potentially important contaminants, pathways, media, sinks and target organisms.

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