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Les enjeux de la filière uranifère au Québec
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Current knowledge, impacts and mitigation measures related to the exploration and mining of uranium deposits in Quebec: a summary

This summary was prepared for Quebec's *ministère du Développement durable, de l'Environnement, de la Faune et des Parcs* and *ministère des Ressources naturelles*

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FOREWORD

This summary was prepared for Quebec's *ministère du Développement durable, de l'Environnement, de la Faune et des Parcs* (MDDEFP) and *ministère des Ressources naturelles* (MRN) but is non-binding. It was prepared in anticipation of the *Bureau d'audiences publiques sur l'environnement*'s upcoming inquiry and public hearings pertaining to the environmental, social and economic impacts of uranium exploration and mining. The goal of this exercise is to inform the public on the issues at stake, consult them and guide the government in its thought process with respect to the future of this industry and environmental protection.

This report was put together by the DIVEX (Diversification of exploration in Quebec) innovation network, under the supervision of professors Georges Beaudoin (Université Laval), Dominic Larivière (Université Laval) and Michel Jébrak (UQAM). DIVEX is an innovation network supported by the *Fonds de recherche du Québec – Nature et technologies* (FRQNT). The DIVEX network comprises researchers and students from Quebec's seven universities that have experience and research programs in the field of mineral resources.

Any reference made to laws or regulations is for information purposes only. These references cannot be used to make decisions or to take action. Readers are thus called upon to refer to the original legal texts to obtain information that has force of law.

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1.1 URANIUM IN THE ENVIRONMENT

Uranium is a radioactive metal that has been naturally present in the environment since the Earth's formation. Very small amounts are found in soil and rocks, as well as in the food and water we consume. It is however more common in nature than gold, and estimates of the natural concentration in the Earth's crust average 2.7 mg/kg. Uranium is also present in natural waters, at concentrations on the scale of micrograms (µg) per litre (Table 1.1).

Table 1.1: Naturally-occurring uranium in the environment

Source	**Uranium concentration, in mg/kg[a] (ppm)**
Porous rock - limestone	2
Hard rock - granite	4
Earth's surface	3
Atlantic Ocean	0.003
Fresh surface water	< 0,001
Groundwater	(0.000) 001-2.6

[a] in mg/L for water *Sources: Vandenhove et al., 2010; GA, 2008.*

In the environment, uranium mainly occurs as uraninite (U_3O_8 or UO_2), an oxide, which is mined from deposits. Small quantities of uranium are also present in a variety of minerals that are more or less common in the Earth's crust.

Uranium occurs in the environment in both soluble and insoluble forms, and various natural processes can either increase or decrease its solubility. For instance, in natural oxidizing environments, that is to say in the presence of oxygen or of bacteria that promote oxidation, insoluble uranium can switch to a soluble form, which increases its mobility in soils and in natural waters (Figure 1.1).

$$UO_{2\ \text{(insoluble)}} \xrightarrow{\text{oxidation}} UO_2^{2+}{}_{\text{(solubilizable)}}$$

$$UO_2^{2+}{}_{\text{(solubilizable)}} \xrightarrow{\text{dissolution}} UO_2^{2+}{}_{\text{(soluble)}}$$

Figure 1.1 : Process of uranium solubilisation.

In its soluble form, uranium may be assimilated by certain living organisms such as plants, micro-organisms, animals and humans. Its impact on the environment is due as much to its chemical character, from being a heavy metal, as its radioactive character.

1.2 RADIOACTIVITY

Radioactivity results from the spontaneous disintegration of an atom's nucleus. The atom, which is an element's smallest component, consists of a positively-charged nucleus and of one or more negatively-charged electrons, which orbit around the nucleus (Figure 1.2). The nucleus is composed of protons (positively-charged particles) and neutrons (neutral particles, no charge). An element can have multiple configurations of the nucleus with different masses, called isotopes. Isotopes differ from one another by the number of neutrons in the nucleus. Each isotope is identified by the name of the element and the number representing the total mass of its nucleus. For instance, the three isotopes of uranium found in the environment are uranium-238 (99.274 %), uranium-235 (0.720 %) and uranium-234 (0.0056 %). These three isotopes form what we call *natural uranium*.

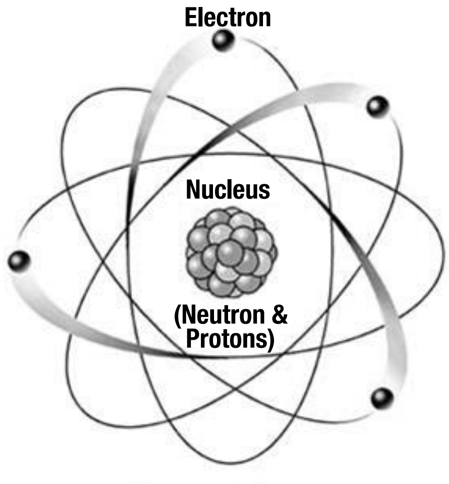


Figure 1.2: Schematic representation of an atom.

The isotopes of natural uranium have unstable nuclei and decay to elements of lower mass as they seek to achieve a more stable state. These radioactive isotopes are termed radioisotopes or radionuclides. Nuclear decay may generate a new, unstable nucleus, which in turn will seek to achieve a stable state, again leading to nuclear decay. This series of decays is what we call the *decay chain* of uranium, and the new isotopes formed are the *daughter products.* The decay chain of uranium-238 comprises radioactive isotopes such as radium-226, radon-222 and polonium-210, which are metals, except for radon, which is a gas. Lead-206 is the final stable isotope for the decay chain of uranium.

Every nuclear decay releases energy in the form of ionizing radiation: this is radioactivity. The three most common types of ionizing radiation for radionuclides of natural origin are alpha, beta and gamma radiation (Figure 1.3).

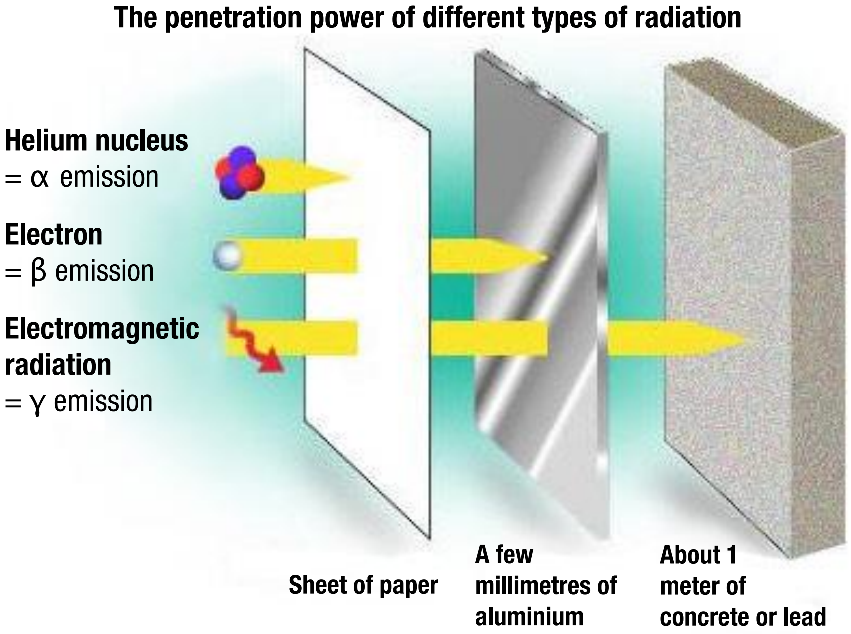
Alpha radiation (α) consists of a high-energy, positively-charged particle with a helium nucleus (He^{2+}). Its energy and size means it reacts with the very first molecules encountered in its path. Consequently, its energy is dissipated by a few centimetres of air or by a single sheet of paper. Alpha particles therefore do not penetrate the surface layer of living organisms. In humans, for instance, they are stopped by dead cells of the skin's outermost layer.

Beta radiation (β) consists of an electron ejected from the atom. It is less energetic than alpha radiation, but has a greater penetration power: it can travel through a few metres of air, and requires at least a sheet of plywood to be stopped. On average, it can penetrate 8 millimetres into living tissue.

Gamma radiation (γ) consists of high-energy photons, which are particles with no charge. This type of radiation is similar to light or X-rays and is extremely penetrative. The effect of gamma radiation can only be attenuated by thick layers of dense material such as lead or concrete.

Atoms of radioactive elements decay at different rates. The rate at which an atom decays is given by its **half-life** ($t_{½}$), the time required for half of the initial atoms to decay. For instance, the half-life of uranium-238 is about 4.5 billion years. Consequently, half of the uranium atoms that were present on Earth at the time of its formation have naturally decayed.

Figure 1.3: Types of ionizing radiation and their penetration power.



Source: IRSN, 2013.

The intensity of a radioisotope's radioactive radiation, or its activity, is given in **becquerels** (**Bq**). A becquerel is equivalent to one nuclear decay per second. The activity arising from uranium in the Earth's crust is about 40 Bq per kilogram of rock. Other primordial radionuclides, that is to say present since the Earth formed, contribute to the natural radioactive background noise. The main primordial radionuclides are, along with uranium-238, thorium-232 and potassium-40.

1.3 EXPOSURE TO RADIATION

The effect of ionizing radiation on living organisms occurs on the cellular scale. The energy from radiation excites molecules such that they gain or lose electrons, which interferes with cellular processes. Living cells have adapted to the presence of natural radioactivity since they started evolving. In fact, they possess mechanisms to repair damage caused by ionizing radiation. However, if the damage is too great, the cells' defence mechanisms become ineffective. This can lead to cells dividing uncontrollably, which can result in the formation of a cancerous tumour.

The dose received by an organism represents the amount of energy from ionizing radiation absorbed per amount of tissue. This measurement of exposure is the *effective dose* and is expressed in **sieverts (Sv).** It accounts for the type of radiation received (alpha, beta or gamma) and the irradiated tissue's sensitivity (reproductive organs, for instance, are more sensitive to ionizing radiation than skin). The effective dose limit, from a non-natural or medical source, is set by the Canadian Nuclear Safety Commission (CNSC) in the Radiation Protection Regulations. The effective dose limit is one millisievert per year (1 mSv/year) for the general public.

Human beings are constantly exposed to three sources of natural radioactivity: cosmic radiation, terrestrial radiation (including radon) and internal radiation from food. In fact, the plants and animals we consume also contain radionuclides because they are exposed to the same terrestrial sources of ionizing radiation. The United Nations Scientific Committee estimates that the dose from natural exposure is about 2.4 mSv/year. This dose varies according to food type and geographical location. For instance, the presence of cosmogenic radionuclides is greater at high altitude than at sea level. The World Health Organization (WHO) reports that at certain high-altitude regions, the dose from natural exposure can be as much as 24 mSv/year.

Human beings are also exposed to additional doses of radioactivity with an anthropogenic origin, that is to say generated by humans. Medical applications (such as X-ray examinations) are the main source of these doses, which amount to about 0.6 mSv/year in Canada. Other sources of anthropogenic radioactivity represent about 1 % of the total artificial dose and arise from, for example, nuclear plants and atmospheric dispersion due to past nuclear tests (Table 1.2). Exposure to natural radioactivity can be greater in some work environments, such as in the mining sector, where workers may be exposed to higher concentrations of natural radionuclides.

Table 1.2: Contributions from various sources of radiation in Canada.

Source		**Contribution (%)**
Natural (88 %):	Radon-222	48
	Gamma radiation	14
	Food (internal sources)	12
	Cosmic rays	10
	Radon-220	4
Artificial (12 %):	Medical applications	11
	Other sources	1

Source: BAPE, 2002.

2 CURRENT KNOWLEDGE OF URANIUM RESOURCES IN QUEBEC

2.1 GEOLOGICAL POTENTIAL OF QUEBEC

Uranium accumulates in several geological environments. In Quebec, four main types of uranium deposits have been identified:

- Sandstones are sedimentary rocks that are formed of old sands. The high permeability of these rocks makes it possible for deep uranium-mobilizing fluids to circulate. When uranium encounters natural barriers, such as redox fronts, it can accumulate. As such, uranium deposits of very high grade, occasionally grading up to 20 % uranium, are found at the base of sedimentary basins, as in Saskatchewan. There are deposits comparable to those in Saskatchewan in the Otish Mountains (three deposits containing uranium resources totalling approximately 16,000 t U).

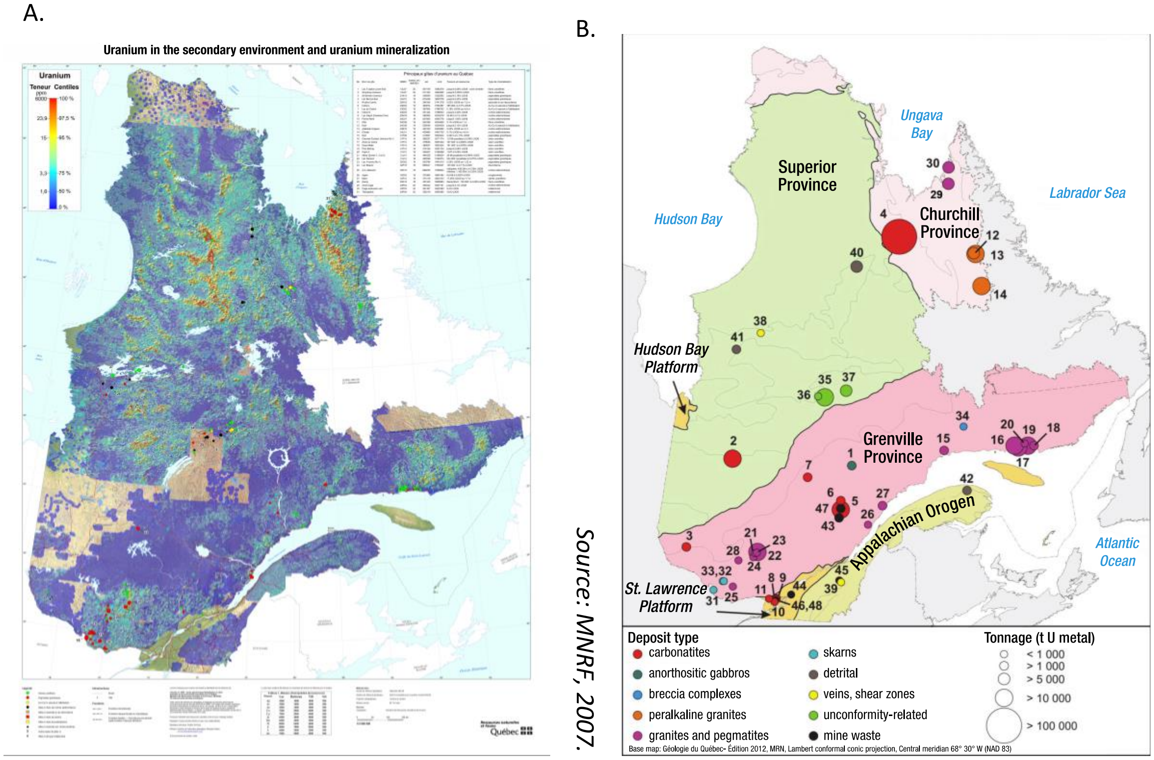
- Conglomerates are pebble accumulations of ancient river beds. During the Precambrian (46000 to 451 million years ago), there was very little oxygen in the atmosphere, so grains of uranium did not oxidize and due to their high density, accumulated at the bottom of rivers. Such deposits have been mined in South Africa and in Ontario. Deposits of this type are found in the James Bay area (two deposits with uranium resources totalling approximately 13,000 t U).

- Granites can accumulate uranium toward the end crystallization, creating high tonnage, low grade deposits, such as those in Namibia. Several small deposits of this kind are identified in the Basse-Côte-Nord, in the Mont-Laurier area and near Ungava Bay. Uranium resources total approximately 29,000 t U.

- The largest uranium deposit in the world, Olympic Dam, in Australia, is associated with ferruginous copper-gold-uranium breccias. Similar showings have been identified in Quebec, in the Basse-Côte-Nord and in Nunavik.

The uranium mineral resources listed in this inventory include all types of mineral resources that have been disclosed in public reports. The different types of mineral resources are not taken into account due to the heterogeneous nature of the data. We cannot presume that all or part of the mineral resources in this inventory will be mined in the future.

The map of uranium concentrations measured in sediments from the bottom of lakes (Figure 2.1A), created by the *ministère des Ressources naturelles* of Quebec, provides a computer-generated image of regional uranium concentrations in the surficial environment. The areas mentioned above are indicated in Figure 2.1 B., as are areas of concentration that are under-explored.



Source: MNRF, 2007.

Legend (Figure 2.1B): 1: Lac à Paul, 2: Montviel, 3: Kipawa (Zeus, Lac Sheffield-2), 4: Ashram (Eldor) / Erlandson No.1, 5: Niobec, Nb Mine, 6: Niobec REE project, 7: Crevier, 8: Manoka (Oka), 9: Oka, (Zone Bond, Wayfair), 10: St-Lawrence Colombium Mine (SLC), 11: St-André-2, 12: Strange Lake B Zone, 13: Strange Lake Main Zone (Lac Brisson), 14: Misery Lake, 15: Lac Kachiwiss, 16: North Shore / Turgeon, 17: Baie Quetachou, 18: Doran (Lacana), 19: Johann Beetz (Drucourt Est), 20: Lac Caron, 21: Tom Dick (Zone Nord 1), 22: Nova (or Renard or Allied (1-3), 23: Mekoos (or Bear, 3-3D), 24: Lac Hanson, 25: Lac Indien, Bain, 26: Lac Fafard, 27: Anomalie C11r4, 28: Capri-2, 29: Secteur North Rae, 30: Secteur Cage, 31: Grand Calumet / Calumet Contact N°3, 32: Zone Matte, 33: Zone de Camp, 34: Kwyjibo, 35: Matoush, 36: Lac Beaver / Zoran, 37: Lavoie / Indice L, 38: Ganiq, 39: Harvey Hill Cu mine, 40: Dieter Lake / Lac Gayot, 41: Apple, 42: Grande-Vallée, 43: Boues Rouges Usine Vaudreuil - Jonquière, 44: Phosphogypses, Varennes, 45: Harvey Hill, residues, 46: Mine SLC, residues, 47: Mine Niobec, slag, 48: Mine SLC, slag. Uranium showings without an estimate of prospective resources are not shown.

Figure 2.1: The Location of uranium resources in Quebec. A. A map of calculated Uranium concentration around the province using lake sediment samples and known uranium showings. B. A geological map of the province showing the various geologic domains, types of deposits and approximate size. The deposit names are listed in the legend.

Globally, Quebec possesses significant uranium resources. These resources are low and medium-grade uranium deposits. There is potential for high-grade deposits comparable to those mined in Saskatchewan but at present, these potential uranium resources are not being developed.

2.2 URANIUM EXPLORATION IN QUEBEC

Uranium exploration is carried out by two types of companies: (1) uranium mining companies, which are often vertically structured as to complete the full nuclear fuel cycle, from mining to reprocessing; (2) junior companies, small companies whose goal is to discover new resources; they can subsequently sell them to bigger companies or attempt to start production themselves.

Many large companies are or have been present in Quebec: Areva Resources Canada has claims in Ungava. Hathor Exploration, a subsidiary of Rio Tinto PLC, is present in the Otish Mountains. CAMECO, the largest Canadian company, has claims in Quebec, in the Otish Mountains for instance.

Quebec is known for its expertise in mineral exploration. Because the exploration techniques for this type of metal are comparable to those used for other metals, many small companies developed an interest in uranium exploration about ten years ago. In July 2013, Quebec had 48 active uranium exploration projects (Figure 2.1B), belonging to 26 separate companies: three projects were at the prefeasibility stage, two of for which uranium is the principle commodity, the third being for rare earth elements. In the Chibougamau area and north of Schefferville, eight were at the advanced exploration stage. There are many other projects at the grass-roots exploration stage that have not yet been drilled. Ressources Strateco is the promoter for the most advanced project in Quebec located in the Otish Mountains. There are about ten more or so small companies with diverse project portfolios that include uranium projects, most in northern Quebec. Approximately 70 % of these companies have their head office in Quebec, the others are located in Vancouver or Toronto.

2.3 USE OF URANIUM IN QUEBEC'S NUCLEAR POWER SECTOR

Nuclear power provides close to 15 % of electricity in Canada, and 40 % in Ontario. Canada has a fleet of 18 CANDU reactors (heavy water reactors) which were designed by Atomic Energy of Canada Limited (AECL). The Canadian nuclear industry provides direct or indirect employment to nearly 66,000 people. With a production nearing 10,000 tonnes of uranium in 2012, Canada ranks second among global uranium producers, behind Kazakhstan.

There is only one site for nuclear energy generation in Quebec, Hydro-Québec's Gentilly-2 power plant, in Bécancour. This nuclear plant was in service from 1983 to 2012, with a 2,156 MWt (thermal power) output, yielding a net electricity production of 635 MWe. Nuclear waste is stored on site in a pool, for a seven-year period. Montreal's *École Polytechnique* has a SLOWPOKE-2 nuclear research reactor; it is a small reactor containing 5 kg of uranium that is 20 % enriched in ^{235}U.

3 LICENCES AND AUTHORIZATIONS FOR URANIUM MINING PROJECTS IN QUEBEC

Licencing is key in controlling mining operations in Quebec, both from a land use and environmental perspective. The number of licences required is greater at the mining stage (and in preparation thereof) than at the exploration stage. Several steps are involved, as are many organizations at all levels of government.

The main ministries concerned are the *ministère des Ressources naturelles* (MRN) and the *ministère du Développement durable, de l'Environnement, de la Faune et des Parcs* (MDDEFP). The Mining Act and the Environment Quality Act form the main legal framework (Table 3.1). This is not an exhaustive list as federal and provincial laws also cover transportation, worker safety and other aspects of the mining industry in general and uranium mining in particular. For uranium mines, a federal agency, the Canadian Nuclear Safety Commission (CNSC), issues the certificates authorizing all activities that involve radioactive materials. Additional procedures and licences are thus required in conjunction to those under Quebec's legislation.

Everywhere across Quebec, uranium mining projects are subject to an environmental assessment, the nature of which depends on the procedure in the area concerned (e.g. north of the 55th parallel, south of the 55th parallel in the territory covered by the James Bay and Northern Quebec Agreement, the Monier area near Labrador, and southern Quebec). Compliance with the Canadian Environmental Assessment Act is also required.

The CNSC does not consider that uranium exploration poses a particular threat to public health and the environment. Therefore the CNSC is not involved before a project reaches an advanced exploration stage and excavation of rock for which radioactivity exceeds a certain threshold is required. However, good health and safety practices for people working in uranium exploration are outlined in the *e3 Plus* principles, a reference document developed by the Prospectors and Developers Association of Canada (PDAC) designed for voluntary implementation.

Aboriginal peoples are taken into consideration throughout the process. In fact, Canadian law recognizes the obligation to consult Aboriginal communities when ancestral rights are identified or claimed, and when operations could have a detrimental effect on these rights. In the case of uranium projects, the CNSC has certain regulations to solicit the input of Aboriginal communities. Furthermore, the Mining Act contains new provisions specific to Aboriginal peoples. Consideration of the rights and interests of Aboriginal communities is an integral part in reconciling mining operations with other possible land uses.

Table 3.1: Summary of the main federal and provincial laws and regulations applied throughout uranium exploration and mining.

Quebec jurisdiction		Federal jurisdiction
MRN	**MDDEFP**	**CNSC**
Mining Act	**Environment Quality Act (EQA)**	**Nuclear Safety and Control Act**
Exploration stage (Prospecting, drilling, sampling, access roads)		
Acquisition of mineral titles (claims). Implementation of regulations (e.g. Regulation respecting standards of forest management for forests in the domain of the State).	Compliance with laws and regulations. Authorization required in case of possible impact to the environment.	
Advanced exploration stage (Access roads and detailed deposit characterization, feasibility study)		
Licence for bulk sampling and approval of rehabilitation plan, if applicable.	Compliance with laws and regulations. If applicable, authorization required in case of possible impact to the environment and/or if activities take place in the James Bay and Northern Quebec territory.	Removal licence required.
Preconstruction and premining stage (Site preparation and layout, construction of infrastructure, underground or open pit design)		
Request for a Mining Lease: Proof of the mine's viability; Approval of the rehabilitation plan; Submittal of a feasibility study and of financial and market opportunity analyses.	Implementation of the environmental assessment procedure (Division IV.1 of Chapter I of the EQA and Chapter II of the EQA): Completion of an environmental impact study; Information sessions, public consultations and potential public hearings; Environmental assessment report; Issuance of a certificate of authorization (CA) in compliance with section 31.5, 164 or 201 of the EQA. Issuance of a CA in compliance with section 22 of the EQA prior to construction and mining.	Completion of the study on potential environmental impacts and mitigation measures. Issuance of a site preparation licence and construction licence. Issuance of an operating licence.
Mining stage		
Rehabilitation plan update.	Request for a depollution attestation. Implementation of an impact surveillance program allowing to monitor compliance with regulations and conditions of authorization	Control measures in order to ensure compliance with regulations and conditions as per the licences.
Site closure, rehabilitation and monitoring stage		
Site security; Implementation of the rehabilitation plan	Environmental monitoring for as long as waste is present; Implementation of a soil rehabilitation plan, if applicable.	Issuance of a decommissioning licence. Issuance of an abandonment licence.

4 INVENTORY OF THE URANIUM SECTOR'S POTENTIAL IMPACTS

4.1 BIOACCUMULATION OF URANIUM IN THE FOOD CHAIN

Some living species have the ability to bioaccumulate, that is to say they can absorb rare chemical substances found in the environment within their organism, such as radionuclides. These substances can be absorbed directly from the surrounding environment, or from food.

Due to its low solubility, uranium bioaccumulation in plants in generally unfavourable. It can however be accumulated by some marine organisms, such as crustaceans.

There are various ways for an organism to absorb an element; the pathway refers to the route taken by an element to an organism. In plants, the main pathway for uranium is by way of the roots, whereas in animals and humans, it is by ingestion.

A solid understanding of the pathways makes it possible to assess whether radionuclides are present within various living organisms, and to anticipate potential impacts related to their disposal in the environment, for instance during mining operations.

4.2 URANIUM TOXICITY

In animals and humans, the chemical toxicity of uranium results from absorption of the contaminant within the organism, either through inhalation or ingestion. The digestive pathway is the most common absorption pathway given the presence of uranium in our food and drinking water. Laboratory studies have demonstrated that, when ingested, gastrointestinal absorption of uranium is low, typically less than 5 % of ingested uranium. The majority of ingested uranium is therefore not absorbed by the organism and is primarily expelled through urine. However, of the amount that is absorbed upon crossing the intestinal barrier (< 5%), a significant portion accumulates in the kidneys. Studies have shown that the chemical toxicity of uranium essentially becomes renal complications/failure. In these studies, toxic effects are observed in laboratory animals when the amount of uranium administered daily, is 5,000 times greater than the maximum daily amounts ingested by the average Canadian population.

Moreover, many studies on uranium toxicity were carried out in laboratories under controlled conditions whereby plant species were exposed to high uranium concentrations. These studies have shown that the toxicity of uranium in plants manifests by a loss in biomass or by a slowdown in growth.

The intensity of an element's radioactive radiation, or of its activity, is expressed in **becquerels** (**Bq**). A becquerel is equivalent to one nuclear decay per second. The activity arising from uranium in the Earth's crust is about 40 Bq per kilogram of rock. In terms of radiotoxicity, natural uranium is a weakly radioactive radionuclide. It emits only a weak amount of alpha radiation due to the long half-life (4.5 billion years) of its main isotope, uranium-238, which makes up more than 99 % of natural uranium. The activity of natural uranium is approximately 25,000 Bq per gram. This means that one (1) uranium atom out of every 1×10^{17} decays every second. This amounts to comparing the mass of a human cell to that of a blue whale. As such, the radiotoxic character of uranium is insignificant compared to its chemical toxicity.

However, despite the weak radiotoxicity of natural uranium, underground uranium mining leads to accumulations on the surface of some of its more radioactive daughters, such as radium-226. The radiotoxicity of these daughters is greater than the radiotoxicity of uranium. For those working in the uranium industry, inhalation is the most common pathway for radionuclide absorption. When extracting uranium ore, radionuclide particles in suspension can be inhaled. In this case, the soluble particles will be dissolved by lung secretions and be circulated by blood thoughout the rest of the organism, after which they will follow the same biological route as particles entering the organism through the digestive track. Insoluble radioactive particles can however remain inside the lungs for long periods of time, and transmit higher radiation doses than those produced by soluble particles that are ingested and then, for the most part, eliminated.

Radionuclides can also enter the organism through inhalation of radon, a product generated by the decay of natural uranium with a half-life of 3.8 days, which represents the most significant source of natural exposure to radiation for human beings. Because it is an inert gas, that is to say devoid of chemical reactivity, it can easily migrate away from fissured rock in the bedrock, or from dust particles in the ambient air (radon cannot escape from solid, unfractured rock, where it remains confined). Inhaled radon that does not decay inside the lungs is expelled upon exhalation. However, radon atoms that have decayed by means of alpha emission become solid daughter products, such as polonium-218 and lead-214, which will in turn emit ionizing radiation.

Many studies have demonstrated that long-term health effects in miners will manifest if protective measures are inadequate. For instance, exposure to radon concentrations that exceed natural levels increases the risk of developing a form of lung cancer and decreases life expectancy. Fine dust particles in the air also represent an occupational health risk. Exposure to these particles is linked to an increase in serious health problems in humans, such as cardiovascular or respiratory diseases.

4.3 OVERVIEW OF MINING STAGES

Activities related to mineral exploration and mining, including uranium deposits, are divided into several stages, and each stage represents a certain risk that radionuclides or other heavy metals will be discharged into the environment.

The first stage is mineral exploration, which consists in looking for new uranium deposits. This is done using various techniques, some being non-intrusive (such as geophysics), and others requiring major or minor excavation work during advanced exploration, such as drilling boreholes or the construction of access ramps.

The next stage is mining of the ore. In Canada, the traditional mining technique consists of excavating the ore by fragmenting it in underground or open pit mines (Figure 4.1).

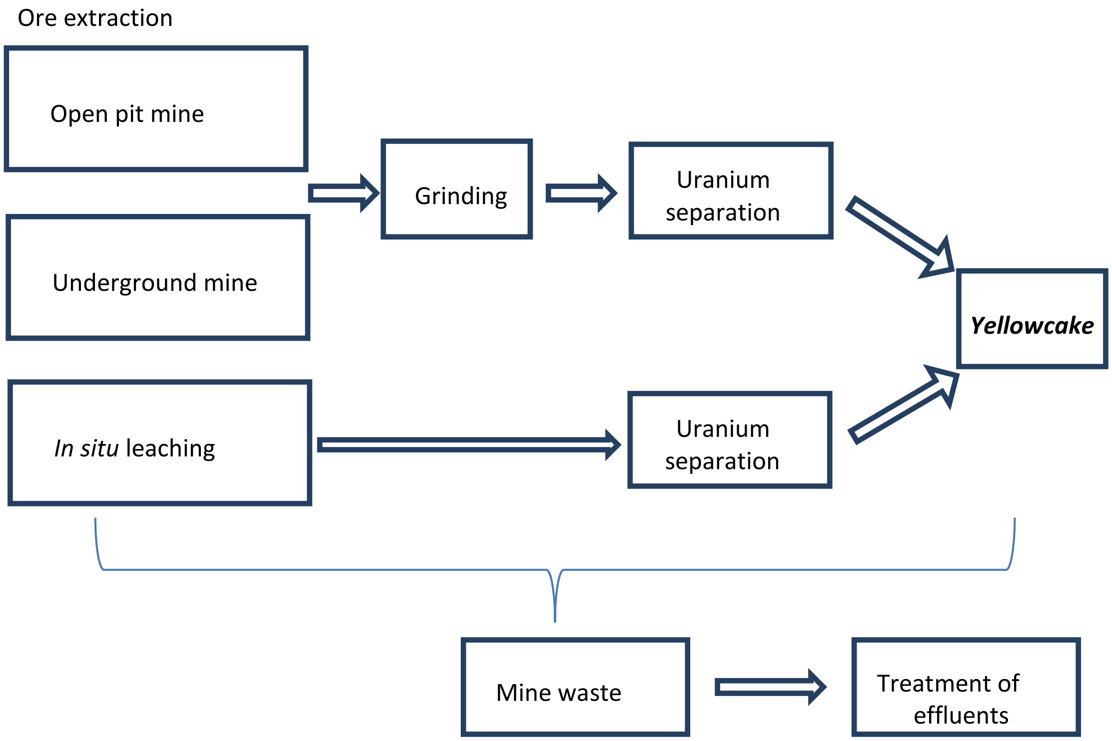


Figure 4.1 : Extraction and transformation of uranium ores

When excavating, rocks are removed in order to access the deposit. These are often called waste rock, which are rocks in which the uranium concentration is at or below natural levels and poses the same risks as waste rock from any other type of mine. They may be stored separately, and some may later be reused. Special mine waste is waste rock that does not contain enough uranium to be considered ore, but the concentration of uranium and radioactive daughters is such that designated storage is required.

Once extracted, uranium ore is ground and the uranium compounds are put into solution using acid. Uranium separation is done in a processing plant, typically located close to the mine. A uranium oxide is produced, termed *yellowcake* (Figure 4.2).

Figure 4.2: Yellowcake powder.

Source: Wikipedia *(http://de.wikipedia.org/wiki/Yellowcake).*

Uranium separation generates plant tailings that contain radioactive daughters. These tailings retain a large part of the ore's original radioactivity, generated over the course of uranium's prolonged nuclear decay, which took place prior to its extraction from the bedrock.

Once mining operations come to an end, either due to resource depletion or unfavourable economic conditions, the mine site must be restored. At this stage, drill holes and excavations are cemented/backfilled, and surface infrastructure is dismantled. Special waste rock and tailings are stored in such a way to prevent environmental contamination, either in tailing facilities or in abandoned pits adapted for this purpose.

4.3.1 EFFLUENTS

Effluent consists of wastewater that is collected over the course of mining operations and stored in staging ponds prior to treatment. Effluent can include water used in mining, rainwater collected on site, or solutions used during the uranium separation process. The treatment used is specific to each site.

Wastewater treatment reduces the concentration of radionuclides, heavy metals and suspended solids. This can be done by adding chemical compounds, such as lime or flocculants, that cause radionuclides to precipitate and may be extracted from the water by filtration or sedimentation. After being treated, wastewater is sampled and thoroughly tested. It must meet environmental standards before being disposed of.

4.3.2 AIR EMISSIONS

Air emissions occur at every stage of mining operations. The excavation of special waste rock, which contains uranium and its daughter products, leads to emissions of radon and dust into the mine environment. High radon concentrations may be observed inside underground installations, as well as in exhaust air.

Surface disposal of special waste rock also generates air emissions, especially if stored at surface without protection against wind erosion. Plant tailings, which contain 70 % to 85 % of the radioactive material found in the original ore, emit gamma radiation and radon gas.

4.4 ENVIRONMENTAL RISKS RELATED TO URANIUM MINING

In the absence of adequate control procedures and treatments, significant environmental impacts will occur following uranium extraction. Radioactive contamination of soil and natural waters can occur when radionuclides are disseminated in the environment, which is possible if contaminated effluents are discharged in the environment, or if waste rock and plant tailings are mismanaged.

Solid waste stored at surface contains radionuclides, which may infiltrate the ground via rainwater. Some waste rock and tailings may generate contaminated mine drainage, such as *acid mine drainage*, which occurs when rocks containing metal sulphides are oxidized by ambient air. In the presence of water or air, these sulphides form sulfuric acid, which has the ability to solubilize many metals in the ore, including uranium.

5 MEASURES TO PROTECT THE ENVIRONMENT IN THE URANIUM SECTOR

5.1 ENVIRONMENTAL MANAGEMENT PROGRAMS IN CANADA AND ABROAD

In the past, there have been significant ecological impacts due to the absence of control measures and inadequate treatment of mine waste and effluents. This was due to the procedures implemented globally that differ significantly from those implemented today, and that health and environmental impacts of radioactive substances were poorly understood. Between 1920 and the end of the 1950s, radioactivity intrigued people and was a symbol of modern times. Radioactive cosmetic creams containing radon were even marketed and sold over the counter in Europe and North America. The lack of scientific knowledge as to the hazards related to radioactivity and the absence of control measures had a negative impact on the health of miners, impacts which were often related to radon exposure.

In order to avoid health and environmental damage related to uranium exploration and mining activities, mining companies and some governments, including Canada and Quebec now practice planning and prevention. Mine sites are developed under very different conditions from the past. Today developers of a resource must consider environmental and social factors that were previously ignored or unknown, in addition to the financial factors. For instance, the rehabilitation of mine sites is often undertaken at the start of mining operations and is ongoing throughout the mine's life in order to minimize the environmental footprint of the mine. Progressive rehabilitation also makes it possible to adapt environmental protection and rehabilitation methods to new technologies and new information and can protect against long-term contamination risks.

To structure this preventative approach, Western mining companies have implemented environmental management programs, such as certification to ISO 14001, which provides a framework for environmental impact management within dynamic system. To maintain this environmental certification, which must be renewed every three years, mining companies must periodically subject themselves to independent audits.

In Canada, the Canadian Nuclear Safety Commission (CNSC) regulates the presence of radionuclides and sets concentration limits. The CNSC also oversees radiation protection measures, that is, procedures applied in order to ensure that workers and the general public are protected against the potentially harmful effects of ionizing radiation. For instance, it monitors the mandatory use of a dosimeter, an instrument records and calculates radiation doses received during a work shift.

5.2 PREVENTION AND MITIGATION MEASURES

Environmental impacts related to mining are mainly caused by the significant volume of rock that must be excavated and the accumulation of rocks at surface, as well as to the accumulation of plant tailings and industrial effluents. Waste rock and tailings increase the risk of exposure to gamma radiation, radon and dust, and increase the risk of radionuclide dispersal in the environment. Consequently, protective measures are now implemented in order to control air emissions and contaminated effluent.

5.2.1 AIR EMISSIONS

The protection of employees against air emissions relies on measures such as confining the ore throughout the various steps of grinding, transportation and processing. In this respect, operators of high-grade uranium mines have instilled extraction techniques that minimize contact between workers and the ore: remotely-controlled mining equipment may be used, and ore is confined in shielded underground conduits during the various extraction processes which reduces emissions of gamma radiation and dust. Radon released in underground tunnels is expelled by ventilation systems. These are designed to renew underground air, such that the workers' exposure is a minimum. Radon is then diluted at the surface by natural ventilation, and radon concentrations recorded on mine sites can be comparable to regional concentrations.

5.2.2 EFFLUENT

The contamination of natural waters is the main pathway for the dissemination of radionuclides in the environment. As such, all the water that is used on mine sites is recovered and treated, which lowers the concentrations of radionuclides, heavy metals, suspended solids and dissolved salt concentrations below the maximum allowable concentrations set by the government. Surface water and groundwater are monitored during mining operations so that the risk of radionuclide accumulation in living organisms, such as fish and aquatic plants that populate nearby waters, can be assessed.

5.2.3 WASTE ROCK AND TAILINGS

Mine waste confined to disposal facilities, contains radionuclides that can leak into the environment during episodes of rain or snow precipitation. Runoff from the tailings disposal facility is collected by a drainage network and transported to a treatment plant.

During mining operations and mine site rehabilitation, waste rock and plant tailings can be covered with water or materials that resist erosion to form a barrier between waste and the atmosphere. This barrier reduces the risk of radionuclide dispersal as well as external exposure due to emissions of radon and radioactive dust. It also absorbs an important part of the gamma radiation emitted.

5.3 PREVENTION AND MONITORING

Before beginning advanced exploration activities or mining operations, mining companies carry out field analyses to characterize the site's biophysical environment. The soil's chemical composition is determined and surface water and groundwater are sampled and monitored.

Once the most appropriate uranium extraction and processing methods have been selected, an environmental monitoring program is developed to reduce the risk of potential contamination and to limit environmental impact. For instance, the quality of surface water and groundwater is monitored in order to prevent the accumulation of radionuclides in living organisms that populate nearby waters and sediments.

A program to supervise and monitor air emissions has been implemented at the Cluff Lake mine site in Saskatchewan, which was mined for more than 20 years, until being decommissioned in 2002. This type of monitoring allowed the CNSC to assess the mean effective dose received by employees from 2001 to 2007. Figure 5.1 demonstrates that radioactive dust and radon dust considerably decrease once mining operations ceased (2002), becoming negligible from 2006 onwards.

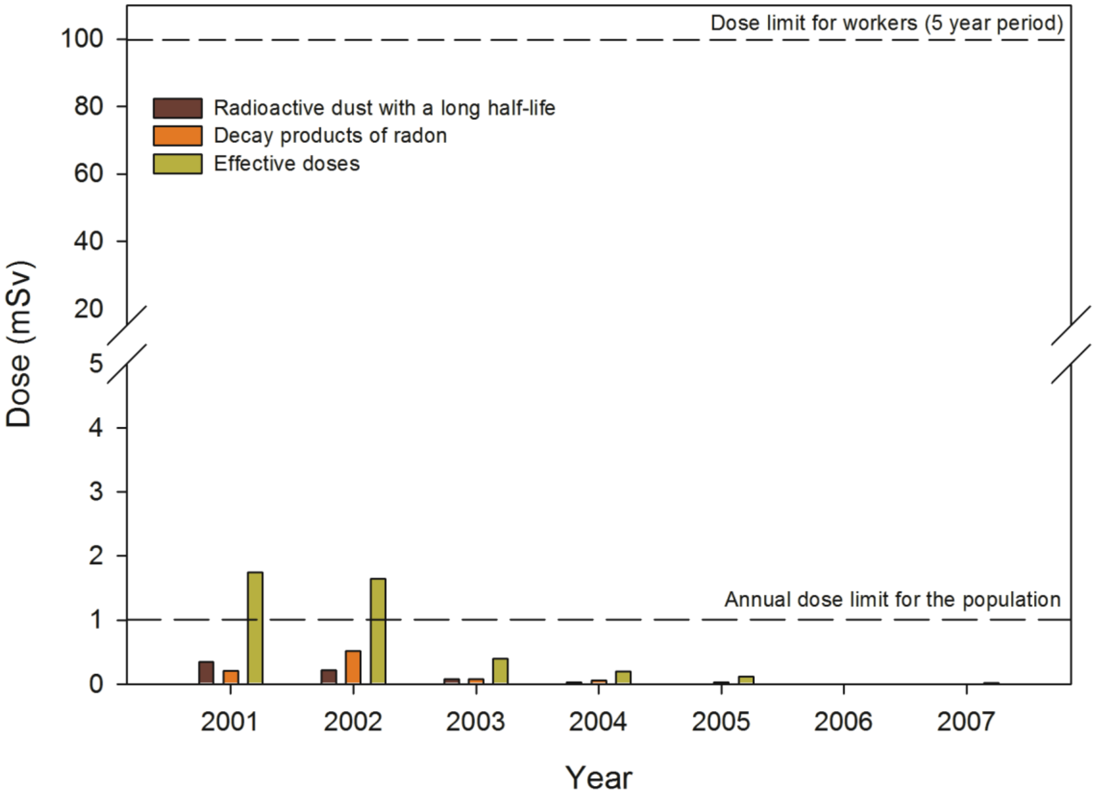


Figure 5.1: Trend for mean dosage received at the Cluff Lake mine from 2001 and 2007.

Source: CNSC, 2009.

The Canadian government closely regulates mine sites on an ongoing basis during operations, as well as years after the end of operations.

5.3.1 MINE SITE RADIOACTIVITY

Radioactivity measured at mines varies from one site to the next and is influenced by factors such as the chemical composition of the ore. In some particular cases, the measured radioactivity may be less than the radioactivity of naturally radioactive regions due to geological factors. For comparison, dose rates recorded at various sites around the world are presented in Table 5.1.

Table 5.1: Rates of radioactivity recorded at various locations.

Dose rate	
Location	**Rate measured (µSv/hour)**
Cluff Lake mine site: natural baseline levels of gamma radiation, in areas not affected by mining (1999)	0.01 to 0.5(a)
Global background	0.09(b)
Granitic areas not affected by mining	0.15(c)
Cluff Lake mine site: highest levels of gamma radiation, observed in the tailings management area, close to the processing plant and the tailings disposal areas (1999)	≥ 5(a)
Dose of cosmic radiation received on commercial airlines, depending on the altitude, location and sunspots	1-10(d)
Rate measured 1 m away from a patient after being administered 0.74 GBq of technitium-99m	10(d)
Beach sand from the seaside resort of Guarapari (Brazil)	20(e)

[a] CNSC, 2003 [b] IRSN, 2011 [c] IRSN, 2009 [d] UNSCEAR, 2008 [e] ULB, 2009.

5.4 RISKS TO EXPOSED POPULATIONS

5.4.1 WORKERS

There is a risk of biological damage from exposure to ionizing radiation to workers. Even though the risk associated with radiation from a natural source is minimal, the risk is higher for uranium mine workers. Consequently, effective dose limits have been set in Canada to protect the general public and workers against overexposure to ionizing radiation. These doses, which exclude radioactivity from a natural or medical source, are 1 mSv/year for the general public and 100 mSv over 5 years, with a maximum of 50 mSv for a single year for workers in the uranium sector. Doses received by workers of the mining sector are mainly from radon and its decay products.

For comparison, the average annual doses received by workers of different sectors in Canada in 2008 are presented in Table 5.2. Doses received during certain radiological examinations are also presented. It should be noted that no dose limit is applied to patients who are undergoing examinations or medical treatment that use ionizing radiation.

Living organisms do not distinguish between natural radiation and artificial radiation: when a radiation dose is received, regardless of its origin, there is no difference in the resulting effects.

Table 5.2: Annual doses per category of employment for Canada and doses received during various radiological examinations.

Employment type	Annual mean dose [(a)] (mSv)
Office personnel	0.04
Dental hygienist	0.01
Industrial radiologist	2.06
Nuclear medicine technician	1.60
Uranium mine: underground miner	2.43
Uranium mine: open pit miner	0.37
Uranium mine: nurse	0.13
Examination	**Acute dose [(b)] (mSv)**
Dental X-ray	0.01
Chest X-ray	0.1
Screening mammography	3
Abdominal computed tomography (adult)	10
Abdominal computed tomography (prenatal)	20

[a] Health Canada, 2008 [b] CNSC, 2012.

The protective measures for uranium miners are the same as those generally used in the mining industry (protection against exposure to heavy metals and dust, for instance), but an additional measures target risks associated with ionizing radiation. Various shielding equipment to minimize exposure to ionizing radiation are used and wearing a dosimeter is mandatory for all workers. The dosimeters are worn while working and are subject to audits by independent agencies, which compile the results and send them to Health Canada. CNSC employees carry out workplace inspections and assess the programs designed to protect workers against radiation.

Protective measures for workers, namely adequate underground ventilation and radiation protection programs, have not always been implemented. Studies report that, in the past, rates of lung cancer related to the presence of radon were much higher for uranium miners than for the rest of the population. Nowadays, important factors such as decreases in exposure time, reduce the risk of developing a lung cancer, and miners today are exposed to very low rates of radon.

The CNSC estimates that by 2030, about 24,000 people will be employed for various periods of time in Saskatchewan uranium mines. Of these, 141 miners are at risk of developing lung cancer, mainly due to tobacco use, and one miner could develop lung cancer due to occupational exposure to radon. For comparison purposes, the Canadian Cancer Society reports that in Canada, in 2013, about 60 out of 100,000 men will have developed a form of lung cancer, which equates to about 14 men out of 24,000.

Given the current state of knowledge, the risk that uranium workers will develop a form of lung cancer that is solely attributable to coming in contact with radon in the workplace is minute.

5.4.2 LOCAL POPULATION

The intensity of radiation decreases exponentially with distance from the source. The dose received by the general public in Canada, following exposure to ionizing radiation within the context of uranium mining, generally represents only a fraction (0.001 to 0.1 mSv/year) of the total allowable dose for the general public (1 mSv/year).

Among the local population, the dose received may come from eating food (vegetables or meat) or from drinking water. For drinking water, uranium concentrations must be less than or equal to the maximum concentration in Canada, which is 20 µg/L. For comparison, surface waters generally have uranium concentrations less than 1 µg/L. The allowable uranium concentration for agricultural soil can be up to 23 mg of uranium per kg of soil, whereas the maximum concentration permitted for industrial soil is 10 times more (300 mg of uranium per kg of soil). These values should serve as a reference for the rehabilitation of mine sites.

6 CONCLUSIONS

Uranium is a radioactive metal that is naturally occuring in the environment (bedrock, water, biosphere). Uranium has an unstable nucleus that slowly decays, emitting ionizing radiation as it decomposes to lighter atoms (its daughters) following a decay chain that ends with the formation of a stable atom. Uranium and the resulting nuclear decay have multiple applications in society, including electricity production, agricultural uses and in the medical sector.

Canada is the second largest uranium producer in the world. Quebec does not produce any uranium for the time being, but several exploration projects at various stages are underway. Quebec has significant uranium resource potential, estimated to be 315,000 tonnes. Less than 30 % of these resources are located in deposits for which uranium is the main product, about 60 % are located in deposits for which uranium is a secondary product that could be developed in addition to other elements. Other uranium resources include industrial and mine tailings.

Uranium exploration and mining fall under Quebec legislation pertaining to mines and the environment, as well as under Canadian law since uranium falls under federal jurisdiction. Commissioning uranium mines is authorized and supervised by the Canadian Nuclear Safety Commission, as are dismantling infrastructure and site rehabilitation after operations have ceased. Applicable laws and regulations in Quebec and Canada concerning environmental aspects and radiation protection serve as reference internationally and are based on proven scientific concepts. Respecting and applying these laws remain the best way to reduce potential impacts related to the exploration and mining of uranium resources in Quebec.

Uranium and its daughters have a potential toxicity due to their chemical and radioactive nature. Uranium radiotoxicity is, however, insignificant compared to its chemical toxicity, and the latter is dependent upon the accumulation and mobility of uranium in the environment. In uranium-rich areas it is vital to comprehensively quantify natural concentrations of uranium in the environment (air and water) and plants that are part of the food supply for living organisms. Awareness and understanding of these concentrations will make it possible to anticipate potential changes in the mobility of radionuclides in the environment. Given the number of physico-chemical parameters that affect the mobility of uranium and its daughters, characterizing biogeochemical mechanisms specific to a mine site will allow for better targeting of these parameters and enable adequate rehabilitation, if applicable. This type of analysis should be planned and supervised by an independent environmental management agency.

The environmental impacts related to the uranium exploration is small, yet increases throughout the more advanced stages of exploration. Exploration drill holes and bulk sampling of ore are the main activities that could have an environmental impact.

During uranium mining and site rehabilitation, dispersal of uranium and its daughters in the environment can be prevented by controlling dust emissions and by applying confinement measures to effluent and mine waste. Protecting workers and the general public against ionizing radiation is done by covering mine waste with materials that absorb the energy released from emitted radiation; these materials also prevent radioactive elements dispersal into the environment. Maintaining radioactive dust and radon concentrations at levels comparable to regional concentrations is possible through the ventilation of confined spaces.

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