Current Knowledge, Impacts and Mitigation Measures Related to the Exploration and Mining of Uranium Deposits in Québec

Report Prepared for Québec'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 report was prepared for Québec'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 view of the *Bureau d'audience publiques sur l'environnement*'s upcoming inquiry and public hearings on the environmental, social and economic impacts of uranium exploration and mining. The goal of this exercise is to inform the public as to the issues at stake, consult with the public, and guide the government in its thought process with respect to the uranium industry's future and environmental protection.

This report was prepared by the DIVEX (Diversification of exploration in Québec) 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 the seven universities in Québec with teaching and research programs in the field of mineral resources.

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ABSTRACT

Uranium is a radioactive metal occurring at low concentrations in rocks, water, soil and organisms. Natural uranium has three isotopes: ^{234}U, ^{235}U and ^{238}U. The atomic nucleus of each uranium isotope undergoes a series of transformations following a decay chain composed of elements with fixed radioactive periods – their half-life. The nuclear decay of uranium releases energy in the form of alpha, beta or gamma ionizing radiation. Each type of radiation has an energy that varies according to its nuclear reconfiguration.

Uranium is mined in 22 countries, either as the main substance or as a coproduct of other substances mined, such as phosphorus or rare earth elements. It is extracted by *in situ* leaching, or excavated from underground or open pit mines. Uranium is used to produce radioactive isotopes that benefit several sectors of the medical and agri-food industries. Its main civilian use is electricity production (accounting for 12 % of global electricity production). There are 440 power plants in the world that use nuclear energy, and they consume about 64,000 tonnes of uranium per year. The price of uranium is determined by supply and demand and global demand is on the rise, which accounts for current high prices. Many mining projects being developed in the world have sufficient uranium resources to meet the anticipated medium-term demand.

In Québec there is good potential for uranium deposits. The geological context suggests that uranium mineralization may be present in sandstones, similar to mineralization in Colorado and Saskatchewan, in conglomerates, and in igneous and metamorphic rocks, such as in Namibia. In Québec, uranium resources are estimated at 315,000 tonnes of uranium, 89 % of which are associated with low-grade intrusive rocks. Approximately 5 % of the uranium resources occur in sandstones of the Otish Mountains sedimentary basin, north of Chibougamau.

In Québec, exploration, mining and mine site rehabilitation are administered under the Mining Act and the Environment Quality Act (EQA). All projects related to the commissioning and operation of an uranium mine, or to the construction of a processing plant, among others, are subject to an environmental impact assessment and review procedure under the EQA. Furthermore, all projects that involve a certain threshold for radioactivity must be authorized by the Canadian Nuclear Safety Commission, and are subject to the Nuclear Safety and Control Act and to the Canadian Environmental Assessment Act.

The annual dose received by an organism is expressed in sieverts (Sv). Depending on geographical location, humans receive an annual dose of approximately 3.5 millisieverts (mSv). Of this amount, 2 mSv comes from natural radioactivity (due to the presence of uranium, thorium, potassium and other radioactive elements in the environment) and 1.5 mSv are from anthropogenic sources, mainly related to medical applications. Canada authorizes an additional dose of 1.0 mSv per year for people exposed to radiation from nuclear facilities, including uranium exploration and mining.

The chemical toxicity of uranium is the same for each of its isotopes, unlike its radiotoxicity, which varies from one isotope to another. Uranium is weakly radioactive, such that its impact on the environment is mainly related to its chemical toxicity. Though uranium is not easily bioaccumulated in plants, it may accumulate in organisms of the lower trophic levels, such as invertebrates. The daughters of uranium, like polonium, are also associated with a chemical toxicity, or a radiotoxicity. At the mineral exploration stage, the environmental impact is low and limited to drilling, and only if uranium mineralization is intersected. Recirculating the drilling fluids in a closed circuit can

reduce environmental impact, whereas used drilling muds that exceed the threshold for radioactivity should be returned down hole. Once drilling is complete, the intervals with uranium mineralization should be cemented to avoid groundwater contamination and radon emissions. When operating an uranium mine, the environmental impact may be reduced by preventing the dispersal of dust by the wind and by properly ventilating confined spaces to avoid radon accumulation. Water from the mine site must be treated to remove radionuclides and other chemical elements with concentrations exceeding authorized limits. Uranium ore is commonly concentrated at the mine site. The environmental impact associated with ore processing may be reduced by proper ventilation to avoid radon accumulation, by preventing fine particulate matter from going into suspension, and by recirculating process waters to limit the amount of effluents requiring treatment. Mine waste is stored in a manner that prevents dispersal by the wind of radionuclide particles, and to prevent contaminated mine drainage. During mine site rehabilitation, underground access points must be cemented. The surface of restored tailings facilities must be covered with water or another material thick enough to absorb ionizing radiation from the daughter radionuclides of uranium.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Absorbed dose	The amount of energy deposited by ionizing radiation per unit of mass of a tissue or material. It is expressed in grays (Gy): 1 Gy corresponds to 1 J/kg.
Actinides	Radioactive chemical elements with atomic numbers 89 to 103. Only the first four : actinium, thorium, protactinium and uranium, occur naturally.
Activity	The rate at which natural transformations, i.e. disintegrations, occur in the nuclei of certain atoms. The activity of a radioactive element is inversely proportional to its half-life ($t_{1/2}$) and is proportional to the number of atoms present (N): $A = (\ln_2/t_{1/2})N$ It is expressed in becquerels (Bq); 1 Bq corresponds to one disintegration per second.
Adsorption	The surface retention of molecules or substances by a solid.
Alaskite	A type of light-coloured granite composed of quartz and feldspar.
Alpha	See *Alpha particle*.
Alpha particle (or alpha radiation)	Particle made up of two protons and two neutrons (exactly like a helium nucleus). It is ejected from the nucleus when certain radioactive elements undergo decay. It is less penetrative than the other two most common types of radiation, beta and gamma. All the energy of an alpha particle is dissipated through ionization over a very short distance, i.e. a few micrometres (μm) of solid material or a few centimetres of air. As such, alpha particles are blocked by a single sheet of paper. It is nevertheless harmful due to reasons that are poorly understood, but probably related to the amount of energy emitted over such a short distance.
Anthropogenic	Refers to an activity or a consequence resulting from the activities of man.
Archean	The first geological period, before 2,500 million years ago.
Atom	Particle of matter that cannot be broken down by chemical reactions. The atom, composed of a nucleus made of protons and neutrons around which orbit electrons, represents the smallest, that is to say fundamental, unit of an element.
Background noise	An element's background noise corresponds to its typical concentration in soil, before any industrial activities are undertaken. With respect to radioactivity, background noise refers to the radiation from natural sources (i.e. cosmic rays, radiation from the ground and surrounding materials, internal sources related to food, as well as common anthropogenic sources) prior to any industrial modifications. On average, humans are exposed to an annual effective dose from background noise of 2 to 3 millisieverts (mSv).
Batholith	A large mass of granite.

Beta particle (or beta radiation)	Particle that is equivalent to an electron, which is ejected from the nucleus when certain radioactive elements undergo decay. It can have a positive or negative charge. Its penetration power is greater than the alpha particle: it can travel for a few metres in air, and a sheet of plywood, or its equivalent, is required to block it, but it only poses a minor risk to living organisms if emitted from an external source.
Becquerel (Bq)	See *Activity.*
Beta	See *Beta particle*.
Bioaccumulation	The process by which a living organism accumulates in its tissues a substance that occurs in its environment.
Bioconcentration factor	Ratio between the activity of a radioelement in an organism and its activity in the surrounding environment.
Biomagnification	The phenomenon by which contaminants accumulate in an organism after ingesting species from the previous trophic level. The tendency of certain chemical substances to become increasingly concentrated at each level of the food chain.
Breccia	Rock made up of at least 50 % angular fragments (greater than 2 mm in size) cemented by a natural substance.
Carbonatite	Intrusive rock that contains at least 50 % carbonate minerals. Carbonatite magmas are very depleted in silica.
CIM	Canadian Institute of Mining, Metallurgy and Petroleum.
Colloid	One or more substances in suspension evenly dispersed within another substance (a liquid, for instance water) forming a two-phase system. In aqueous environments, colloidal particles are very large compared to water molecules.
Core shack	Where diamond drill core is stored.
cpm	Counts per minute.
Daughter	Name given to all intermediate products in a decay chain. Radon is among the daughters of uranium-238.
Decay chain	A series of radioelements that spontaneously disintegrate to the next element, until a stable form is achieved. The first member of the series is termed the parent, the intermediate members are the daughters, and the last, stable member is the end product.
Decay (or disintegration)	A nuclear reaction by which the nucleus of an atom undergoes a spontaneous transformation and loses mass. This loss of mass is associated with the emission of one or several types of ionizing radiation.
Decommissioning	Safe storage and dismantling of nuclear facilities.
Deposit	A mineral accumulation that can be profitably mined.
Deterministic effects	Clinically-observed effects that occur when the dose reaches a threshold, the gravity of which depends on the dose received. Deterministic effects are observed when high doses (500 mSv and up) are received (for instance, after a nuclear disaster or a

	medical treatment) and cause significant cell loss in tissues. These effects can manifest themselves in humans by vomiting, hair loss and thyroid gland failure.
Diuranate	Uranium anion, occurring in many common compounds. Uranates naturally tend to form this complex ion.
Dosimetry	Quantitative determination of the dose absorbed by an organism, expressed as energy per unit of mass.
EDP	Electronic Personal Dosimeter.
Effective dose	The dose obtained by multiplying the absorbed dose by a weighing factor that takes into account the biological effects associated with the different types of ionizing radiation. The effective dose is expressed in sieverts (Sv).
Electron	An elementary particle with a very low mass and a negative charge. It is a constituent of the atom.
Element	Simple substance made up of atoms, which cannot be broken down. Hydrogen and uranium are elements. Many elements can combine to form compounds.
Euxinic	An environment that lacks oxygen and is rich in reduced sulphur, such as isolated marine basins.
Flocculant	A reagent that triggers flocculation, which is the formation of aggregates of a substance suspended in liquid.
Gamma	See *Gamma radiation*.
Gamma radiation	Photons emitted during the natural transformation (decay) of the nuclei of radioactive atoms. With an energy that is typically greater than X-rays, gamma rays are very penetrative and can only be blocked by dense shields, such as lead or a 1-metre thick concrete wall.
Gray (Gy)	Unit of an absorbed dose. A Gy corresponds to the absorption of one joule of energy per kilogram of tissue.
Grouting	To fill fractures in a rock mass with mortar.
Half-life ($t_{1/2}$)	The period of time required for half of a radioactive substance's atoms to undergo decay. The length of the half-life is unique to each element, and varies from a millionth of a second to billions of years.
IAEA	International Atomic Energy Agency, which is the United Nations' governing body for nuclear matters; created in 1956.
Ion	Atom or molecule that has gained or lost one or many electrons, lending it an electrical charge. For instance, the alpha particle, which is a helium atom that has lost two electrons, is a positively-charged ion.
Ionization	Ion-generating process. Certain conditions such as high temperatures and electrical discharges are possible causes. Ionizing radiation ionizes atoms or molecules in its path.
Ionizing radiation	All types of radiation that generate ions. Alpha, beta and gamma rays are types of

	ionizing radiation.
Isotope	One of the different forms a given element may take on. An element always possesses the same number of protons, which defines its chemical character. Isotopes differ based on the number of neutrons in the nucleus. This variation is reflected in the physical properties of the isotope, such as mass, stability and radioactivity.
Ligand	An atom, ion or molecule with chemical functions that enable it to bind to one or several central atoms or ions.
Leachate	A liquid that results from leaching.
Leaching	Method for extracting soluble products using a solvent.
Lead (Pb)	Natural element with the atomic number 82 and with a mean atomic mass of 207. Very dense metal with 29 isotopes, 3 of which (lead-206 to lead-208) constitute the stable end products of several radioactive sequences. The 210 isotope is radioactive: it emits beta radiation and its half-life is 22 years.
Macrophyte	An aquatic plant that is visible to the naked eye.
Metasediments	Sedimentary rocks that have been metamorphosed under high temperature and pressure conditions, due to burial in the Earth's crust or contact with an intrusion.
Mineral reserves	The portion of mineral resources that can be profitably mined on the basis of a preliminary feasibility study. "Proven" and "probable" reserves may be defined, with a decreasing degree of precision and confidence.
Mine waste	All materials and substances, both solid and liquid, that are rejected during mining and milling of ore, or during the preparation, concentration and enrichment of a substance. Mine waste includes scrubbing sludges and dust from the treatment of wastewater and from air emissions. Final effluents are not considered mine waste.
Mineral resources	All known or interpreted accumulations of minerals that have, or can have, an intrinsic value (industrial minerals, such as diamond) or that contain, or can contain a substance (such as copper or zinc), and for which there is a current or future need in society. "Measured", "indicated" and "inferred" mineral resources may be defined, with a decreasing degree of precision and confidence. Only "measured" and "indicated" mineral resources can be taken into account when evaluating the economic potential of a mineral deposit. Mineral resources termed hypothetical or speculative have not yet been identified, but are presumed to occur in an area based on geological interpretation. These resources are mainly used to determine the mineral potential of an area.
Neutron	Primary particle of the nucleus, with no charge and with a mass 1.0014 times greater than that of a proton. When it is ejected from the nucleus, it can cause ionization. A free neutron is unstable and has a half-life of about 13 minutes.
NI 43-101	National Instrument (NI) 43-101 is a regulation adopted by Québec's National Assembly. It came into effect in December 2001, in order to regulate the disclosure of information pertaining to the mineral projects by companies subject to the *Autorité des marchés financiers du Québec*.

Ore	A naturally-occurring mineral substance for which the quantity, location and composition are such that it can reasonably be expected to yield one or more commercially viable products.
Orogen	A mountain chain resulting from the collision of two continents.
Paleoplacer	Ancient placer deposit now converted to rock from through lithification.
Pegmatite	Crystalline rock with very large crystals.
Phytoextraction	The use of accumulator plants to absorb and accumulate, within their harvestable parts (leaves, roots, etc.), soil contaminants that often occur in trace amounts.
Pitchblende	Fine-grained uraninite (UO_2), typically black in colour.
Placer	Accumulation of heavy mineral grains that are detached by erosion from the primary sources of mineralization and concentrated by sedimentary processes involving various means, such as gravity, water, wind and ice.
Polonium (Po)	Natural element with the atomic number 84 and with a mean atomic mass of 209. Product generated from the decay of radon; it has 27 isotopes (polonium-192 to polonium-218), all of which are radioactive. The 210, 214 and 218 isotopes are alpha emitters with short half-lives and are part of the radioactive sequence of uranium-238.
Proterozoic	Geological period from 2,500 to 541 million years ago.
Proton	Elementary particle with a positive charge that, along with neutrons, composes the nucleus of an atom. Its mass is about 1,837 times greater than an electron. The atomic number of a natural element is given by the number of protons in its nucleus: protons define an element's chemical character.
Radioactive	Exhibiting radioactivity.
Radioactivity	Phenomenon resulting from the ability of certain element nuclei to spontaneously transform, by undergoing decay, into another element. Radioactivity manifests itself by the emission of ionizing radiation.
Radionuclide	Radioactive element.
Radium (Ra)	Natural radioactive element with the atomic number 88. Its most common isotope is radium-226. It is an alpha emitter, with a half-life of 1,600 years. White metal associated with uranium and other minerals; it occurs in trace amounts in nature. Its decay generates radon.
Radon (Rn)	Natural radioactive element with the atomic number 86, radon has 35 known isotopes, all of which are radioactive. The most stable among them is radon-222, an alpha emitter with a half-life of 3.8 days. Radon is a rare odourless and colourless gas. It is an intermediate product of the decay chain of uranium-238. The decay products of radon-222 are radioactive isotopes of lead, bismuth and polonium, with the stable isotope of lead-208 being the series' end product.
Refractory	Quality of a material whose composition, shape and structure resist extreme temperature and pressure conditions.

Rhizofiltration	Soil remediation technique that uses submerged plant roots to capture pollutants. The roots are collected once they are saturated in pollutants.
Showing	A mineralized occurrence that can lead to the discovery of a mineral deposit.
Skarn	Calc-silicate rock that results from the interaction of calcium-rich rocks, such as limestone, and silica-rich rocks, such as granite.
Specific activity	The number of disintegrations undergone by a radioactive substance per unit of time and per unit of mass. It is expressed in becquerels per kilogram (Bq/kg), as per the International System (SI) of units.
Stochastic	Refers to phenomena that partly involve an element of chance and that are the subject of statistical analyses.
Sievert (Sv)	Unit from the International System of Units that is used to measure the equivalent dose, the effective dose or the dose rate (for instance, in µSv/h).
Stochastic effects	Effects that occur in the long term following a certain probability. There is no threshold under which it can be said for sure that no effects will occur. Stochastic effects most commonly manifest themselves in humans and in animals in the form of cancers and genetic anomalies, and as such, a latent period is usually observed.
Thorium (Th)	Grey metal belonging to the actinide series, thorium is a natural radioactive element with the atomic number 90 and an atomic mass of about 232. The thorium-232 isotope has a half-life of 1.4×10^{10} years.
TLD	Thermoluminescent dosimeter.
TSP	Total suspended particles.
UDEPO	The IAEA's global uranium deposit database (*World Distribution of Uranium Deposits*).
Unconformity	A stratigraphic contact within a sedimentary package marked by a series of layers that are not in parallel with underlying older rocks, indicating a period of erosion.
Uraninite	Uraninite is mainly composed of uranium dioxide (UO_2), but also typically comprises tetravalent (U^{4+}) and hexavalent (U^{6+}) atoms of uranium yielding a U_3O_8 composition.
Uranium (U)	Grey metal belonging to the actinide series, uranium is a natural radioactive element with the atomic number 92 and a mean atomic mass of about 238. The main isotope, uranium-238, has a half-life of 4.5×10^9 years and represents 99.274 % of natural uranium, the other natural isotopes being uranium-234 (0.006 %) and uranium-235 (0.720 %). The decay of uranium-238 gives rise to 13 radioactive isotopes, which include uranium-234, radium-226 and radon-222.
Waste rock	Rocks extracted during mining operations that do not contain sufficient amounts of the substances of interest for mining.

1 INTRODUCTION

Uranium is a metal that is naturally occurring in the environment. Uranium is radioactive , due to its unstable and slowly-decaying atomic nucleus resulting in the release of energy in the form of ionizing radiation. The energy released from the nuclear decay of uranium can be harvested to produce electricity. Nuclear decay and ionizing radiation have multiple applications in society, from medical imaging and food sterilization, to use in smoke detectors.

This report aims to provide an overview of operations pertaining to the uranium industry in Québec, from exploration and mining to rehabilitation (Figure 1.1). The topics of uranium and radioactivity will first be introduced, followed by an overview of uranium applications in society. The industrial chain for uranium in Québec will then be discussed. However, the civilian applications of uranium and the storage of radioactive waste generated by the reactors that produce energy or radioisotopes for medical or industrial use will not be addressed.

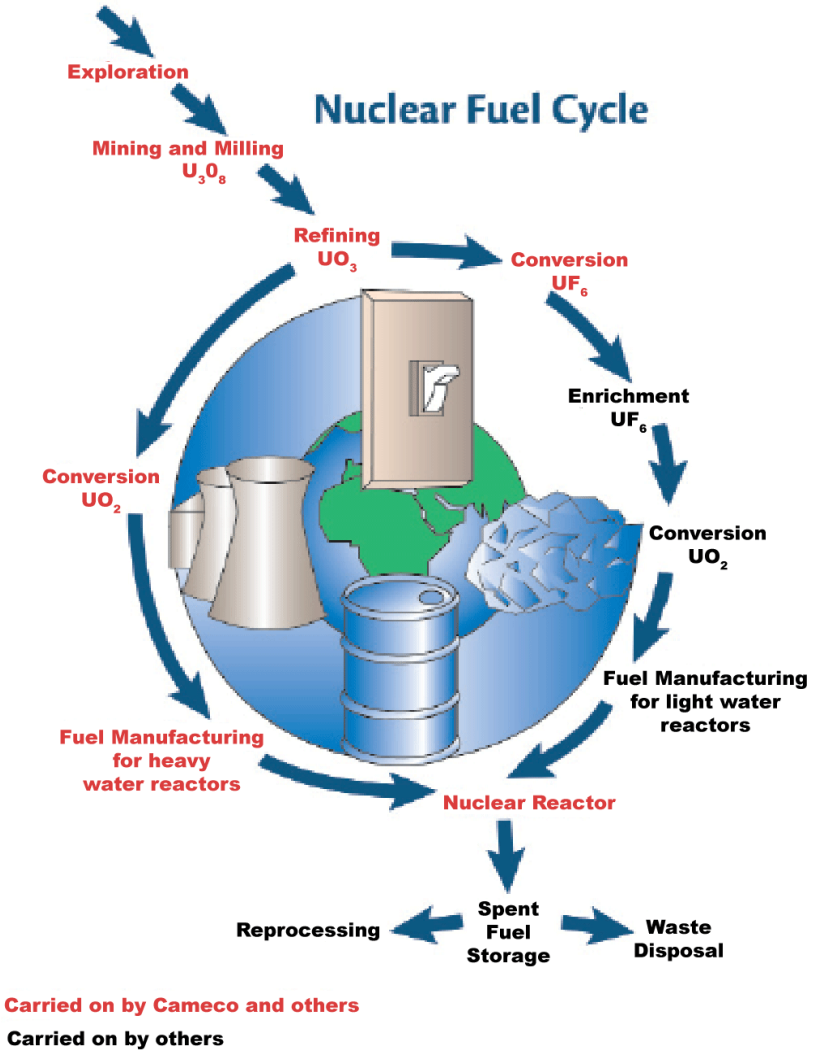


Figure 1.1: Diagram illustrating the nuclear cycle. The steps described in this report are in green, the steps that use natural uranium fuel and which are a specialty in Canada are in red, and the steps implemented elsewhere are in black. In Canada, the conversion step produces two types of products: UO_2 and UF_6. UO_2 is directly shipped to fuel fabrication plants to make natural uranium fuel (non enriched). Only UF_6 is sent off for enrichment. It is also important to note the there are no enrichment plants in Canada and that UF_6 is exported to countries that have such facilities.

This report provides a comprehensive overview of the potential presented by Québec's uranium resources. Only primary resources (main product, coproduct and waste) generated by mining and metallurgical operations are addressed. Secondary uranium resources generated by industrial processes or power generation are not discussed. An overview of the legislation pertaining to the uranium sector is then presented, in chronological order, from exploration to mine site rehabilitation. The report provides a picture of the potential impacts related to the exploration and mining of primary uranium, both chemical and radiological, on the fauna, flora and on the general public, for both workers of the uranium industry and for communities located close to mine sites. An overview of the main environmental protection measures related to the exploration and mining stages is then presented, including mine site rehabilitation, followed by recommendations to ensure the responsible and sustainable management of Québec's uranium sector.

2 URANIUM AND RADIOACTIVITY

Summary

- Uranium is a radioactive metal that occurs naturally at low concentrations in rocks, water, soil, and organisms.
- The solubility and mobility of uranium in the environment significantly affects its ability to be absorbed by living organisms or to interact with non living matter.
- When undergoing transformations, uranium releases energy in the form of ionizing radiation. The three most common types of ionizing radiation are alpha and beta particles, and gamma radiation.
- The energy from radiation is transferred to living cells. If the damage is too great, the cells' repair mechanisms become ineffective, which may lead to the formation of cancerous tumours.
- The doses received by an organism are expressed in sieverts (Sv). Humans receive a total annual dose of about 3.2 mSv, of which about 2.0 mSv are from natural radioactivity and about 1.2 mSv from artificial exposure, mainly medical in origin. However, these doses vary with geographical location.

  The effective dose limit, or maximum dose, established in Canada to protect people against overexposure to ionizing radiation from nuclear facilities or authorized nuclear substances is of 1 mSv per year for the general public, in addition to the dose received under normal conditions.

2.1 URANIUM IN THE ENVIRONMENT

Uranium, is a chemical element of the actinide series and is a naturally-occurring radioactive metal that is found at very low concentrations in water, soil and rocks. Its average natural concentration in the Earth's crust is estimated to be 2.7 mg/kg, which is equivalent to 2.7 g/tonne or 2.7 parts per million (ppm) (Vandenhove et al., 2010), but marked variations can be observed from one location, or one substance, to another (Table 2.1). For instance, mafic rocks (such as basalt) contain less than 1 mg/kg of uranium, whereas felsic rocks (such as granite) contain more than 4 mg/kg. The United Nations' Scientific Committee reports that global uranium concentrations vary, on average, between 0.3 and 11.7 mg/kg (CCME, 2007). In uranium deposits, however, concentrations can range from 300 mg/kg to more than 200,000 mg/kg.

Small amounts of uranium are present in natural surface waters and groundwater, essentially developing from the dissolution of minerals that contain uranium in rocks and soil. Uranium occurs in these waters on the scale of micrograms per litre (between 0.001 and 2,600 µg/L). The dispersal of uranium in the environment relies in large part on chemical factors, such as its solubility in water, and on natural biological and geological factors, such as soil leaching and biological transport, but is also the result of human activity, such as mining and the application of phosphate fertilizers (CEAEQ (1), 2013).

Like many other metals that occur as minerals within rocks and soil, uranium forms strong chemical bonds with oxygen, the most abundant element in the Earth's crust. The chemical interactions between these two elements leads to the formation of uraninite (mainly UO_2) in rocks, uraninite is a solid that is weakly soluble in water and stable under a large range of environmental conditions. Under certain conditions in water this interaction manifests itself by the preferential formation of the uranyle ion (UO_2^{2+}), a soluble and mobile ion form of uranium.

Among uranium's numerous isotopes, only three occur naturally in the environment: uranium-238 (99.274 % of atoms), uranium-235 (0.720 % of atoms) and uranium-234 (0.0056 % of atoms) (atoms are referred to as isotopes if their nuclei has an identical number of protons but a different number of neutrons). These three isotopes, which follow this ratio in all uranium ores, constitute what is referred to as natural uranium. There are other isotopes of uranium (e.g. uranium-236), but these are essentially the result of nuclear activity. Despite the fact that the widespread industrial use of uranium gives people the impression that it is the most common radioelement in the environment, it is neither the single nor most common primordial radioactive element (i.e. present since the Earth's formation). Natural radionuclides are divided into three categories: primordial radionuclides, cosmogenic radionuclides and radionuclides derived from the decay of primordial radionuclides (a radionuclide, or radio-isotope, is a radioactive isotope).

Primordial radionuclides have always been present in rocks, soil, water, animals and plants. The main primordial radionuclides are potassium-40, uranium-238 and thorium-232. The latter, which occurs in the Earth's crust at concentrations from 8 to 12 mg/kg (CEAEQ (2), 2013), is, on average, three times more abundant than uranium. Cosmogenic radionuclides, such as carbon-14, arise from gaseous molecules in the Earth's atmosphere being bombarded by cosmic rays. Other radionuclides, such as radium, polonium and certain isotopes of lead, occur naturally in soil, rocks and natural waters at very low concentrations. Their presence is due to the decay of natural uranium and thorium.

Table 2.1: Natural uranium concentrations in the environment.

Source	Uranium concentration in mg/kg (ppm)
Porous rock – limestone	2
Hard rock – granite	4
Earth's surface	3
Atlantic Ocean	0.003 mg/L (3 µg/L)
Fresh surface water	< 0.001 mg/L (< 1 µg/L)
Groundwater	0.000001-2.6 mg/L (0.001-2,600 µg/L)

Sources: Vandenhove et al., 2010; GA, 2008.

2.2 RADIOACTIVITY

2.2.1 THE ATOM AND THE DECAY CHAIN OF UNSTABLE NUCLEI

The atom is the smallest part of an element. The atom consists of a positively charged nucleus and of one or many negatively charged electrons, which orbit around the nucleus (Figure 2.1). The nucleus, which represents more than 99.9 % of the atom's mass, is made up of protons (positively-charged particles) and neutrons (neutral particles, with no charge). The atoms of two different elements have a different number of protons. Protons define an element's unique chemical character.

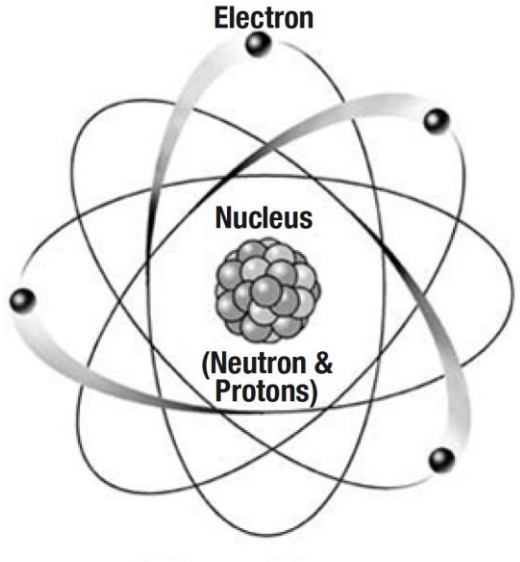


Figure 2.1: Schematic representation of an atom.

However, a given element can have many different nucleus configurations, known as isotopes, that differ from one another by the number of neutrons they possess. Each isotope is identified using the name of the element and the mass of its nucleus, which corresponds to the sum of the masses of protons and neutrons. For instance, the three

isotopes of natural uranium are uranium-238 or ^{238}U (92 protons, 146 neutrons), uranium-235 or ^{235}U (92 protons, 143 neutrons) and uranium-234 or ^{234}U (92 protons, 142 neutrons).

All the isotopes of uranium are radioactive. The naturally-unstable nuclei of these atoms spontaneously undergo decay in trying to achieve a more stable nuclear configuration, with a lower atomic mass. These nuclear decays release energy in the form of ionizing radiation: this is radioactivity. The term ionizing is used to qualify this type of radiation since it possesses enough energy to produce ions in the irradiated environment. Although there are several types of ionizing radiation, three are particularly common for natural radionuclides: alpha, beta and gamma radiation. The nature and characteristics of these three types of radiation will be discussed later on.

The nuclear reconfiguration that arises following an element's nuclear decay may produce a new unstable nucleus, which, in trying to achieve a more stable state, will in turn undergo decay. This series of decays is referred to as the decay chain (or radioactive series). The radionuclides produced by all these nuclear reconfigurations are the "daughters" of the original radionuclide at the top of the decay chain (i.e. ^{238}U, ^{235}U and ^{232}Th). For instance, the decay chain of ^{238}U comprises 14 radioactive elements (including ^{238}U) and ends with the production of a non radioactive lead isotope, lead-206 (^{206}Pb; Table 2.2a). All the elements with decay chains involving uranium isotopes are metals, except for radon, which is a gas. It should be noted that the 238 and 235 isotopes of natural uranium are primordial isotopes, whereas uranium-234 is a decay product of ^{238}U. The physicochemical properties of the various isotopes are presented in Table 2.3.

The radioactive period of an element, commonly called the half-life ($t_{½}$), is a property unique to each isotope and corresponds to the time required for half of the atoms initially present to undergo decay (Figure 2.2). The half-life of uranium-238 is 4.5×10^9 years. As such, half of the atoms of uranium-238 present on Earth when it formed 4.5 billion years ago have transformed to lead.

Table 2.2a: Decay chain for the 238 and 235 isotopes of uranium.

Half-lives and main types of radiation emitted					
Decay of uranium-238			**Decay of uranium-235**		
Isotope	**Half-life**	**Main types of radiation**	**Isotope**	**Half-life**	**Main types of radiation[(a)]**
Uranium-238	4.5 billion years	α	Uranium-235	710 million years	α, γ
Thorium-234	24 days	β, γ	Thorium-231	25.6 hours	β
Protactinium-234	1.2 minutes	β, γ	Protactinium-231	33,000 years	α, γ
Uranium-234	250,000 years	α, γ	Actinium-227	21.8 years	β
Thorium-230	77,000 years	α, γ	Thorium-227	18.7 days	α, γ
Radium-226	1,600 years	α, γ	Radium-223	11.4 days	α, γ
Radon-222	3.8 days	α	Radon-219	3.9 seconds	α, γ
Polonium-218	3.1 minutes	α	Polonium-215	1.8 thousandths of a second	α
Lead-214	27 minutes	β, γ	Lead-211	36 minutes	β, γ
Bismuth-214	20 minutes	β, γ	Bismuth-211	2.2 minutes	α, γ
Polonium-214	0.16 thousandths of a second	α, γ	Thallium-207	4.8 minutes	β
Lead-210	22.3 years	β, γ	Lead-207	Stable	none
Bismuth-210	5.01 days	β			
Polonium-210	138 days	α			
Lead-206	Stable	none			

[a] RCNET, 2013.

Table 2.2b: Decay chain for the 232 isotope of thorium.

Decay of thorium-232		
Isotope	**Half-life**	**Main types of radiation**
Thorium-232	14 billion years	α
Radium-228	5.7 years	β
Actinium-228	6.1 hours	β, γ
Thorium-228	1.9 years	α, γ
Radium-224	3.7 days	α, γ
Radon-220	55.6 seconds	α
Polonium-216	0.15 seconds	α
Lead-212	10.6 hours	β, γ
Bismuth-212	61 minutes	α or β, γ [(a)]
Polonium-212	30 microseconds	α
Thallium-208	3.1 minutes	β, γ
Lead-208	Stable	none

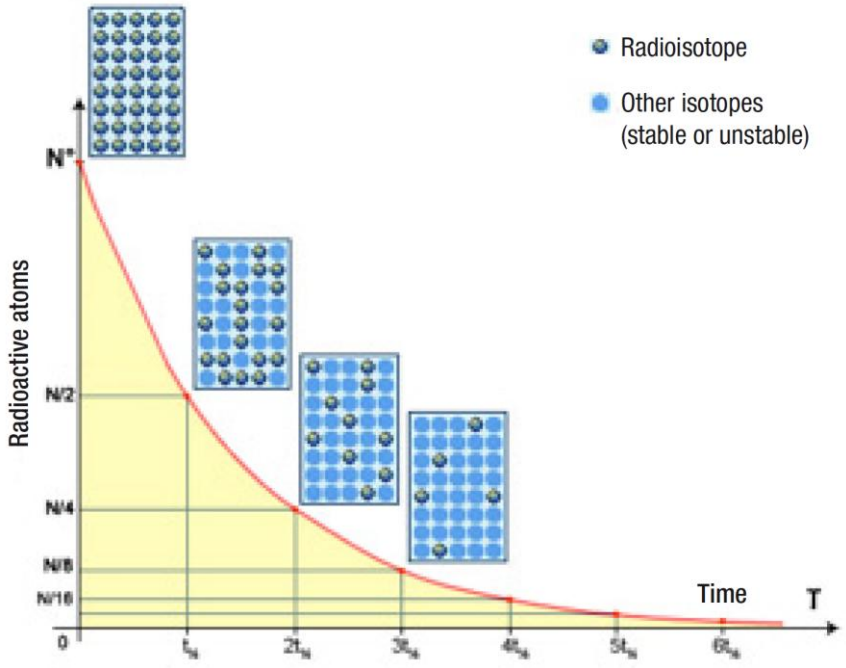
[a] One or the other is produced depending on whether bismuth-212 emits an alpha or beta particle.

Source: BAPE, 2002.

Table 2.3: Characteristics of the different isotopes of natural uranium.

Isotope	**^{234}U**	**^{235}U**	**^{238}U**
Half-life (years)	2.5×10^5	7.1×10^8	4.5×10^9
Molar mass (g/mol)	234.04	235.05	238.05
Weight %	0.0056	0.720	99.274
Radioactivity %	48.9	2.2	48.9
Type of radiation	Alpha, gamma	Alpha, gamma	Alpha
Energy of the alpha particle (MeV)	4.8	4.4	4.2
Specific activity (Bq/g)	2.31×10^8	8.0×10^4	1.24×10^4

Sources: Winter, 2010; Bleise et al., 2003; IAEA, 2014.



Source: Gagné, 2013.

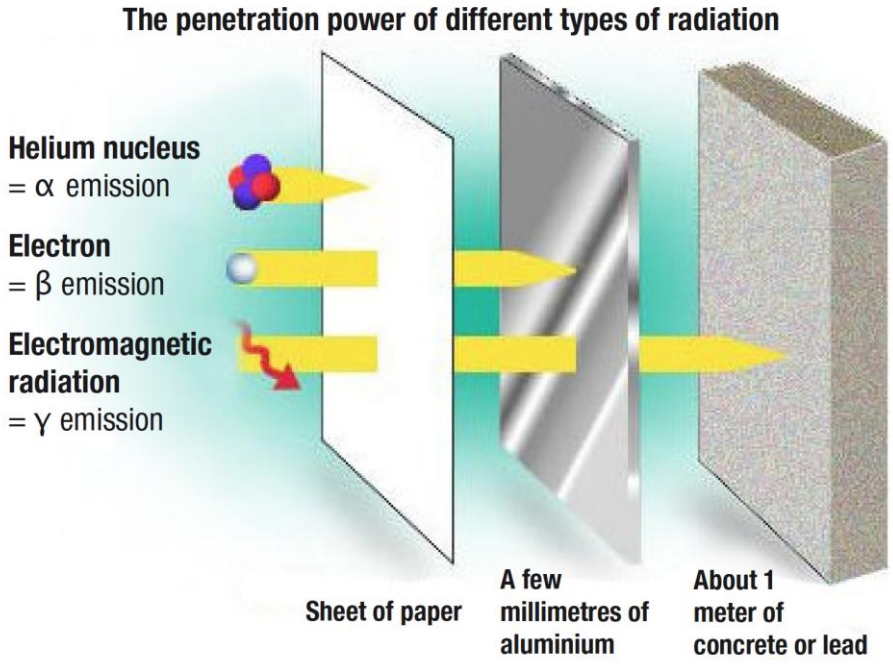
Figure 2.2: Representation of the half-life.

2.2.2 TYPES OF IONIZING RADIATION

The alpha particle (α) is made up of two protons and two neutrons, which form a high-energy helium nucleus (He^{2+}). Because of its mass and high charge, compared with other types of ionizing radiation, all the energy of an alpha particle is dissipated through ionization over a very short distance, i.e. a few micrometres (µm) of solid material or a few centimetres of air (Figure 2.3). Consequently, alpha particles do not penetrate the epidermis or the surface layers of living organisms, and the risk of external exposure for the living is therefore negligible. On the other hand, elements that emit alpha particles are particularly harmful if they are found inside an organism (through ingestion or inhalation) (CEAEQ (3), 2013), since the alpha particle emitted transfers all of its energy to the neighbouring cells of the radionuclide's deposition site, such as in the lungs.

The beta particle (β^-) is an electron ejected from the atom, with a very small mass and a negative charge. Given its small size, it has a greater penetration power than the alpha particle: it can travel through a few metres of air, and at least a sheet of plywood is required to block it (Figure 2.3). On average, it can penetrate 8 mm into living tissue, yet it is less harmful than the alpha particle. It represents only a minor risk to the living, unless it is produced inside an organism, for instance if ingested (BAPE, 2002).

Gamma radiation (γ) is composed of photons, which have no charge nor mass. This type of radiation is similar to natural light or X-rays, making it more penetrating. It easily passes through organisms, and the impact can only be attenuated by thick layers of dense material such as lead or concrete (Figure 2.3). Gamma radiation is less harmful to the organism than other types of radiation when emitting elements are ingested: unlike alpha particles, the energy of gamma radiation is dissipated when it is transferred to cells, and a large portion of this energy escapes the organism without much interaction.



Source: IRSN, 2013.

Figure 2.3: The penetration power of the different types of ionizing radiation.

2.2.3 Activity

2.2.3.1 The activity of a pure radionuclide

The activity of an element corresponds to the rate of nuclear reconfigurations (which is equivalent to the rate of disintegration). The rate is specific to a specific situation, and is expressed in becquerels (Bq); one becquerel corresponds to one disintegration per second. The activity of a pure substance depends on the number of radioactive nuclei it contains.

The specific activity corresponds to the number of disintegrations of an element per unit of time and per unit of mass. It is expressed in Bq/g. Equation 1 shows the relationship between an isotope's specific activity and its radioactive period. It demonstrates that the intensity of the activity is related to the half-life ($t_{1/2}$): the shorter the half-life, the more radioactive a isotope is for a given mass.

$$A/m = N \times \ln 2 / t_{1/2} \times Mm \quad (1)$$

where A is the specific activity of an isotope

m is the mass of the isotope

N is the number of atoms

ln 2 is a constant (0.693)

$t_{1/2}$ is the half-life

Mm is the molar mass of the isotope

The specific activity makes it possible to compare the level of radioactivity of different radionuclides. For instance, polonium-210 has a very high specific activity of 166 TBq/g, which corresponds to 1.66 x 10^{14} disintegrations per second per gram of pure ^{210}Po. For comparison purposes, a gram of this isotope emits as many alpha particles as 13.5 tonnes of uranium-238 or 4.5 g of radium-226. The specific activity generated by the isotopes of natural uranium is about 25,000 Bq per gram of pure natural uranium.

2.2.3.2 THE SPECIFIC ACTIVITY OF A RADIONUCLIDE WITHIN A SOLID

For a natural substance, such as uranium ore comprising atoms of uranium-238 and its daughters, the total activity that is measured, which is the sum of the activities of each radionuclide present. Compared to the activity of a pure, natural uranium sample (25,000 Bq/g), the activity of uranium and its daughters in the Earth's crust is about 40 Bq per kilogram of solid (0.040 Bq/g).

When the activity of a radionuclide (pure or in a solid) is measured within a volume of air or water, the activity is normalized to the volume of the sample in question, expressed in Bq/L or Bq/m^3.

2.3 POTENTIAL RISKS ASSOCIATED WITH RADIOACTIVE SUBSTANCES

When assessing radiotoxic risk, the radionuclides that present a long-term risk for the environment are determined based on various criteria (CEAEQ (3), 2013). For instance, radionuclides for which the concentrations measured on site exceed normal concentrations observed in the area can be retained. All radionuclides with a half-life of more than one month can also be automatically retained. In the case of a uranium mine, if the most abundant uranium isotope (uranium-238) and its decay chain are considered, the following radionuclides meet this last criterion: ^{238}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Pb and ^{210}Po. Uranium-235 must also be included which, despite being present in low amounts compared to uranium-238, represents an activity that is not negligible.

Radon is a particular case since it is a gas. Even though the half-life of radon-222 is less than one (1) month, it is long enough (3.8 days) for it to migrate from the soil to the atmosphere, where is may be inhaled by living organisms and continue its decay sequence inside these organisms. It must therefore be taken into account. The other natural isotopes of radon (^{218}Rn, ^{219}Rn and ^{220}Rn), which arise from the decay chains of uranium-238, uranium-235 and thorium-232, have very short half-lives (35 milliseconds to 55.6 seconds). Consequently, they do not significantly migrate away from soil or bedrock, and therefore represent a low radiological risk compared to radon-222 (Wilkening, 1990).

2.4 RADIATION DOSE

When a tissue is irradiated, the ionizing radiation's energy is transferred to the tissue's cells. The *absorbed dose* is defined as the amount of energy that is transferred by ionizing radiation to a given amount of tissue, and is expressed in grays (Gy). One Gy corresponds to the absorption of one joule of energy per kilogram of tissue.

The absorbed dose rate adds the concept of time and is expressed in grays per unit of time (Gy/h, for instance). The effects observed for a given dose rate vary with exposure time.

To convert the energy deposited in tissue to an effective dose, weighing factors (Table 2.4) are used, which take into account the type of radiation. For instance, the emission of an alpha particle inside an organism will cause much more damage than a beta particle. The effective dose takes these variations into account and is expressed in sieverts (Sv). The effective dose rate is expressed in sieverts per unit of time (e.g. microsieverts per hour, µSv/h).

Table 2.4: Weighing factors for determining equivalent doses.

Type of radiation	Weighing factor
Gamma radiation	1
Beta radiation	1
Alpha radiation	20

Source: Tremblay, 2013.

The effects of ionizing radiation, when received by living organisms, are divided into two large categories:

- Deterministic effects:

  These are clinically observed effects that manifest themselves when the dose reaches a certain threshold (~ 500 mSv), the gravity of which depends on the dose received. These effects can result from a nuclear disaster or a medical treatment, and translate to a significant loss of cells in tissues (Tremblay, 2013). In humans, this is manifested by vomiting, hair loss or thyroid gland failure. In the case of strong, localized, external radiation, the first visible effect resembles a skin burn (erythema).

- Stochastic effects:

  These are long-term effects occurring based on a probabilistic theory, where no threshold can be set to ensure that no effects will occur. Nonetheless, there is a linear relationship between the dose received and the effects observed (Tremblay, 2013). In humans and animals, these effects most commonly occur in the form of cancers or genetic anomalies, and as such, a latency period (that can range from five years to several decades) is usually observed (CNSC (2), 2009).

When a tissue is irradiated, ionizing radiation causes damage to the cell's most sensitive component, deoxyribonucleic acid (DNA). If the cell can fully recover after suffering DNA damage, no effect will be observed on the organism. If however, with time, a cell has accumulated too much DNA damage, or if it is unable to effectively repair itself, uncontrolled cell division may occur, which leads to the formation of cancerous tumours (a consequence of stochastic effects). Inadequate cell repair can also lead to cell suicide. If many cells are destroyed in this way, tissue disease results and deterministic effects can soon be observed, such as vomiting and hair loss.

2.4.1 RADIATION FROM NATURAL AND ARTIFICIAL SOURCES

2.4.1.1 RADIOACTIVITY FROM NATURAL SOURCES

There are three sources of natural radioactivity: cosmic radiation, terrestrial radiation (including radon) and internal radiation from food.

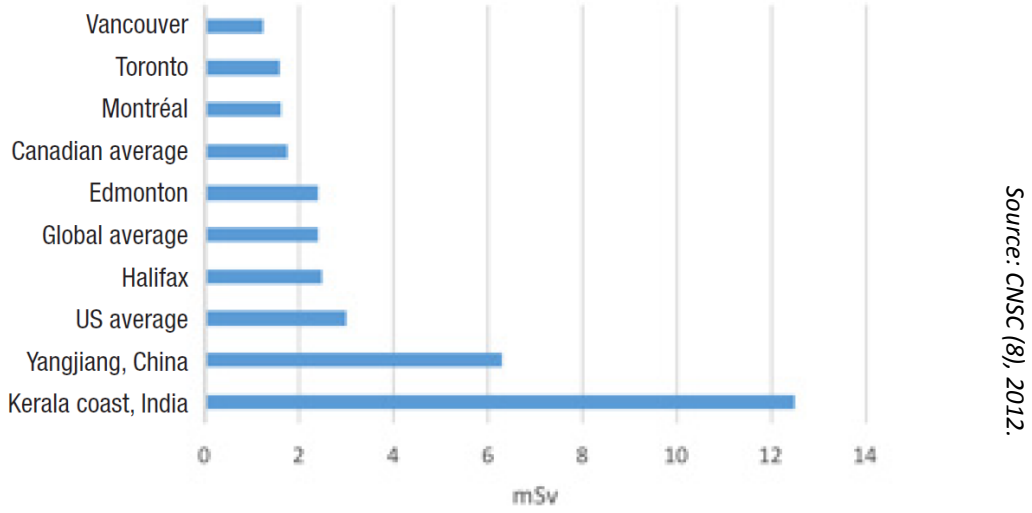
Cosmic radiation that reaches the Earth is of a solar or galactic origin. It is composed of nuclei and elementary particles with high energy, well above that of terrestrial radiation, whether natural or anthropogenic (that is to say resulting from human activity). The intensity of cosmic radiation is greater at high altitude than at sea level.

Terrestrial radioactivity arises from radionuclides in soil, such as uranium-238, thorium-232 and their daughters, as well as potassium-40, all of which have been present in the crust since the Earth formed. Radionuclides are also present in food, given the plants and animals we eat are exposed to the same sources of terrestrial ionizing radiation. The United Nations Scientific Committee estimates that the mean dose from natural exposure is about 2.4 millisieverts (mSv) per person per year (UNSCEAR, 2000). This dose varies according to the type of food

consumed and geographical location. For instance, radiation from a cosmic source is of 0.35 mSv/year in Victoria, British Columbia, and reaches 0.56 mSv/year in Calgary (GA, 2008). Figure 2.4 illustrates how the mean dose from natural exposure received in certain Canadian cities compares with that observed elsewhere in the world.

Natural radioactive background level exists, to which all organisms are exposed. However, some circumstances can lead to increased radioactivity (IRSN (1), 2013).

- The accumulation of radon-222, a gaseous element derived from the decay of uranium-238 in poorly ventilated places, particularly uranium-rich bedrock.
- The production processes and technologies of certain industrial activities (e.g. extractive industries, such as the extraction and processing of uranium ore) will alter the natural radioactive equilibrium of the extracted material and lead to the accumulation, post-processing, of daughter isotopes in mine tailings. In such cases, natural radioactivity is increased by technology. This accumulated radioactivity represents a risk of human exposure and environmental dispersal.



Source: CNSC (8), 2012.

Figure 2.4: Mean annual effective dose from a natural source.

2.4.1.2 RADIOACTIVITY FROM ARTIFICIAL SOURCES

We are also exposed to doses of radioactivity from artificial sources. Artificial sources of radiation that include medical interventions (X-rays, diagnoses, treatments) represent a dose of about 1.2 mSv/year (CNSC (8), 2012). Other artificial sources of radioactivity, which are minor compared to those of medical origin, arise from, for example, nuclear plants or atmospheric fallout from past nuclear weapons testing. The Canadian Nuclear Safety Commission (CNSC), which is the federal agency that regulates nuclear facilities and materials in Canada, sets limits for radiation doses to protect people against overexposure to ionizing radiation from nuclear facilities or nuclear substances authorized in Canada. For the general public, the dose limit is set to 1 mSv per year. It should be noted that the dose limit does not apply to patients who are undergoing medical examinations or treatments that use ionizing radiation. Radioactive substances used in medicine for a diagnosis or therapy, generate effective doses from 0.01 to more than 70 mSv (Mettler et coll., 2008). Typical doses received for various types of x-rays are presented in Table 2.5.

Table 2.5: Dose transmitted to organs for different types of x-ray examinations.

Examination	Organ	Dose (mSv)
Dental X-ray	brain	0.01
Chest X-ray	lungs	0.1
Screening mammography	breasts	3
Abdominal computed tomography (adult)	stomach	10
Abdominal computed tomography (prenatal)	stomach	20

Source: CNSC (8), 2012.

Table 2.6 demonstrates that most of the radiation to which humans are exposed is of natural origin (88 %) and that most of the artificial radiation is from medical sources (11 %). It is important to note that an increase in the frequency and types of interventions administered over the last few decades (Loftus et coll., 2013) has tended to alter this proportion. The CNSC estimates that natural radiation currently represents about 60 % of the annual dose whereas medical interventions represent about 40 % (CNSC (8), 2012).

Living organisms do not distinguish between radiation from a natural or artificial source. When a radiation dose is received, there is no difference in the resulting effects, whether the radiation is from a natural or artificial source.

Table 2.6: The 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.

Exposure to natural radioactivity can be greater in certain work environments, such as in the mining sector, where workers may be exposed to natural radionuclides accumulations in ore, or in the aviation sector, where a flight crew with 20 hours of air time per month is exposed to doses of up to 5 mSv/year.

2.5 CHEMICAL CHARACTERISTICS OF URANIUM AND ITS MOBILITY IN THE ENVIRONMENT

The solubility of uranium in a particular environment affects its ability to be absorbed by various organisms. The chemical toxicity of uranium is therefore related in large part to its solubility and mobility in the environment (the behaviour and chemical toxicity of uranium are the same for all its isotopes, unlike radiotoxicity which is specific to each isotope). The tendency of uranium to solubilize in certain environments depends on its chemical properties and on other geological and biological factors (Vandenhove et al., 2010). These factors are presented below and summarized in Table 2.7.

2.5.1 OXIDATION STATE

The oxidation state of uranium, which is its electronic state in relation to its elementary configuration, affects its solubility. In natural environments, uranium has two stable oxidation states:

- U^{4+}, the immobile tetravalent form that is found, for instance, in uranium dioxide (UO_2), the main component of uraninite;
- U^{6+}, the soluble hexavalent form that is the most common form in aqueous environments (Sheppard et coll., 2005), which occurs as the uranyl ion, UO_2^{2+}.

Under certain chemical conditions, such as in oxidizing, acidic environments, tetravalent uranium is oxidized to form the UO_2^{2+} uranyl ion. The uranyl ion may interact with different chemical molecules naturally present in the environment to form more or less soluble compounds, each which has a different chemical mobility.

Inversely, in a reducing environment (such as in the absence of oxygen), hexavalent uranium is reduced and precipitates as UO_2, an immobile form.

The oxidation state of uranium does not only depend on the presence of oxygen, but also on the presence of micro-organisms, of the decomposition products of wood, natural gas or sulphides within the rocks and sediments, which all possess the ability to reduce hexavalent uranium (Sachs et coll., 2006).

2.5.2 SPECIATION

When uranium is dissolved, it interacts with different organic or inorganic molecules, forming various chemical species. The speciation of uranium includes all these chemical species (Table 2.7). Each species has unique properties, such as its solubility in water. Whether a species forms or not depends on multiple factors such as ambient pH, its redox potential, the chemical composition of the soil and the presence of microorganisms. It is important to know the speciation of uranium in order to predict which form it will take under particular environmental conditions, and therefore estimate its mobility in the ecosystem.

For instance, under acidic (low pH), oxidizing conditions, the dominant uranium species is UO_2^{2+}, the uranyl ion, a mobile and water-soluble species. This ion may however interact with different minerals such as clays (CEAEQ (1), 2013), which reduces its mobility in the environment. In acid soils with high proportions of clay minerals, uranium will have reduced mobility. Under neutral pH conditions, hydroxy-type compounds (e.g. UO_2OH^+) will progressively form (CCME, 2007), whereas in alkaline environments (high pH), carbonate compounds are the main species (e.g. UO_2CO_3, $UO_2(CO_3)_2^{2-}$). These negatively-charged or neutral carbonate compounds are very stable in water and are not generally absorbed by surrounding substances. Consequently, under high pH conditions, such as in soils or alkaline aqueous systems with carbonate ligands (CO_3^{2-}), uranium may be transported in the ecosystem over large distances.

2.5.3 SORPTION

Sorption is the process by which uranium is adsorption at the surface of a solid. Various sorption mechanisms exist, but electrostatic interactions, i.e. the interactions between positively charged and negatively charged particles, often play an important role in this process (Adamczyk and Warszynski, 1996). Certain substances that naturally occur in soil have an electrostatic charge, meaning the molecules on the surface have too many electrons (the surface is negatively-charged), or possess too few electrons (the surface is positively-charged). Dissolved uranium, which commonly occurs as charged particles, can then interact with these types of substances and be adsorbed.

Sorption alters the availability and mobility of uranium in the environment. For instance, in acidic environments, the soluble UO_2^{2+} uranyl ion can interact with oxides at the surface of minerals and be adsorbed. Under certain conditions, negatively charged clays behave like sequestering soils and reduce uranium mobility. Uranium migration is therefore slower in a clay-rich soil compared to other types of soil, the physical properties of clay-rich soil, the low permeability compared to sandy soils, also reduces the percolation rate of water transporting dissolved uranium (Sheppard and Thibault, 1984; IRSN (2), 2013). Uranium may also be adsorbed onto the surface of colloidal particles in water. A colloid is a suspended substance, with particles evenly distributed throughout another substance, a liquid such as water for instance. Colloidal particles are very large compared to water molecules. Because these suspended particles are mobile, uranium can be transported in surface waters or groundwater (Othmane, 2012).

Sorption (and desorption) of various elements (calcium, magnesium, iron, etc.) is constantly occurring in nature and significantly affects the mobility of uranium in the environment.

2.5.4 GEOMICROBIOLOGY

Geomicrobiology is the study of bacteria that "metabolize" metals such as manganese and uranium. The bacteria are able to transform surrounding molecules, like uranium compounds, by altering their oxidation state, in the same way animals transform oxygen into carbon dioxide.

Some bacteria can therefore reduce the oxidation state of uranium and transform it into an insoluble form, which ultimately reduce its mobility in the environment. On the other hand, other micro-organisms can oxidize uranium (increasing its oxidation state and its solubility), thus increasing its availability. There are also bacteria that can decrease the amount of uranium in the environment through processes of intracellular accumulation.

The transformation and accumulation of metals through bacterial activity have a major impact on the mobility and availability of various toxic metals in the environment, such as uranium. Geomicrobiology is used nowadays as a natural way of restoring uranium mine sites (Selenska-Pobkell, 2002; Markich and Twining, 2012).

2.5.5 BIOAVAILABILITY

The bioavailability of uranium is how readily it is assimilated by various living organisms.

Uranium occurs naturally in soils, but the ability to be absorbed by organisms is depends on the chemical form since metal in its reduced and solid form cannot be directly assimilated by organisms. For instance, uranium dioxide (UO_2), which is the main uranium compound in uraninite ore (in which uranium occurs as reduced U^{4+}), is not bioavailable. However, when it is oxidized, the resulting uranyl ion UO_2^{2+} (found under certain conditions such as acidic environments (Jeambrun, 2012)), is uranium's most bioavailable form. Consequently, the more acid the soil, the higher the assimilation rates of uranium by plants.

A laboratory-run study on mustard shoots demonstrated the effect of pH, or level of acidity, on the bioavailability of uranium. This study was able to show that the uranium concentration in the shoots was very low (5 mg/kg), even if the shoots were exposed to soils to which large amounts of uranium had been added (750 mg/kg). When the researchers increased the acidity of the soil by adding citric acid, the concentration of uranium in the shoots went from 5 mg/kg to 5,000 mg/kg (CEAEQ (1), 2013;Huang et al., 1998).

Although there are many transfer modes, uranium is mainly transferred from the soil to plants by way of the roots. However, it tends to be adsorbed and remain at the surface of root tissues. Consequently, uranium concentrations in plants will often be higher for the roots than for the rest of the organism (IAEA, 1985).

This concept of bioavailability is closely related to that of bioaccumulation, which is the ability of certain organisms to absorb an element that occurs at very low concentrations in the environment. It is also related to bioconcentration, a phenomenon observed when an organism, after having accumulated a contaminant from its environment, exhibits contaminant concentrations that are higher than in the environment. In a study of the transfer of radionuclides between aqueous environments and fish tissue in the Elliott Lake area (Ontario, Canada), Pyle and Clulow (1997) measured ^{226}Ra concentrations in fish bones that were 110 to 170 times greater than in surrounding waters, and 20 to 30 times greater than in lake sediments.

Generally, concentrations reported for metals in guidelines and regulations refered to total extractable metals. These criteria are based on models that are applied rather conservatively, as they are likely to be used in a variety of scenarios. When the criterion is not exceeded, we conclude that the risk is acceptable, except in certain cases. If the criterion is exceeded, there are two possible options: We can conclude that the risk is not acceptable and proceed with risk management, or we can refine the risk estimate by doing a study that is specific to the site or issue in question.

In the case of the second option, bioavailability is one of the parameters assessed. This assessment requires a certain number of tests (e.g. identifying the chemical species present, selective chemical extractions, bioassays to evaluate the toxicity for various receptors and routes of exposure) and the results will only apply to a specific site or issue. If the results obtained demonstrate that the risk is acceptable for a particular case, despite exceeding the criterion, we cannot conclude that the criterion is invalid overall. Because these tests are quite extensive and the results are difficult to interpret, bioavailability studies are usually only applied in major or particularly complex cases.

Table 2.7: Summary of the characteristics of uranium and the processes that affect its mobility in the environment.

Factor affecting mobility	Observed form	Characteristics
Oxidation state	Tetravalent form U^{4+}	- Immobile form - solid UO_2 (main component of uraninite) - Present in reducing environments
	Hexavalent form U^{6+}	- Can form soluble compounds, which increases its mobility - Uranyle ion UO_2^{2+} - Present in oxidizing environments - Present in small proportions in uraninite as solid UO_3
Speciation of the hexavalent form	Uranyle ion UO_2^{2+}	Acidic to neutral pH: Uranium is soluble but may interact with fixed substances, which significantly reduces its solubility
	Carbonate species (UO_2CO_3, $UO_2(CO_3)_2^{2}$)	Basic pH: · Very stable in water · Not easily absorbed by substances · Very mobile uranium that can be transported over long distances in the ecosystem
Sorption	Uranyle ion UO_2^{2+}	· Interacts with negatively-charged or oxide-bearing substances · Reduced mobility
Geomicrobiology	Tetravalent form U^{4+}	Can be oxidized by certain bacteria
	Hexavalent form U^{6+}	Can be reduced by certain bacteria
Bioavailability	Solid UO_2 (U^{4+})	Not easily assimilated by living organisms
	Uranyle ion UO_2^{2+} (U^{6+})	· Most easily absorbed species · Reduced mobility if absorbed
	Carbonate species (U^{6+}) (UO_2CO_3, $UO_2(CO_3)_2^{2}$, etc.)	· Easily absorbed by living organisms · High mobility

2.6 MOBILITY OF THORIUM AND THE DAUGHTERS OF URANIUM: RADIUM, POLONIUM AND LEAD

Thorium mainly occurs in the environment in the 4+ oxidation state. The chemical properties of tetravalent thorium are similar to those of tetravalent uranium. Like tetravalent uranium, it is not very soluble in the environment, although its solubility increases in highly acidic environments (pH < 3), where it can occur in the ionized form (Th^{4+}). If the pH increases, it quickly forms non soluble hydroxy-type compounds ($Th(OH)_4$) and oxides, as well as carbonate or phosphate compounds (IRSN (6), 2013). Thorium therefore remains almost insoluble under natural

conditions: even though it is three times more abundant in the Earth's crust than uranium, it rarely occurs in measurable amounts in natural waters.

Like uranium and all actinides, thorium forms strong bonds with oxygen atoms. In its soluble form, it binds with various iron oxides (such as goethite (Fe(O)OH)) and clays, and may also bind with oxygen atoms in suspended inorganic matter. Thorium as an element is not very soluble, and under acidic pH conditions where it occurs as an ion, it is mostly associated with the solid phases of the ecosystem. Its mobility in the environment is low compared to that of uranium.

Radium has only one oxidation state in the environment (2+). This ion can form soluble salts in aqueous environments in the form of chlorides ($RaCl_2$), bromides ($RaBr_2$) or nitrates ($Ra(NO_3)_2$), but forms highly insoluble compounds with hydroxides ($Ra(OH)_2$), carbonates ($RaCO_3$) and sulphates ($RaSO_4$) (Schweitzer and Pesterfield, 2004; Kirby and Salutsky, 1964). Generally speaking, radium is not very mobile in soils as it binds easily to clay-rich soils, other types of soils, as well as to organic matter (Jeambrun, 2012).

Unlike radium, polonium have many forms and oxidation states throughout the entire range of pH. At a lower or neutral pH, depending on the environment's redox potential, polonium can occur at the 2+ oxidation state (Po^{2+}) or the 4+ oxidation state (solid PoO_2). In alkaline environments, it mainly occurs in its tetravalent form (e.g. as soluble PoO_3^{2-} or insoluble $Po(OH)_2$). However, the insoluble and immobile polonium 4+ ion is the main form found in natural environments. Like thorium, it interacts with the surface of various substances (such as organic clays), which reduces its mobility (Jeambrun, 2012).

In nature, lead occurs mainly in the 2+ oxidation state, regardless of pH. In acid to neutral environments, it mainly occurs in its soluble $PbOH^+$ form, whereas in basic environments, it precipitates to form a PbO oxide (Schweitzer and Pesterfield, 2004). Lead remains an element with very low solubility, being quickly and highly absorbed by soil matrices (Jeambrun, 2012).

As discussed above, the mobility of uranium and its daughters in the environment is complex and requires an understanding of the chemical and biological aspects of the environment. This understanding is essential given that the mobility and availability of an element have a significant impact on exposure (human, plants and animals).

3 URANIUM AND SOCIETY

Summary

Uranium is a heavy metal that is abundant on Earth, particularly in granites and sedimentary rocks. Its radioactivity is due to its slow transformation into lead, which produces a small amount of heat. The two main isotopes are uranium-238, the most abundant, and uranium-235, fairly rare. Uranium is soluble and mobile under surface conditions. It was first used as a dye, then in medical applications. When the instability of uranium-235 was discovered in the mid XXth century, its military and civilian applications were developed to produce electricity. Twelve percent (12 %) of global electricity is produced by the 440 commercial power plants, and uranium is used to produce the radioisotopes used in medicine, agriculture and the food industry. Power plants consume about 64,000 tonnes of uranium per year, 55,000 tonnes of which come from mines, the rest is from the reuse of nuclear weapons and spent nuclear fuel. The number of power plants is increasing very slowly, and they are becoming more and more efficient. It is anticipated that in 2035, the demand for uranium will be between 98,000 and 136,000 tonnes. Twenty-two countries mine uranium, whether through *in situ* leaching (e.g. Kazakhstan) or open pit mining (e.g. Namibia) for deposits located close to the surface, or through underground mining for deep deposits (e.g. Saskatchewan). Uranium is also a coproduct of other substances mined, such as phosphorus and rare earth elements.

3.1 WHAT IS URANIUM USED FOR?

Uranium was first used to give glass, ceramic and earthenware a yellow or green colour. The Aboriginal Navajo and Ute peoples used carnotite, a uranium mineral, to decorate their bodies. In the XIXTH century, uranium salts were used to treat diabetes, ulcers and tuberculosis. At the beginning of the XXTH century, radium, another very radioactive element, was being extracted from uranium ores, which was used in anti-cancer treatments and to make luminescent paint. When radium undergoes decay, it produces radon, a radioactive gas. Radium has chemical properties that are comparable to those of calcium.

The work of physicians, such as Niels Bohr, Albert Einstein and Leó Szilárd, initially led to the use of uranium's radioactive properties for military applications, followed by civilian applications. Shortly before the Second World War, Enrico Fermi and his team discovered that the nucleus of uranium-235 becomes unstable when it receives a neutron: it divides into fragments, through fission, and releases a large amount of energy as heat and gamma radiation. This occurs as a chain reaction and led to a nuclear explosion. This technology was developed in the United States by the Manhattan Project, leading to the nuclear bombing of Hiroshima and Nagasaki in 1945.

At lower uranium-235 concentrations, fission may be controlled and releases heat: this is what happens in nuclear power plants. The heat produced is extracted using heavy water (rich in deuterium or $^{2}H_2O$), or using more complex liquid coolants. Uranium's energy potential is considerable: one kilogram of natural uranium provides enough energy to run a 1000 W radiator for more than 14 years, whereas one kilogram of petroleum would be able to run it for 12 hours, and one kilogram of coal, for 6 hours. Smaller research reactors also exist. There are 280 of these in the world, 7 of which are in Canada; one belongs to the *Université de Montréal* (*École Polytechnique*).

Radioactivity produced in nuclear plants has made it possible to develop civilian applications in several domains including medicine and agriculture. In most cases, the radioisotopes produced from the decay of uranium are used. Uranium also has maritime and military applications.

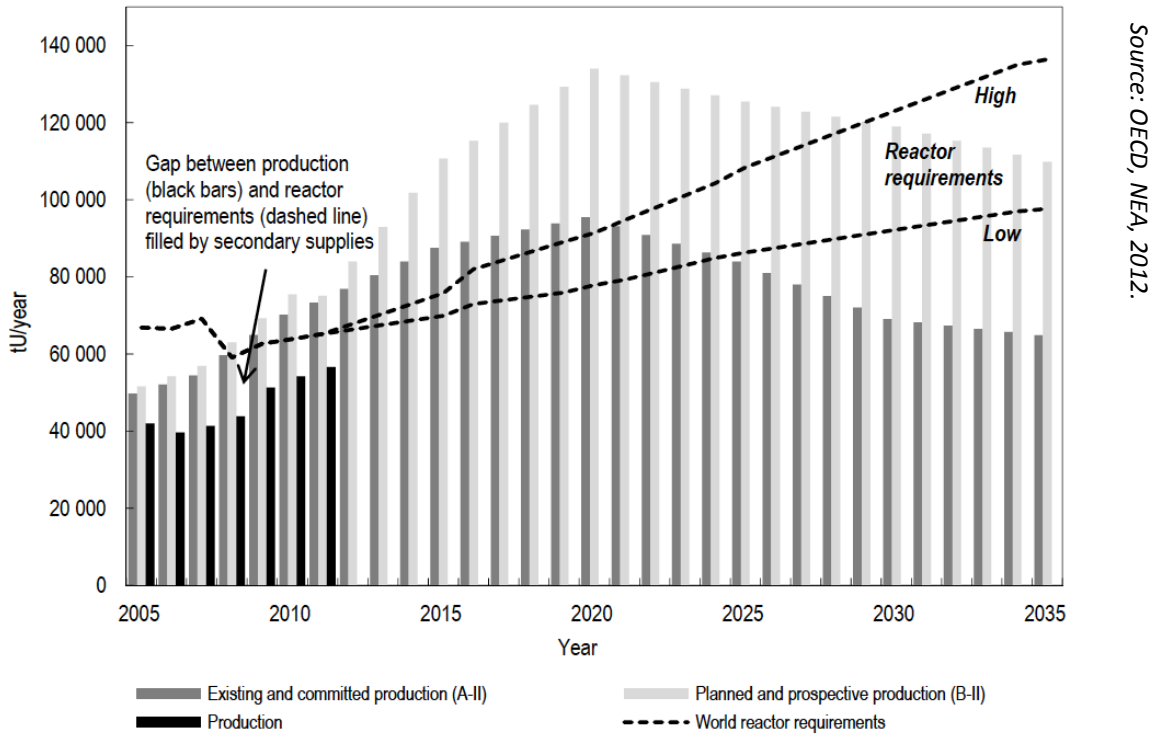
3.2 WHAT IS THE GLOBAL CONSUMPTION OF URANIUM AND HOW WILL IT EVOLVE?

Nuclear electricity has been produced since 1954, and reactors exist in 33 countries. At the end of 2010, there were 440 commercial reactors linked to electricity grids throughout the world, representing a capacity of 375 GW, which accounted for 12.3 % of global electricity production and 5.1 % of total global primary energy. Total uranium consumption was 63,875 tonnes, 54,670 tonnes of uranium were produced by uranium mines (primary production). Military and civilians stocks made up the difference in supply.

For the last 10 years, the number of nuclear plants, and their total electrical capacity, has remained stable. This illustrates the difficulties involved in commissioning new production facilities. There has been very little turnover in the global nuclear fleet. In 2002, the median age of nuclear plants was 19 years old, and went up to 27 years old in 2011. Given the rise in global energy consumption, the proportion of nuclear energy in the global energy supply has decreased in favour of hydrocarbons, coal and renewable energies.

The construction of nuclear plants requires significant time and money. Consumption may then be anticipated on the basis of installed nuclear capacity. The number of reactors is slowly increasing, and they are becoming more and more efficient. As such, it has been possible to reduce the demand in uranium per kWh in Europe by 25 % in 20 years.

The International Atomic Energy Agency (IAEA) has reported that 5,900 GW (gigawatts, with 1 GW = 10^9 W) of additional electrical capacity would be needed by 2035 if the demand continues to grow at the current rate and if facilities are revitalized (Figure 3.1). Two thirds of the demand will come from China and India. In 2012 in light of the Fukushima Daiichi disaster, the IAEA revised this prediction to an annual demand between 501 GW and 746 GW in 2035. This revised estimate is probably still optimistic; however, each GW of new capacity requires 300 to 450 tonnes of uranium to start and about 150 tonnes of uranium to maintain annual production. We may estimate that in 2035, uranium demand will be between 97,645 and 136,385 tonnes per year.



Source: OECD, NEA, 2012.

Figure 3.1: Current and anticipated annual uranium production and the estimated uranium demand of nuclear reactors worldwide, up to 2035.

Any predictions should be considered with caution since the demand for uranium is influenced by several conflicting factors: the growing use of electricity required by demographic growth and climate change, the competitive edge of nuclear energy as opposed to other sources (petroleum, coal, shale gas...), waste management, and the public's attitude toward nuclear energy. Furthermore, the nuclear fleet is growing old, with 289 reactors worldwide over the age of 25 and installation of new reactors is slow. As such, if the life expectancy of nuclear plants is not extended, the global nuclear capacity could rapidly decline.

3.3 WHAT ARE THE SOURCES OF URANIUM?

A deposit is an accumulation of minerals that is sufficient to be mined profitably (Jébrak et Marcoux, 2008). Its grade must be such that the profits generated by uranium extraction exceed the operating and processing costs. Grades of uranium deposits are extremely variable, from a few hundred grams per tonne (300 ppm at Rössing, in Namibia) to hundreds of kilograms per tonne (almost 20 % at McArthur River, in Saskatchewan). The size of a deposit also plays a key role: a low-grade deposit is more likely to be mined if the ore volume is considerable.

Mined deposits can contain up to tens of thousands or tonnes of uranium. They are relatively small deposits compared to the massive iron, copper or coal mines. The depth of the deposit determines the operating costs, a deposit near or at surface costs less than a deep one. Mining method varies significantly and have a considerable effect on production costs. Finally, mineral associations can either facilitate mining (such as when uranium occurs in soluble minerals, or if economically viable coproducts are present, like gold, rare earth elements or nickel), hinder it, or may even be prohibitive if uranium is trapped inside refractory minerals.

In nature, a large number of sedimentary, intrusive and metamorphic processes concentrate uranium to economic grades (Dill, 2010; Cuney, 2010). This is why uranium deposits can be discovered in different types of rocks. For several decades, the IAEA has been working on a uranium deposit classification scheme. Widely used, this classification scheme is based on the type of host rock and on the processes that concentrate uranium. It is therefore a mixed classification, but appropriately reflects industry challenges. A more homogeneous classification based on deposit genesis was proposed by Cuney (2009, 2010) and Skirrow et al. (2009).

Uranium is mainly extracted from mines where it is the principal economic commodity (Table 3.1), but it may also be associated with other substances and constitute a coproduct (if the value is sufficient), or occur in mine waste that has not been optimized. Industrial waste can be a secondary sources of uranium, if uranium processing has not been optimized. Finally, uranium from military and civilian stocks, as well as from spent nuclear fuel, may also be recovered for use as fuel in nuclear plants.

Table 3.1: Sources of uranium.

Source/nature	
Primary (mine)	Principal product
	Coproduct
	Mine waste
Secondary	Industrial waste
	Nuclear fuel recycling

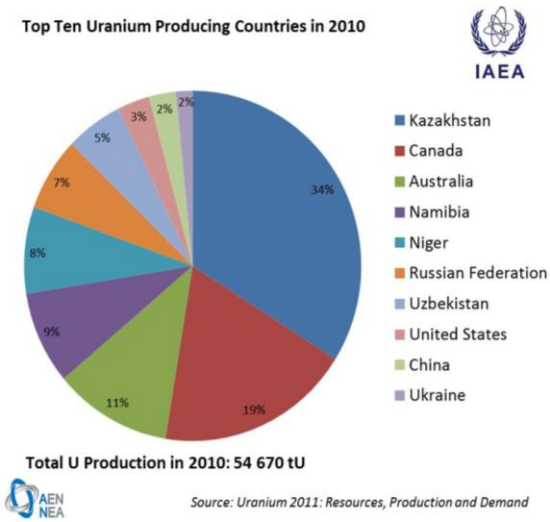
3.4 URANIUM PRODUCTION

Uranium was discovered in Europe, but the first viable uranium deposits were discovered in Colorado in 1898. Their first application was, however, to produce radium, a rare radioactive element derived from the decay of uranium: Pierre and Marie Curie had required 8 tonnes of pitchblende to produce 1 gram of radium, and the American uranium production between 1912 and 1922 totalled only 172 grams! In Canada, the first uranium showing was discovered in 1847 on the eastern shore of Lake Superior. Uranium was subsequently found in a mica pegmatite in Québec, in 1897, most likely close to Gatineau.

3.4.1 GLOBAL URANIUM PRODUCTION

In 2012, the total production from uranium mines totalled 58,394 tonnes, meeting 86 % of the demand from nuclear reactors worldwide, the remainder being met by fuel from secondary uranium sources. This is 25 % more than in 2008, an increase that can be attributed to Kazakhstan, who is currently the top producer in the world. The growth in production was less in Canada, China, Namibia, Nigeria, the United States and Uzbekistan (Figure 3.2).

Twenty two countries declared production in 2010, which is two times more than in 2008 (and three countries more than in 2012), with Malawi starting up production and Germany recovering uranium from rehabilitated mines (Figure 3.3). The future of uranium production will rely on mines currently being developed; there are more than ten of these, mostly in Australia, Canada, Namibia and Kazakhstan.



Source: OECD, NEA, 2012.

Figure 3.2: The top ten uranium-producing countries in the world.

Uranium production in the OECD countries fell by about 3 % in one year, meeting close to 31 % of the OECD countries' uranium needs in 2011. To feed reactors in OECD countries, it became necessary in the last few years to call upon imports and secondary uranium sources, such as uranium stocks, reuse spent fuel, dismantled nuclear weapons and the re-enrichment of depleted uranium. The principle secondary source results from an agreement between the United States and Russia (HEU), signed in 1993, that aimed to transform Soviet weapons into 15,000 tonnes of nuclear fuel. This agreement expired in 2013.

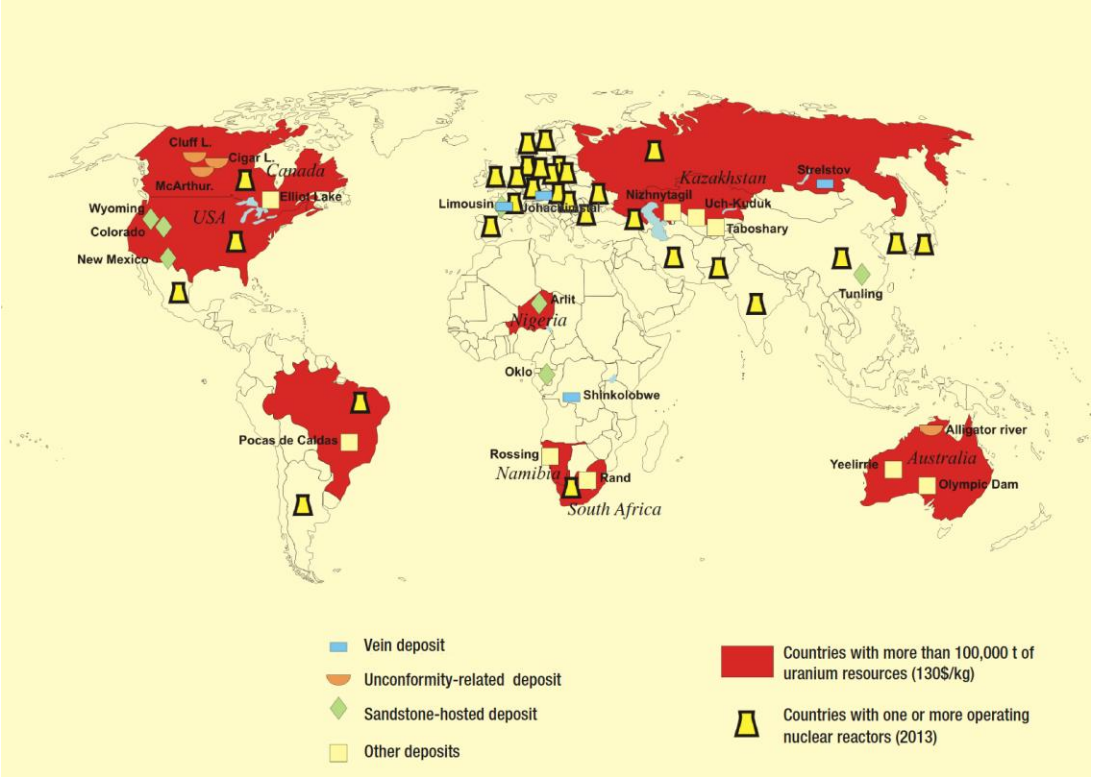


Figure 3.3: Map of the main uranium deposits, producing countries and nuclear power plants, in 2012.

3.4.2 How is uranium mined?

Most uranium mines use technologies that are similar to those used in other metal mines. They are nonetheless the object of a particular surveillance in terms of health and safety. Given the diversity of uranium deposits and the significant variation in grade (from hundreds of ppms to tens of percent), there are also a large variety of mining technologies for this metal. The main four techniques are:

- Mining by *in situ* leaching is currently the most used technique in the world (39 % of uranium produced). This mining method, commonly used for salt, is being developed in Kazakhstan for uranium. However, it requires the use of solvents, either acidic or alkaline, when the deposit is located at depth.

- Underground mining comes in second (32 % of uranium produced); this is the main method used in Saskatchewan due to the depth of the deposits. When grades are greater than a few percent, a highly-automated mining method is required, occasionally without any direct human intervention.

- Open pit mining accounts for 23 % of global production; it is the classic quarry model, used for ores that are close to the surface.

- Uranium can be a coproduct in gold, copper or other metal mines. Six percent of global uranium comes from such sources. These mines may be underground or open pit mines.

Regardless of the type of mine, the timespan from discovery to development and commissioning is always very long, with a current median of about 25 years. This is due to the particular technical challenges posed by very high-grade deposits (such as Cigar Lake, in Saskatchewan, which was discovered in 1981 and is not yet mined), but also to regulatory requirements, which are particularly strict for uranium-related projects.

3.5 THE EVOLUTION OF URANIUM PRICES

Uranium economics are based on a balance between primary and secondary production and consumption. The economic history of uranium is marked by a series of pivotal events (Figures 3.4 and 3.5):

- Production peaked for the first time after the Second World War, to meet military needs related to the Cold War;
- The first civilian nuclear power plant was commissioned in 1957;
- Large unconformity-related deposits were discovered in Canada (1968) and Australia (1969);
- In 1973, the oil crisis led people to believe that nuclear energy could be an alternative solution to fossil fuels, which resulted in a sharp rise in prices: whereas the first civilian transactions hovered around 6 $ US/lb of U_3O_8, prices jumped to 45 $ US/lb of U_3O_8;
- The largest uranium deposit in the world was discovered at Olympic Dam (Australia) in 1975; until 2000, this deposit produced 1,000 to 2,000 tonnes of U_3O_8 per year, then 3,000 to 4,000 tonnes per year since;
- The disasters at Three Miles Island (1979) and Chernobyl (1986) slowed down nuclear growth and cast doubt as to its trustworthiness; the slow-down, or even halt of nuclear programs led to the creation of significant stocks. Prices hit a low (7 to 8 $ US/lb of U_3O_8) in 1992;
- The end of the Cold War and dismantling of the Eastern Block (1990) and of the USSR (1991) gave access to the stocks of the ex-USSR allowing military uranium to be reused in power plants as of 1993; prices continued to fall, dropping below Western production costs;
- As of 2002, an awareness of declining secondary sources and greenhouse gas emissions from electricity production using fossil fuels coupled with a growing hope to once again build power plants, provoked a rise in prices (2003), leading to an exploration boom; a fear of shortage causes prices to climb to more than 100 $ US/lb U_3O_8 in 2007. The biggest mining company in the world, BHP-Billiton PLC, considers quadrupling production at the giant Olympic Dam deposit.
- The Fukushima Daiichi disaster in 2011 led many countries to rethink their nuclear energy policy, causing a drop in uranium prices and reducing the intensity of global exploration.

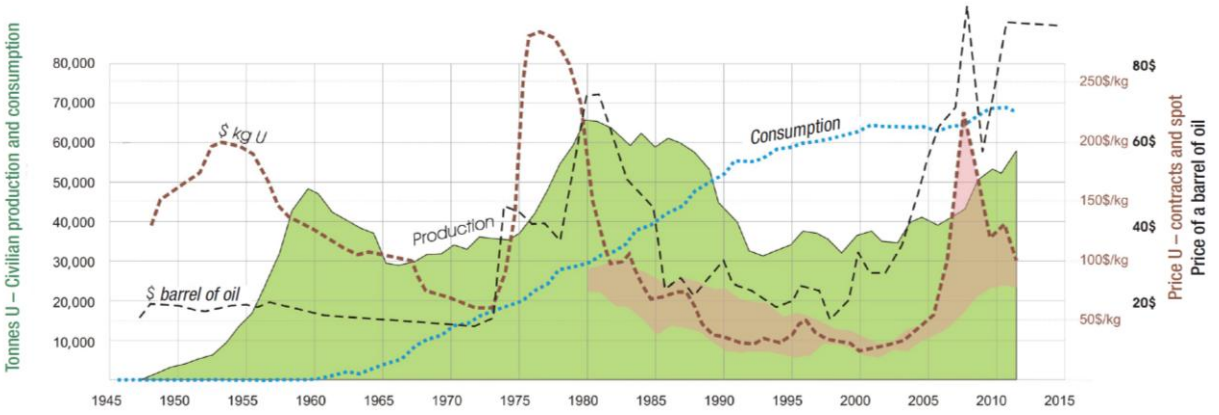


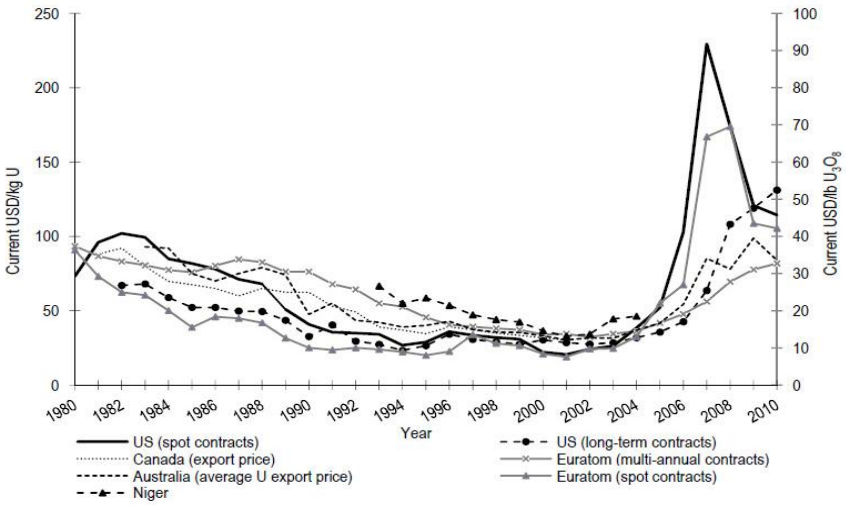
Figure 3.4: Evolution of primary production (green), consumption (blue dashed line) and prices for uranium and oil since 1945. The pink area corresponds to the variation in prices between the spot market and long-term market for uranium.

We can see the impact of energy crises on uranium and oil prices between 1975 and 1985, followed by an increase in production and a rise in commodity prices as of 2005.

Supply and demand as well as prices have evolved considerably over the last 30 years. The price of uranium as it exits the mine is about the same as the cost of processing. Under current conditions, the price of ore represents less than one quarter of the cost to produce nuclear energy.

Uranium is traded in three forms with varying degrees of purity: yellowcake, composed of pure U_3O_8, UF_6, and *Separative Work Unit* (SWU, which represents the work required to separate the U-235 and U-238 isotopes), in $ US/kg of U as UF_6. There are two types of prices for uranium: the long-term price and the spot price, which represents about 15 % of the market. When a nuclear power plant is built, the plant operator guarantees its supply by purchasing uranium for a number of years (3 to 15 years). The spot price applies to relatively small contracts, with same year delivery, with a slightly lower price than long-term contracts (SIDEX, 2004).

How will uranium prices evolve in the coming years? They will in part reflect the ratio of production to consumption but the market is relatively opaque due to private long-term contracts (Capus, 2010). Prices are also sensitive to political aspects (such as anti-nuclear movements in Western countries) and strategic planning.



Source: Australia, Canada, Euratom Supply Agency, Niger, United States.

1. Euratom prices refer to deliveries during that year under multi-annual contracts.

2. Beginning in 2002, Natural Resources Canada (NRCan) suspended publication of export price pending policy review.

Source: OECD, NEA, 2012.

Figure 3.5: Evolution of spot and long-term uranium prices since 1980.

Production-wise, a large number of projects are currently under construction across the world. In Australia, the Ranger 3 Deeps (Northern Territory), Wiluna (Western Australia) and Lake Maitland (Western Australia) projects will be ready for production in 2014-2015. There is also Yeelirrie (Western Australia) and the Olympic Dam mine extension (South Australia), two well-known deposits that could be mined in the near future. In Canada, the Cigar Lake deposit may finally reach the production stage, despite serious technical issues. In Namibia, the Rössing South mine is currently being developed, and the Valencia and Trekkopje projects are at a very advanced stage. In Kazakhstan, several new mine sites are using *in situ* leaching techniques that should significantly increase production. Together, these deposits should be enough to meet the demand and thus help to maintain a fairly low price of uranium. However, with the United States-Russia HEU program (*Highly Enriched Uranium; Megatons to Megawatts Program*) no longer in effect, other ways to compensate the primary uranium deficit will have to be found, especially for the American market, which is particularly deficient. In the medium term, known resources and deposits in development should meet the forecasted demand easily.

Consumption-wise, we expect an increase in demand despite the Fukushima Daiichi disaster. Nuclear energy is one of the ways to generate power, and reactors are currently under construction in China, India, Korea and Russia. Chinese companies are involved in a large number of mining projects in order to secure supply for their nuclear fleet. Kazakhstan, the top uranium-producing country in the world, is also an Asian country. In OECD countries, if a tendency for power plants average age is to continue to increase, demand could potentially decrease. In these counties, public opinion, which is varied, will play a key role. Any delays, whether related to production or to the commissioning of new plants, could affect and perhaps even put pressure on prices.

Finally, the uranium market, like other metal markets, is evolving toward heavier financialization, including hedging against forward investments, which could promote instability in prices.

4 THE URANIUM INDUSTRY IN QUÉBEC

Summary

Both large companies and juniors have prospected for uranium in Quebec. There are more than twenty exploration companies with projects in Quebec, the majority of which also have their head office in the province; Ressources Strateco's Matoush project is the most advanced.

Canada is the second largest uranium producer in the world. There are 18 nuclear reactors in Canada. The Gentilly-2 reactors were shut down in 2012; a waste storage area remains. A research reactor is located at the *École Polytechnique de Montréal.* Candu Energy Inc., which specializes in the design and supply of nuclear reactors, is a subsidiary of SNC-Lavalin Inc., headquartered in Montréal. There are no uranium processing facilities or fuel fabrication plants in Quebec.

4.1 EXPLORATION COMPANIES

Uranium exploration can be carried out by two types of companies: (1) uranium mining companies, which are often vertically structured as to follow the cycle of nuclear combustion from mining to reprocessing; and (2) junior companies, which aim to discover and develop new mineral resources; they can subsequently sell them to bigger companies, or attempt to start production themselves.

Several large companies are currently active in Québec or have conducted exploration work in the province in the past. CAMECO, a Canadian company and the top producer in the world, was born from the privatization of two Canadian Crown companies. CAMECO has exploration projects in the Otish Basin, among others. The second largest producer, AREVA, is a French company born from the privatization of the activities of the *Commissariat à l'énergie atomique*. Areva Resources Canada, its subsidiary, has claims in the Ungava area. Hathor Exploration, a subsidiary of the mining company Rio Tinto PLC, is present in the Otish Mountains.

Québec is recognized for its knowledge in mineral exploration. Ten years ago, several junior companies showed interest in uranium exploration following an increase in uranium prices. Ressources Strateco holds the most advanced project in Québec, located in the Otish Basin. Other junior companies do not specialize in uranium and have a diverse project portfolio, including projects in northern Québec. This is the case of Azimut Exploration Inc., Denison Mines Corp., Dios Exploration Inc., Ditem Explorations Inc., Globex Mining Enterprises Inc., Midland Exploration Inc., Quest Rare Minerals Ltd., Uracan Resources Ltd, and Virginia Energy Resources Inc. About 70 % of these companies are headquartered in Québec, the others have headquarters in Vancouver or Toronto.

Finally, many companies hold mining rights in areas with uranium potential, such as Abitex Resources Inc., A Better Search Inc., Energizer Resources Inc., Entourage Mining Ltd., Gimus Resources Inc. (Jourdan), Resources Maximan Inc., Richmond Minerals Inc., Sheridan Platinum Group Ltd., Starfire Minerals Inc., Uragold Bay Resources Inc., Uranium Valley Mines Ltd. and X-Terra Resources Corporation.

4.2 USE OF URANIUM IN QUÉBEC'S NUCLEAR POWER SECTOR

Nuclear power provides close to 15 % of electricity in Canada, and 40 % in Ontario (Table 4.1). Canada has a fleet of 18 CANDU reactors (heavy water reactors) which were designed by Atomic Energy of Canada Limited (AECL). In 2012, the national production capacity was of 12,600 MWe across five sites: Pickering, Darlington and Bruce (Ontario), Gentilly (Québec), and Point Lepreau (New Brunswick).

The Canadian nuclear industry provides direct or indirect employment to nearly 66,000 people. With close to 10,000 tonnes of uranium produced in 2012, Canada ranks second among global uranium producers, behind Kazakhstan.

Table 4.1: Activities of the Canadian uranium industry for 2013. The number in parentheses corresponds to the facility located in Québec.

Type	Anticipated	Construction	Commissioning	Production	Shut down	Closing	Dismantling	Other	Total
Mine and uranium extraction	-	-	-	3	1	-	9	1	14
Conversion	-	-	-	4	-	-	-	-	4
Fuel fabrication	-	-	-	4	-	-	1	-	5
Spent fuel storage	-	-	-	6 (1)	-	-	-	-	6
Reprocessing and reuse of spent fuel	-	-	-	1	-	-	1	-	2
Related industrial operations	-	-	-	2	-	-	5	2	9
Total	**0**	**0**	**0**	**20**	**1**	**-**	**16**	**3**	**40**

Source: IAEA, 2013.

4.2.1 ELECTRICITY PRODUCTION AND CONSTRUCTION OF NUCLEAR REACTORS

There is only one site for nuclear energy generation in Québec, Hydro-Québec's Gentilly-2 power plant in Bécancour. Gentilly-1, a prototype, operated for a few months in the 1970s and Gentilly-2 operated from 1983 to 2012, before being permanently shut down in December 2012. It operated at 2,156 MWt (thermal power), with a total net output of 635 MWe (electrical power). There were no active nuclear power plants in Québec in 2013 (Hydro Québec, 2013).

The energy company Candu Energy Inc., a subsidiary of the SNC-Lavalin Group Inc., specializes in designing and supplying nuclear reactors, as well as in providing products and services related to nuclear reactors. The subsidiary was born in 2011 after SNC-Lavalin purchased the "commercial CANDU reactors" division of the AECL. Candu Energy Inc.'s headquarter is located in Mississauga, Ontario. CANDU reactors have unique characteristics, such as the capacity to use natural uranium (non enriched) and other types of fuel, such as uranium recovered from light water reactors, mixtures of low enriched uranium (LEU) and plutonium (Pu) oxides, thorium (Th) and actinides.

4.2.2 URANIUM PROCESSING FACILITIES AND FUEL FABRICATION PLANTS

There are no such installations in Québec. The yellowcake produced in Canada is purified to UO_3 oxide at the uranium refinery in Blind River (Ontario; Cameco Corporation) and at the conversion and nuclear fuel fabrication plants in Port Hope (Ontario). Uranium is then made into fuel pellets at the GE Hitachi Nuclear Energy Canada Inc. plants in Toronto and Peterborough (Ontario), and at the Cameco Fuel Manufacturing Inc. plant in Port Hope (Ontario).

4.2.3 RESEARCH REACTOR

There is only one nuclear research reactor in Québec and it is located at the *École Polytechnique de Montréal.* It is a SLOWPOKE-2 reactor. The following description is provided on the *École Polytechnique de Montréal*'s website http://www.polymtl.ca/nucleaire/en/LTN/SLP.php):

"The main piece of equipment is the SLOWPOKE nuclear reactor. This small pool-type reactor operated from 1976 to 1997 with the original fuel, 1 kg of 93% enriched uranium. In 1997, thanks to an NSERC Major Installation Grant, the reactor was refuelled with 5 kg of uranium enriched to 20% in U-235. Instrumentation is also available for training nuclear engineering students in reactor kinetics. "

4.2.4 NUCLEAR WASTE AND MATERIALS GENERATED BY THE NUCLEAR SECTOR

There is an irradiated fuel dry storage area (IFDSA) on site at Gentilly-2. The irradiated fuel removed from the reactor spends at least seven years in a storage pool next to the reactor before being stored in CANSTOR dry storage modules located inside the plant's perimeter. There are nine operating CANSTOR modules at the Gentilly-2 plant (Hydro-Québec, 2013).

Spent fuel is stored inside these modules until being reprocessed at a later time. The final storage step for radioactive waste remains to be determined. A second solid radioactive waste management facility (SRWMF) is also located at Gentilly. Low- and medium-level radioactive waste is stored at the SRWMF (NRC, 2013).

5 URANIUM RESOURCES IN QUÉBEC

Summary

A uranium deposit consists of a mineral accumulation that can be profitably mined. Current uranium prices allow both low-grade (0.03 % U) and very high grade (20 % U) uranium deposits to be mined. Given the province's geological potential, deposits are anticipated in sandstones, comparable to those in Colorado and Saskatchewan, in conglomerates, and in intrusive and metamorphic rocks. Currently, there are about fifty exploration projects in Québec for which uranium is the main substance of interest. Seven projects are at an advanced exploration stage. Three projects are the pre-feasibility stage, namely two uranium deposits in the Otish Basin northeast of Chibougamau, and one uranium-bearing rare earth elements deposit northeast of Schefferville. Based on the inventory of resources, the province possesses significant resources on the global scale for low-grade and medium-grade uranium deposits.

5.1 TYPES OF URANIUM DEPOSITS

Different types of uranium deposits are presented below. These different deposit types formed in a wide range of geological environments, and in some cases, such as for Saskatchewan deposits, within a given time period in the Earth's history.

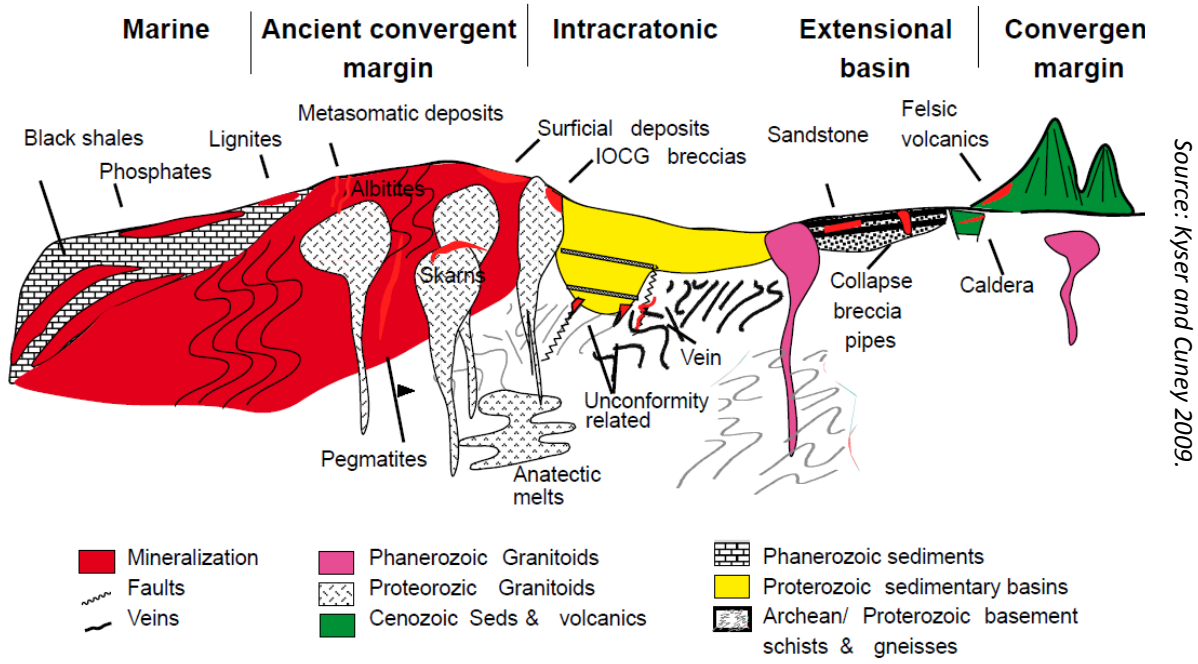
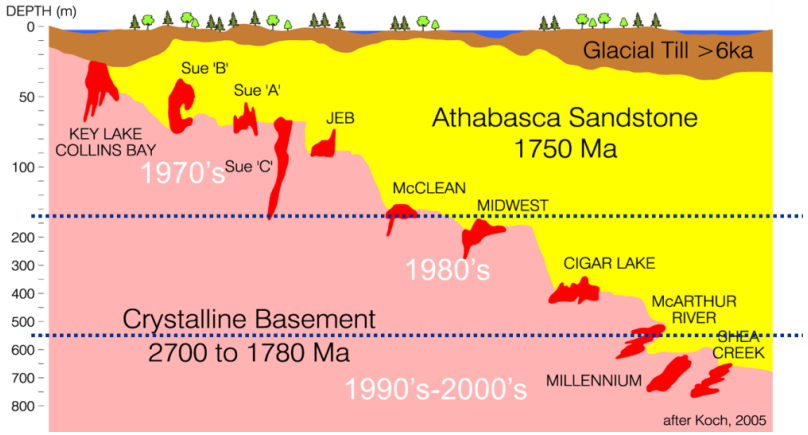


Figure 5.1: Schematic location of the different types of uranium deposits.

5.1.1 Unconformity-related deposits

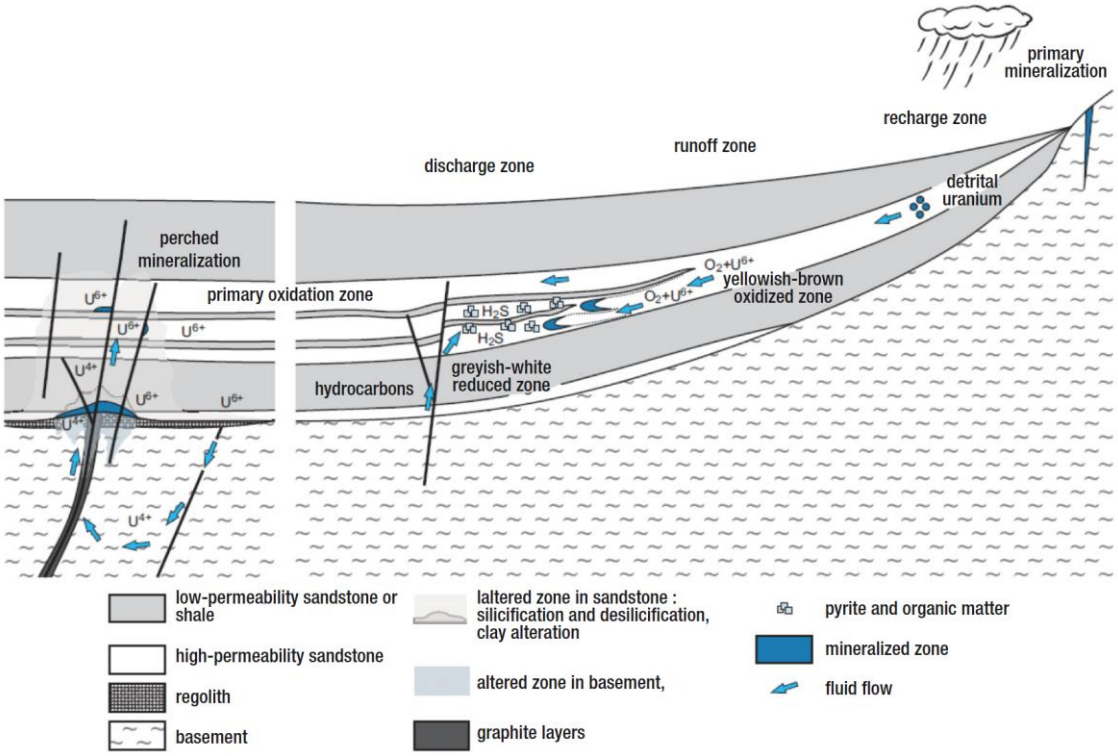
Unconformity-related deposits are uranium accumulations occurring close to the contact between older, highly deformed basement rocks and younger, undeformed sedimentary rocks, i.e. sandstones (2.1 to 1.6 billion years or Ga) (Figure 5.2). These deposits were discovered in the mid XXTH century in Canada (Athabasca Basin, in Saskatchewan and Thelon Basin, in Nunavut) and in Australia (Northern Territory). Similar basins have been identified in Canada (Otish Basin, in Québec) and in Russia. These deposits represent about one third of global uranium resources. They are generally small in size, measuring a few hundred metres in length, and have a complex geometry; they may be extremely uranium-rich. For instance, the McArthur River deposit contains 147,000 t U_3O_8 and is the most uranium-rich deposit in the world, grading on average 17 % U_3O_8, more than 100 times greater than other sandstone deposits. The Key Lake processing facility is the largest mill in the world. Mineralization consists of uraninite, pitchblende and coffinite, and may contain nickel, platinum and gold as coproducts. These deposits are the result of uranium being leached from the basement rocks and sandstone host by saline waters, and precipitated in reducing zones.



Source: D. Thomas, personal communication, 2006.

Figure 5.2: Position at depth of unconformity-related uranium mineralization in the Athabasca Basin (Saskatchewan) and the time frame for discovery: the highest grade and deepest deposits were discovered several decades after exploration first began. Ma: million years

Sandstone is a significant source of uranium in the world, and represents 18 % of global resources. *In situ* leaching is used to mine this type of deposits in Kazakhstan, whereas underground or open pit mining is the preferred method in many other countries. Deposits of this type are fairly common throughout the world, and they range in age from Proterozoic (<2,500 million years or Ma) to Tertiary (<65 Ma). There are significant deposits in North America (Colorado, Wyoming), South America (Argentina), Africa (Nigeria, South Africa and Gabon), Asia (Kazakhstan, Uzbekistan), Australia and Europe (France, Germany). Uranium is generally sourced from nearby rock formations undergoing erosion, and transported by deep basinal fluids (Figure 5.3). Uranium precipitates in mixing zones or near reducing rocks, such as rocks with abundant organic matter or sulphide minerals. They form low-grade, high-tonnage deposits. Detailed studies reveal many forms: roll-fronts, tabular, veins, or related to specific stratigraphic levels. Roll-front deposits result from the interaction between oxidizing and reducing groundwater fluids. They also contain vanadium, molybdenum, selenium and arsenic. Tabular deposits occur in permeable sandstone channels, often at various levels within large sedimentary basins (like those in Niger or Colorado). Lithological deposits result from the fixation of uranium onto organic matter. Those in the Franceville district in Gabon demonstrate a rare process: two billion years ago, high uranium concentrations, the isotopic ratios of that uranium and the presence of water led to the formation of several small natural nuclear reactors, such as in Oklo. There are several potentially uranium-bearing sandstone units in Québec, in the north of the province (James Bay Lowlands, Labrador Belt) as well as in the Appalachian Mountains.



Source: Jébrak et Marcoux, 2008.

Figure 5.3: Sandstone and unconformity-related deposits.

5.1.2 IOCG DEPOSITS

IOCG deposits (iron oxide copper gold), or U-Cu hematite breccias, are deposits that combine iron, copper in gold in large breccia complexes. This deposit style was first discovered in 1975 in South Australia by Western Mining. Although no radiometric anomaly was observed, ore analyses indicated that uranium concentrations were present, averaging 600 grams of uranium oxide per tonne (600 ppm or 0.06 % U_3O_8). Olympic Dam quickly became one of the largest uranium deposits in the world, ranked first based on reserves, and the current operator is considering an expansion project which would include the recovery of uranium as a coproduct. From the start, this deposit has been the subject of heated debates in Australia. Its massive size has led the Federal Labor Party to review its position on the banning of uranium in Australia and to implement the three mine policy, restricting the number of simultaneously active uranium mines in the country to three. Over the last 30 years, deposits of this type have been discovered in Australia, Chile and Brazil, but uranium is not recovered, due to low grades. Showings have been identified in Canada, particularly in northern Québec and in the Gaspésie area.

5.1.3 CONGLOMERATE DEPOSITS

Conglomerate-hosted deposits are located within very ancient river beds, dating back to the Archean (more than 2.5 Ga (billion years ago)). They form placer deposits, which represent 13 % of global resources. Ancient placers (paleoplacers) may contain heavy, dense minerals trapped within pebbles: gold nuggets, pyrite grains, uranium minerals (uraninite, uranothorite, brannerite) and occasionally platinum and rare earth elements. Deposits of this type are identified in three regions: Blind River–Elliot Lake in Ontario, Jacobina, in Brazil, and the Witwatersrand, in South Africa, where more than 165,000 t U_3O_8 have been produced. These deposits are among the first to have been mined and uranium grades range from 100 to 1,000 ppm. Uranium placers only occur in rocks from the

Archean, when the atmosphere contained very little oxygen; in more recent times, these minerals would have been dissolved in rivers and could not have been transported as detrital grains. Deposits of this type could be discovered in conglomerates of the Apple and Sakami formations in the James Bay area, for instance, where showings have been identified.

5.1.4 INTRUSIVE DEPOSITS

Intrusive deposits are low-grade, but commonly high-tonnage deposits occurring in highly metamorphosed ancient basement rocks. The classic example for this type of deposit is Rössing, in Namibia, mined since 1976. Uranium is finely disseminated in pegmatites, which are very coarse-grained granitic rocks. The grade is very low, around 300 ppm U_3O_8. These uranium concentrations result from the high-temperature melting of uranium-rich sediments, and their inclusion in the formation of granite. These deposits are relatively common, and have been known for a long time in Canada, in the Grenville Province, both on the Ontario side (Bancroft Mine, located between Ottawa and Toronto, mined after the Second World War), and the Québec side, in the Basse Côte-Nord region for instance, or in Labrador. There are also likely to be many uranium accumulations of this type in the Superior Province.

5.2 OTHER TYPES OF URANIUM DEPOSITS

Uranium concentrations may occur in some volcanoes. These volcanoes have a felsic composition (silica-rich), occasionally causing large caldera-forming eruptions. Uranium accumulates in permeable zones, enabling the circulation of uranium-enriched fluids though porous volcanic layers such as tuffs and fault zones. Deposits of this type are known in many parts of the world; the Streltsovka deposit (the top producing deposit in Russia) is one of them. Uranium occurs as pitchblende and is associated with molybdenum, mercury, selenium and fluorine. It is possible that ancient equivalents to this type of deposit will be discovered in Québec, but none are known at this time.

Metasomatic uranium deposits are related to alteration zones along faults. They are known to occur in Brazil (Espinharas), Mozambique (Tete), Ukraine (Zheltye Vody), Cameroon (Kitongo), Queensland, Australia (Valhalla), Canada (Beaverlodge), India (Jaduguda), Russia (Yakutie) and Kazakhstan (Kokchetav). Alteration is thought to result from intrusions or metamorphism. It is possible that deposits of this type will be discovered in Québec.

Surficial uranium concentrations have been identified in modern rivers and hypersaline lakes in the deserts of Australia (Yeelirrie) and Namibia (Langer Heinrich). These concentrations are related to carnotite crusts in sand, occurring with gypsum, carbonates (calcrete), iron oxides and salt. The Langer Heinrich deposit has been mined since 2007, has a grade of 550 ppm U_3O_8, and mining very low-grade open pits (less than 100 ppm U_3O_8) has been considered. Open pit mining, however, would require significant investments (particularly water) and a particular processing method for this type of ore. It is unlikely that this type of deposit will be discovered in Québec given that they require a long period of meteoric alteration under arid conditions to form.

Karst breccias are rock collapses in karst related to the formation of limestone caves by hydrothermal fluids. Mineralization comprises uraninite, uranium vanadates and phosphates. These deposits are almost exclusively found in Arizona. In particular, the old Orphan mine is located at the heart of the Grand Canyon National Park in Colorado. Deposits of this type are unlikely to be found in Québec, yet potentially-mineralized carbonate formations are known (Gatineau, Gaspésie, Labrador).

Sedimentary phosphate is mined for use as fertilizers in agriculture and plays an important role in global food production. The main sedimentary deposits in the world correspond to coastal basins with abundant fish bones and organic matter. Phosphate within these basins contains 50 to 200 ppm of uranium, marine phosphates contain less

uranium than those rich in organic matter. Uranium substitutes for calcium within the crystal structure of apatite, the main phosphorus mineral. The top producer in the world is Morocco, and Moroccan phosphates are uranium-rich. Even though they are low-grade, they contain very large amounts of ore, yielding concentrations of several million tonnes of uranium (about 7 Mt in Morocco). However, uranium mining related to phosphates has, until recently, posed a significant technological and financial challenge. Deposits of this type also known to occur in the Central African Republic (Bakouma), Kazakhstan (Melovoe), Jordan and Florida. There are no sedimentary phosphate deposits in Québec.

A skarn is a type of rock that forms when carbonate-rich rocks close to a heat source, typically an intrusion, are heated. Uranium-bearing hydrothermal fluids can infiltrate skarns. Such is the case at Mary Kathleen, a deposit in Queensland, Australia that is enriched in uranium (uraninite) and in rare earth elements. The mine was in operation from 1958 to 1963, and from 1976 to 1982. It produced 8.2 Mt of ore, from which approximately 8,900 tonnes of U_3O_8 were extracted. A similar showing was discovered in the Ungava region.

Exceptional uranium concentrations occasionally occur in black shales where metals can be concentrated by organic matter under reducing conditions. In Sweden, the several metre-thick alum shales of Cambrian age that have been mined for alum, which is used in tanning and to fix colour in textiles, for metals (uranium, vanadium, nickel) and for hydrocarbons. Uranium resources at this deposit are estimated at 1.7 million tonnes (Andersson et al., 1985). Similar black shales occur in Estonia (*Dictyonema Shale*), in Germany and in the United States.

Uranium-rich veins include many styles deposits. "Five element" veins or "BiCoNi" veins combine bismuth (Bi), cobalt (Co), nickel (Ni), silver (Ag) and uranium (U). They have been documented in Central Europe, as well as in several other environments. In Canada, such deposits have been mined in the Great Bear Lake area (at Port Radium for instance). There are also many pitchblende veins that have been mined, most notably in Europe (France, Germany, Czech Republic). It was these veins that led to the discovery of radium.

Lignite is low-quality coal that may contain uranium; it is found in Kazakhstan, Greece, Germany and the Czech Republic. Lignite is not directly mined, but may have acted as a geological source that was subsequently concentrated to form other types of uranium deposits.

Seawater has long been considered a potential source of uranium. In fact, the ocean is thought to contain more than four billion tonnes of uranium; however, the grade is currently too low (3 ppm, or 3 milligrams per tonne of seawater) to be viable for extraction.

5.3 THE GEOLOGICAL POTENTIAL OF QUÉBEC

The province of Québec is composed of five geological provinces: 1) the Archean basement of the Superior Province; 2) the Proterozoic basement of the Churchill Province; 3) the Proterozoic Grenville Province; 4) the St. Lawrence Platform and Monteregian intrusions; 5) the Paleozoic Appalachian Province. In Québec, the Archean basement can be overlain by a few Proterozoic sedimentary basins (the Otish and Mistassini basins located in the south part of the Superior Province) and ten or so small slivers of Proterozoic sedimentary basins (such as the Sakami Formation) (Pauwels, 2005).

The primary uranium resources in Québec will be presented below according to their geological environment (Figures 5.4 and 5.5). Mineral resources are quantities of mineralization that are known or interpreted on the basis of geological knowledge. There are several classifications for the various types of mineral resources used in different countries. With regard to uranium, the International Atomic Energy Agency has adopted a particular

framework for uranium resources. The different mineral resource categories are defined based on their degree of uncertainty: the most certain resources are Reasonably Assured Resources (RAR).

Mineral reserves are the mineable part of resources with demonstrated profitability. These are the resources with the highest level of confidence. Mineral resources for which the tonnage and grade have been defined are qualified, in decreasing order of confidence, as "measured" or "indicated". Other types of mineral resources are more speculative because the quantity and grade are not as well defined. Some types of mineral resources are only interpreted, again on basis of geological knowledge, and their existence has not yet been proven. The existence of the more speculative mineral resources is highly uncertain; however, this concept remains useful for governmental planning as well as for regional-scale mineral exploration.

In Québec, as elsewhere in Canada, public companies are subject to provincial securities authority, namely the *Autorité des marchés financiers du Québec* (AMF). Provincial governments, like the Québec government, have adopted the "National Instrument 43-101 Standards of disclosure for mineral projects" which defines, among other things, the types of mineral resources a company can disclose. In the following inventory of uranium mineral resources, all types of publicly-disclosed resources have been compiled, regardless of quality. Because mineral resources may have been disclosed prior to the implementation of NI 43-101, thereby using different classification guidelines, it would be very difficult to apply a common classification scheme to all mineral resources disclosed. The different types of mineral resources are therefore grouped together without being assigned a descriptive term to qualify them. Hypothetical, speculative and other categories for highly uncertain mineral resources are not taken into account.

Because uranium is a mobile metal in oxidizing environments, it can accumulate in several geological contexts. In Québec, the deposit types most likely to be significant and of economic interest are:

- **Sandstone deposits.** There are many sandstone deposits in North America, in the western U.S. (Colorado, Wyoming, Texas) as well as in Saskatchewan, the Northwestern Territories and Nunavut. There are two sub-groups: low-grade and high-grade. In low-grade deposits, uranium that was originally dispersed in sandstone (ancient sand) is remobilized by oxidizing waters and accumulates as lenses in redox fronts (“roll fronts”) or close to fragments of fossilized wood or organic matter. These deposits are large and spread out. They are mined using open pit and underground methods (United States, Niger). This type of mineralization occurs in the Labrador Belt, in the Churchill Province. In high-grade deposits, as in Saskatchewan, uranium accumulates along the contact between the Archean basement, which is made of old, highly deformed rocks, and the overlying sandstone basin. The name "unconformity" is used to refer to this contact. These deposits are small and very rich in uranium, occasionally containing up to 20 % U, such as the McArthur River deposit in Saskatchewan. They are for the most part mined using automated underground methods. Three medium-grade deposits are known (Otish Basin, in the Superior Province). These are the only deposits with reserves in Québec, and they represent a resource of 16,300 t U. Moreover, there are many prospects of this type in the James Bay area.

- **Conglomerate deposits.** These deposits represent ancient pebble accumulations in rivers. During the Archean, when the atmosphere had very little oxygen, uranium could be transported as small detrital grains without being dissolved, as is the case nowadays in oxidizing environments. These small, very dense grains accumulated in sands and conglomerates, which also occasionally hosted gold. The largest deposit of this kind is the Witwatersrand Basin in South Africa, which is also the world's largest gold deposit. The ore grades 4.4 g/t gold and 64 g/t U. In Ontario, the Blind River and Elliot Lake conglomerate deposits have been mined. Conglomerate deposits occur in Québec, particularly in the James Bay area, in the Superior

Province, where Sakami-type basins are thought to contain at least 13,300 t of uranium in two low-grade deposits.

- Uranium can be associated with **intrusive deposits** in alaskites and pegmatites. These deposits are rarely mined given their low grade. However, one of the most important mines in the world is located in Rössing, Namibia, where Rio Tinto is currently mining a very large, low-grade uranium deposit (598 Mt at 245 g/t U_3O_8), of almost 150,000 t U. There are many showings in Québec, particularly in the Grenville Province (in the Basse-Côte-Nord region, in the Mont-Laurier sector) and in the Churchill Province, in the Ungava region. In the Grenville Province, the potential resources are estimated at 28,900 t U divided into six low-grade deposits, and 52,600 t U divided into six very low-grade deposits. In the Churchill Province, two recently discovered areas represent more than 6,000 t U with a low grade.

- **IOCG deposits.** For this type of ore, gold, copper and uranium are mined. Iron may also be recovered, and on occasion rare earth elements. The exceptional Olympic Dam deposit, in South Australia, has an average grade of 204 g/t U_3O_8 for reserves of 8,946 Mt at 0.75% Cu, 0.30 g/t Au and 1.26 g/t Ag. How these deposits formed is still poorly understood, but they have been discovered in many places across the world, and there are many similar showings in Québec, in the Basse-Côte-Nord and in Nunavik.

It is worth mentioning that there are no deposits in Québec formed by the infiltration of meteoric waters. These deposits are very common in warmer climates, at lower latitudes. Québec's climate is not favourable to uranium transport, and the ice cap retreated only very recently (~6,000 to 7,000 years ago). Recent glacial action has resulted in a generally young topography, exposing rocks at surface that have barely been weathered. This does not favour the dissolution of uranium in rocks by water. The occurrence of peat bogs in Québec is also worth mentioning. Peat bogs can trap the traces of uranium or other metals that may be circulating in surface waters.

The geochemical map of uranium concentrations in lake bottom sediments, created by the *ministère des Ressources naturelles du Québec*, provides a computer-generated image of potentially uranium-rich zones (Figure 5.4). These uranium-rich zones are shown in Figure 5.4, as well as areas of concentration that remain under-explored. This map only shows concentrations occurring at the surface, and more specifically concentrations where uranium is hosted by refractory minerals or organic matter. The map is therefore an approximation, which can be used to determine broad areas of interest. In fact, the mobility of uranium under oxidizing surface conditions and entrapment within anoxic sediments (oxygen-poor) in the bottom of lakes can generate regional-scale artefacts on the map.

5.3.1 Churchill Province and Labrador Belt

These areas contain three types of mineralization:

- There are rare metal (rare earth elements, zirconium, yttrium, beryllium, niobium, tantalum) and uranium deposits associated with peralkaline granites: 42,509 t U spread across three deposits located in the eastern part of the province, within the Mistasin batholith (1.2 Ga) (Misery Lake, Strange Lake B Zone and Main Zone). The mineral potential for uranium is vast.

- Along the western edge of the Churchill Province, the Labrador Trough (New Québec Orogen) hosts the Eldor deposit, the most significant uranium resource in Québec: 114,985 t U. This alkaline intrusion of Proterozoic age (1.8 Ga) has only been partially explored.

- The central northern part of the province (or the Core zone) contains metasedimentary rocks in the Torngat Orogen (Lake Harbour Group). Discoveries were recently made in this area, spurred by the

measurement of a significant uranium anomaly in lake bottom sediments. Although the existence of resources has not yet been demonstrated, work carried out between 2006 and 2010 led to the discovery of hundreds of showings, some quite significant, with resources estimated at more than 6,000 t U. They are located in granitic pegmatites and in associated adjacent metasediments.

The Archean basement (< 2.5 Ga) in this area has been affected by episodes of deformation and metamorphism during the Trans-Hudson orogeny (~ 1.85 to 1.75 Ga). During this time, the erosion of basement rocks led to the formation of Paleoproterozoic volcanic-sedimentary basins (~ 2.1 to 1.85 Ga) where uranium from the eroded granitic basement accumulated. Sediments within these basins underwent partial melting during the last orogenies. This gave rise to granitic melts, which concentrated uranium within pegmatites. As such, there is significant additional potential for Rössing-type uranium accumulations in this area. The base and structural roots of these ancient Proterozoic basins, within older basement rocks, may also have led to the formation of unconformity-related deposits (Athabasca Basin, Saskatchewan), which could be partially preserved (Kintyre-type, Western Australia).

5.3.2 GRENVILLE PROVINCE

This province has the most uranium showings in all of Québec. This area was the subject of intense exploration efforts between 1950 and 1970 and the region is easily accessible due to its proximity to the St. Lawrence estuary. As a result, there are several small deposits that have been partially developed. Based on the inventory, several categories of deposits are identified:

- Pegmatites and pegmatitic granites in the Grenville metasediments (Mont-Laurier and Wakeham basins). In total, 81,434 t U spread across 12 low-grade or very low-grade deposits were inventoried. These are Rössing-type deposits, but have potential for very high tonnage. In the Wakeham Basin (Baie-Johan-Beetz, Côte-Nord), the mineralization grades between 100 and 212 g/t U. The Mont-Laurier Basin has higher grade resources (424 to 840 g/t U), but known tonnages are low.

- Mineralization in magnetite-fluorite-allanite breccia complexes closely related to fluorite-rich granite intrusions (IOCG) at Kwyjibo (estimates indicate > 348 t U). This type of mineralization is known to occur at economic concentrations elsewhere in the Grenville (Michelin deposit, 69.3 Mt at 763 g/t U, 52,924 t U in Labrador and the Bancroft deposit in Ontario). The potential represented by skarn-type mineralization (Cu, Au, Mo and U) associated with granitic intrusions in western Québec, in the Outaouais region (Grand Calumet, Calumet Contact 3 and Matte) is limited (877 t U)..

- Alkaline complexes in the Grenville are also promising hosts to uranium mineralization. Interest in these carbonatite and nephelinic syenite alkaline complexes was originally due to interest in niobium exploitation. Some of the complexes are enriched in tantalum, uranium and thorium, in addition to rare earth elements. In total, there are three significant complexes: Crevier, Saint-Honoré (Niobec) and Kipawa (Zeus). Uranium is present either in the rare earth resources (where it is associated with monazite and bastnaesite) or in niobium resources (pyrochlore, uranpyrochlore, columbite, apatite). A total of 15,989 t U are inventoried.

5.3.3 PROTEROZOIC BASINS IN THE SUPERIOR PROVINCE

Several Proterozoic sedimentary basins occur in the Superior Province. These depressions in the Archean basement are the relics of a much larger basin that covered the continental crust during the Proterozoic. The Otish and Mistassini basins, located at the southern edge of the Superior Province, are both significant in size: ~200 x 70 km. The Otish Basin contains three medium-grade unconformity-related deposits, discovered during the 1970s and

1980s, totalling 16,268 t U (933 to 4,871 g/t U). This type of mineralization is very lucrative and produces the most profitable uranium resources in Saskatchewan. Given the size of the two basins and the mineral potential for this deposit type, the chance of new discoveries is very high. There is a third, smaller basin next to Hudson Bay, made up of sedimentary rocks of the Richmond Gulf and Nastapoka groups. There are uranium showings in contact with the unconformity. The third basin also has a strong mineral potential, but it is partly located within the Tursujuq National Park.

Ten or so small basins have been preserved from erosion and contain sandstones and conglomerates with paleoplacer-type mineralization. Resources totalling 13,296 t U, between two low-grade deposits, have been inventoried. Gold, silver, as well as the minerals zircon, monazite and iron oxide concentrations are associated with the mineralized zones. This type of mineralization could be developed for its polymetallic potential (gold, silver, thorium, uranium, rare earth elements). From a uranium potential perspective, this mineralization is not as interesting because uranium is a coproduct occurring in partially refractory minerals, such as brannerite.

5.3.4 Alkaline complexes

The Superior Province contains the Montviel alkaline intrusion and carbonatite. There is potential for rare earth elements, niobium and accessory uranium, with 13,031 t U inventoried. Uranium commonly occurs in zones that are distinct from rare earth element zones. Other alkaline intrusions and carbonatites have been discovered, but have not been assessed. A few syenite intrusions are known in the province. The potential for discovery therefore exists for this deposit type in the Superior Province, which is under-explored, and poorly known.

5.4 Uranium resources as coproduct and mine waste

In the long-term, deposits with uranium as the sole commodity and high-grade deposits are less common (Table 5.1). There are several deposits in Québec for which uranium is either very low grade, or does not occur as the main substance. These uranium resources are divided according to the geological process which formed them. Based on this classification, the following subgroups are defined:

Deposits related to intrusive processes

1. Rare earth, niobium and rare metal deposits in carbonatites or alkaline rocks: 145,125 tonnes of U across ten very low-grade deposits (<0.03 %) (Churchill Province, Superior Province, Grenville Province and the St. Lawrence Platform).
2. Deposits containing rare earth elements, zircon, yttrium, beryllium, niobium, tantalum in rare metal peralkaline granites: 42,509 t U across three deposits (Mistassin batholith, located close to the Labrador border).
3. Apatite deposits associated with gabbro-anorthosite intrusions: potential for more than 3,537 t U, with an extremely low grade (Grenville Province).

Deposits related to hydrothermal processes

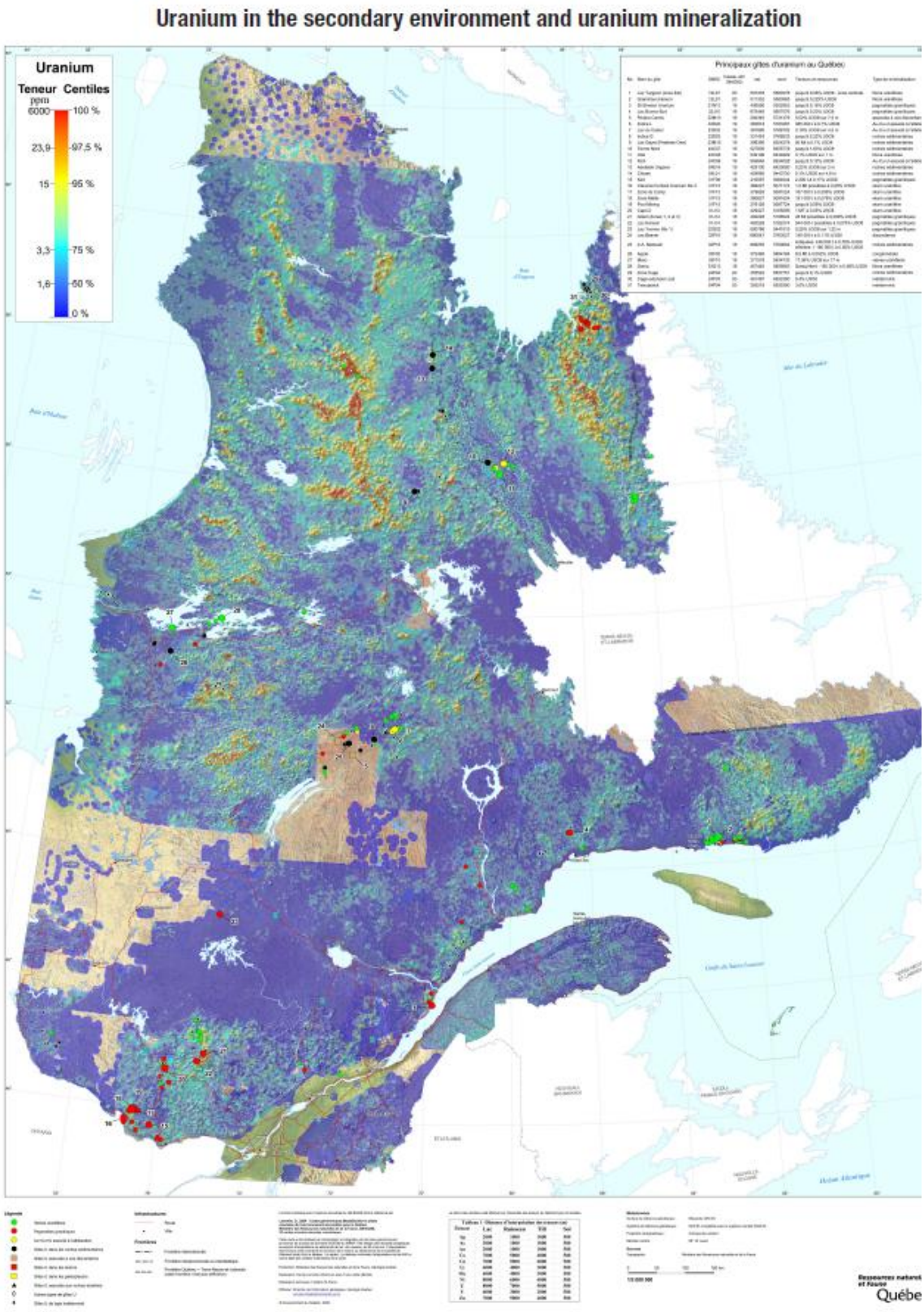
4. Skarns associated with copper-, molybdenum- and uranium-rich granites: 877 t U across three deposits (Outaouais region, in the Grenville Province).
5. Stratiform Cu-Ag-U deposit associated with graphite schists reworked by hydrothermal veining in Appalachian nappes: > 45 t U in a very low-grade deposit (Appalachian Province).

Syn-sedimentary deposits

6. Aluminous claystone formations treated to extract alumina and other rare metals: 2,808 t U (potential) in a very low-grade deposit (Appalachian Province).

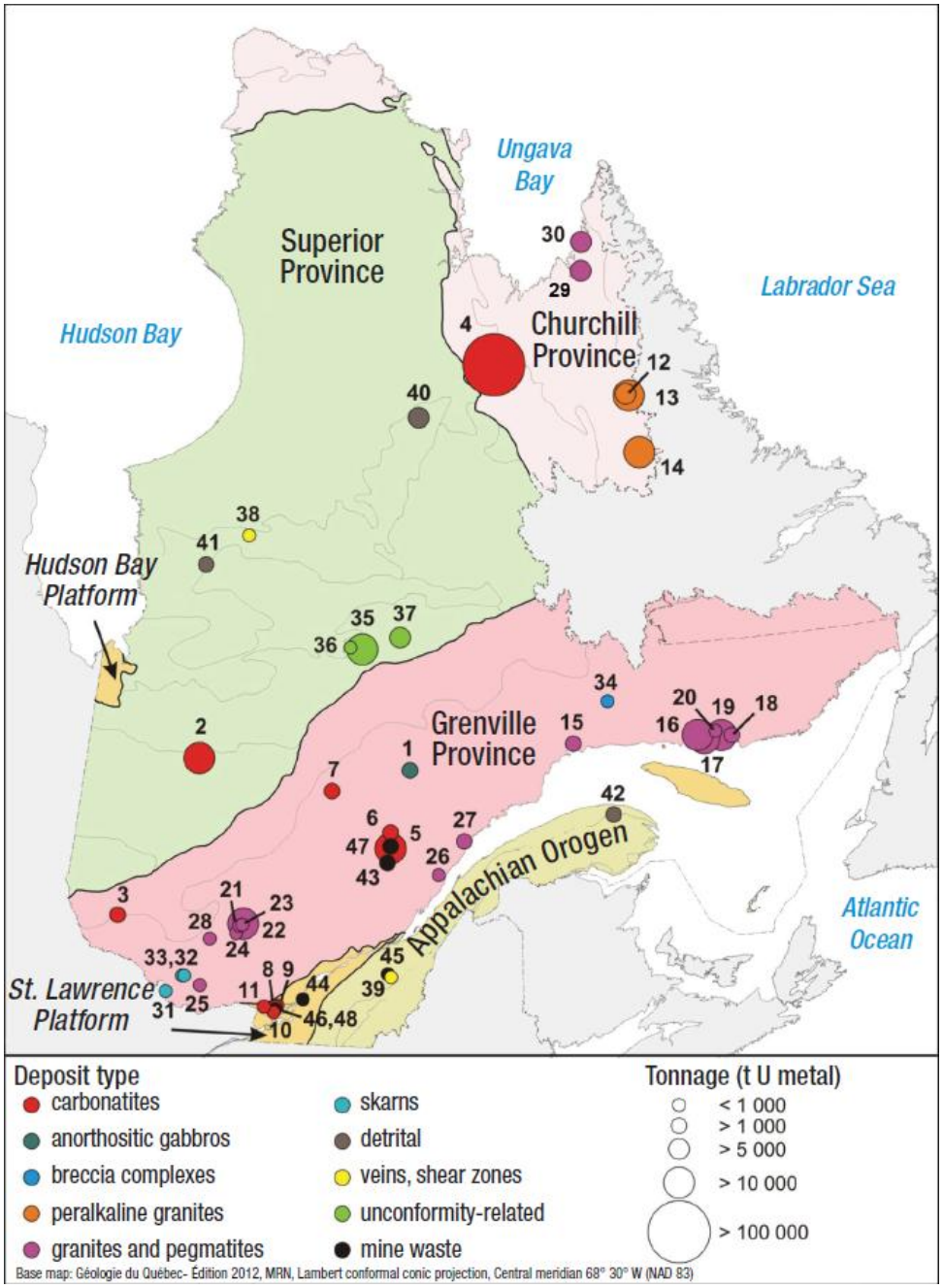
Otherwise, there are several sites in Québec that transform ore containing traces of thorium and uranium in order to extract the following substances:

- Phosphorous (phosphoric acid) from imported phosphate ores;
- Aluminium in bauxite from imported ores;
- Niobium (ferroniobium) from carbonatites in Québec;



Source: MRN, 2007.

Figure 5.4: Uranium grade in lake bottom sediments and the locations of uranium mineralization.



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 a potential resource estimate are not shown.

Figure 5.5: Locations of uranium resources in Québec.

5.5 URANIUM EXPLORATION PROJECTS IN QUÉBEC

A mining company or an exploration company can be considered to be a player in the uranium industry if it has:

- Undertaken exploration or assessment work for uranium resources,
- Sought to produce uranium as a by-product,
- Commissioned a mine where uranium could be optimized,
- Begun uranium production.

In Québec, based on these four criteria, there are 50 active exploration projects belonging to 27 separate companies (Table 5.1).

Regional exploration projects that have not been subject to resource assessment work are not mentioned. Abandoned projects with uranium showings are not mentioned either; they are inventoried by the MRN and are reviewed in the province's uranium resource inventory.

The "advanced exploration" category corresponds to exploration that encompasses consecutive drill holes and excavations, etc. following the discovery of mineralized showings. When a company has demonstrated the presence of a mineral resource (tonnage and grade), it can go into production. This corresponds to the pre-feasibility study, in which mineral reserves are defined (Table 5.1).

The next steps after advanced exploration include the construction of mining infrastructure, mining over a given period, mine closure and dismantling and finally with mine site rehabilitation. At the time being, these steps are not being undertaken in Québec.

Table 5.1: Uranium exploration projects in Québec (as of July 29, 2013).

Project and nature of project	Ownership	Location	Substances	Status
Matoush (deposit)	Strateco Resources Inc.	Chibougamau, 275km NE	U	Pre-feasibility
Lavoie (deposit)	Abitex Resources Inc. (AREVA)	Chibougamau, 275km NE	Au, U	Pre-feasibility
Strange Lake (deposit)	Quest Rare Minerals Ltd.	Schefferville, 240km NE	TR, Be, U, Zr, Nb,	Prefeasibility
Rivière Camie	Cameco	Chibougamau, 275km NE	U	Advanced exploration
Lac Turgeon (deposit)	Uracan Resources Ltd.	Sept-Îles, 250km E	U	Advanced exploration
Ganiq (project)	Midland Exploration Inc.	James Bay	U	Advanced exploration
Apple (deposit)	Strateco Resources Inc.	Radisson, 75km SW	Au, U	Advanced exploration
Dieter Lake (project)	Denison Mines Corp.	Fort Mackenzie, 140km SW	U	Advanced exploration
Grand Calumet (project)	Globex Mining Enterprises Inc.	Ottawa, 90km WNW	F, Th, U	Advanced exploration
Lac Kachiwiss (project)	Rio Tinto plc (Hathor Expl.)	Chibougamau, 20km NE	U	Advanced exploration
North Shore (project)	Uracan Resources Ltd.	Sept-Îles, 305km ENE	U	Advanced exploration
Costebelle (project)	Uracan Resources Ltd.	Sept-Îles, 320km ENE	U	Exploration
Cigare (project)	Virginia Energy Resources Inc.	Chibougamau, 310km NE	U	Exploration
Lorenz Gully (project)	Virginia Energy Resources Inc.	Chibougamau, 310km NE	U	Exploration
Peribonka (project)	Virginia Energy Resources Inc.	Chibougamau, 310km NE	U	Exploration
Trident (project)	Virginia Energy Resources Inc.	Chibougamau, 310km NE	Au, U	Exploration
Marc André (showing)	Virginia Energy Resources Inc.	Lac Laparre	U	Exploration
K9 (showing)	-	James Bay district	U	Exploration
Domino (showing)	-	James Bay	U	Exploration
Manitou (showing)	-	Mont-Laurier	U	Exploration
Baie-Johann-Beetz (project)	Gimus Resources Inc. (Jourdan)	Havre St-Pierre, 85km E	U	Exploration
Capri (project)	-	Val d'Or, 90km SW	U	Exploration
Doran (project)	Entourage Mining Ltd.	Havre St-Pierre, 85km E	U	Exploration
Drucourt/Lac Caron (project)	A Better Search Inc.	Sept-Îles, 204 km E	U	Exploration
Eclat (project)	Strateco Resources Inc.	Chibougamau, 270km NE	U	Exploration
Epsilon (project)	Abitex Resources Inc.	Chibougamau, 350km NE	Au, U	Exploration
Hotish (project)	Midland Exploration Inc.	Chibougamau, 260km NNE	Cu, Au, TR, Ag, U	Exploration
Hunters Point (project)	Globex Mining Enterprises Inc.	North Bay, 90km NE	Au, TR, Ag, U	Exploration
Kert (project)	-	Ottawa, 60km NNW	Cu, Mo, U	Exploration
Lac Colombet (project)	Richmond Minerals Inc.	North part of Lac Colombet	Cu, Au, U	Exploration
Lindsay (project)	X-Terra Resources Corporation	North Bay, 95km NE	Au, TR, U	Exploration
Lordeau (project)	Starfire Minerals Inc.	Québec, 830km NNW	Cu, Ag, U	Exploration
Matoush Extension (project)	Strateco Resources Inc.	Chibougamau, 290km NE	U	Exploration
Mistassini (showing)	Strateco Resources Inc.	Chibougamau, 239 km N	U	Exploration
Mistassini/Otish (project)	Uranium Valley Mines Ltd.	Central northern Québec	U	Exploration
Nanuk (project)	Quest Rare Minerals Ltd.	Schefferville, 195km NE	U	Exploration
North Rae (project)	Azimut Exploration Inc.	Schefferville, 430km N	U	Exploration
Notamiche (project)	Resources Maximan Inc.	Mont-Laurier, 65km N	Cu, Pb, Mo, Ni,	Exploration
Otish Basin (project)	Virginia Energy Resources Inc.	Chibougamau, 310km NE	U	Exploration
Otish Mountains (project)	Virginia Energy Resources Inc.	Chibougamau, 200km N	U	Exploration
Otish (project)	Strateco Resources Inc.	Chibougamau, 280km NE	U	Exploration
Otish (project)	Ditem Explorations Inc.	Chibougamau, 243km NE	U	Exploration
Beaver Lake (showing)	Ditem Explorations Inc.	Chibougamau, 300km NE	U	Exploration
Pool/Halliwell (project)	-	Ottawa, 88km NW	TR, U	Exploration
Rupert River (project)	Sheridan Platinum Group Ltd.	Chibougamau, 310km NW	U	Exploration
Sagar (project)	Energizer Resources Inc.	Mistamisk Lake	Cu, Au, U	Exploration
Upinor (project)	Dios Exploration Inc.	Eastmain, 110km NE	U	Exploration
Uskawanis Lake (project)	Uragold Bay Resources Inc.	Radisson, 180km SW	U	Exploration
Wakeham (project)	Jourdan Resources Inc.	Havre St-Pierre, 70km NE	U	Exploration
Waseco (project)	AREVA SA	Schefferville, 204km NW	U	Exploration

5.6 THE URANIUM PRODUCTION POTENTIAL OF QUÉBEC

Québec's production potential may come from three different sources:

1. Primary resources where uranium is the main substance;

2. Primary resources where uranium is a coproduct that contributes to the ore's value;

3. Mine waste and tailings available for reprocessing.

We have compiled the mineral data available in the public domain, and compared them with data from the IAEA and MRN. The IAEA lists 17 deposits in Québec in its UDEPO database (resources ranging from 94,400 to 205,000 t U). This dataset is incomplete and contains mistakes, as well as duplicates. Data from the MRN is different, but also incomplete. Data pertaining to resources with uranium as a coproduct was taken from public sources. All primary resources (main substance, coproduct), mine waste and tailings are presented together for the first time in this inventory.

We estimate Québec's uranium resources to be 315,000 t (Tables 5.2 and 5.4). Medium-grade resources in unconformity-related deposits (like those in Saskatchewan), most likely to be mined in the short term, only represent 16,113 t U, the majority of which are in the Matoush deposit, in the Otish Mountains. A few key points regarding mineralization types encountered must be addressed:

- Very high-grade deposits found elsewhere in Canada are exceptions, and mining of these deposits remains limited;
- Of the 314,851 t of uranium resources, 278,615 t are intrusive in origin, which represents **89 % of total uranium resources** inventoried (Table 5.2);
- Of the 278,615 t U of intrusive origin, 191,172 t occur as an optimizable coproduct in Québec's vast resources in rare earth elements, niobium, tantalum and other rare metals. This represents **61 % of total uranium resources** inventoried
- Aside from the two deposits in the Otish Basin (Matoush and Lavoie), deposits have a low uranium grade (0.3 % U), even a very low (< 0.03 % U).

Table 5.2 : Inventory of uranium mineral resources in Québec (2013).

Deposit no.	MRN no.	Name of deposit/site	Mining company	Type of deposit	Tonnage (10^6 t)	U (g/t)	U (t)	Total %
Medium-grade deposits (0.1 to 1.0 % U)								
35	32P16-1001	Matoush	Strateco Resources Inc.	Unconformity	2.27	4871	11,067	3.51
37	23D02-1001	Lavoie / Showing L, 38:	AREVA Resources Canada	Unconformity	1.14	4444	5066	1.61
Low-grade deposits (0.03 to 0.1 % U)								
36	32P16-0001	Lac Beaver / Zoran		Unconformity	0.15	933	135	0.04
22	31J14-0005	Nova (or Renard or Allied (1-3)	Nova Uranium Corp.	Alaskite/pegmatite	31.80	*840*	*26,712*	8.48
30		Cage Sector	AREVA Resources Canada	Pegmatite/metasomatite	*5.00*	*800*	*4000*	1.27
31	31F15-0026	Grand Calumet / Calumet Contact No.3	Globex Mining Enterp. Inc.	Skarn	1.00	678	678	0.22
32	31F15-0014	Matte Zone		Skarn	0.18	661	120	0.04
24	31J14-0013	Lac Hanson	Nova Uranium Corp.	Alaskite/pegmatite	0.54	636	346	0.11
23	31J14-0004	Mekoos (or Bear, 3-3D)	Nova Uranium Corp.	Alaskite/pegmatite	0.52	539	283	0.09
29		North Rae Sector	Azimut Exploration Inc.	Pegmatite/metasomatite	*4.00*	*500*	*2000*	0.64
40	23M15-0001	Dieter Lake / Lac Gayot	Denison Mines Inc.	Paleoplacer	19.31	487	9405	2.99
33	31F15-0013	Zone de Camp		Skarn	0.17	475	79	0.03
41	33F02-0004	Apple	Strateco Resources Inc.	Paleoplacer	8.50	458	3891	1.24
38	33G13-0010	Ganiq	Midland Exploration Inc.	Vein, shear zone	0.27	435	115	0.04
28		Capri-2	Starfire Minerals Inc.	Pegmatite/metasomatite	1.00	*424*	*424*	0.13
26	22C04-0002	Lac Fafard		Pegmatite	0.09	395	37	0.01
27	22C11-0001	C11r4 Anomaly		Pegmatite	3.56	300	1068	0.34
Very low-grade deposits (<0.03 % U)								
21	31J14-0001	Tom Dick (Zone Nord 1)	Nova Uranium Corp.	Alaskite/pegmatite	0.27	229	62	0.02
17	12L07-0008	Baie Quetachou	Uracan Resources Ltd.	Alaskite/pegmatite	93.45	*212*	*19,811*	6.29
18	12L08-0003	Doran (Lacana)	Entourage Mining Ltd.	Alaskite/pegmatite	10.89	211	2298	0.73
25	31F09-0008	Lac Indien, Bain		Pegmatite	0.13	178	23	0.01
15	22J08-0001	Lac Kachiwiss	Rio Tinto plc (Hathor Expl.)	Alaskite/pegmatite	16.60	136	2258	0.72
19	12L08-0005	Johann Beetz (Drucourt Est),	Gimus Resources Inc.	Alaskite/pegmatite	100.00	*110*	*11000*	3.49
16	12L07-0003	Côte-Nord / Turgeon	Uracan Resources Ltd	Alaskite/pegmatite	162.15	104	16912	5.37
20	12L08-0001	Lac Caron		Alaskite/pegmatite	2.00	*100*	*200*	0.06
							117991	**37.48**
Deposits with uranium as a potential coproduct								
34		Kwyjibo (Josette)	SOQUEM Inc.	Breccia complex	*0.8*	*435*	*348*	0.11
4	24C-16-0003	Ashram (Eldor) / Erlandson No.1	Commerce Resources Corp.	Alkaline complex	422.74	*272*	*114985*	36.52
8	31G-09-0017	Manoka (Oka)	x	Alkaline complex	0.2	*175*	*35*	0.01
13	24A08-0001	Strange Lake Main Zone (Lac Brisson)	Quest Rare Minerals Ltd.	Peralkaline granite	54	146	7884	2.50
39	21L-06-0021	Harvey Hill Cu Mine		Vein, shear zone	0.45	100	45	0.01
3	31L15-0015	Kipawa (Zeus, Lac Sheffield-2)	Matamec Explorations Inc.	Alkaline complex	16.314	62	1011	0.32
2	32F15-0004	Montviel	GéoMégA Resources Ltd	Alkaline complex	250.6	52	13031	4.14
12		Strange Lake B Zone	Quest Rare Minerals Ltd.	Peralkaline granite	492.5	50	24625	7.82
14		Misery Lake	Quest Rare Minerals Ltd.	Peralkaline granite	*200*	*50*	*10000*	3.18
7	32H07-0001	Crevier	MDN Inc.	Alkaline complex	40.792	39	1591	0.51
9	31G-09-0014	Oka, (Zone Bond, Wayfair)	Niocan Inc.	Alkaline complex	*13.85*	*29*	*402*	0.13
11	31G/09-0021	St-André-2		Alkaline complex	*20*	*20*	*400*	0.13
10	31G-08-0003	St-Lawrence Colombium Mine (SLC)	Ressources min. Augyva Inc.	Alkaline complex	16.69	16.9	282	0.09
5	22D-11-0012	Niobec, Nb Mine	IAMGOLD Corp.	Alkaline complex	794.51	*15*	*11918*	3.79
1		Lac à Paul	Ressources d'Arianne Inc.	Gabbro / anorthosite	655	*5.4*	*3537*	1.12
6		Niobec REE project	IAMGOLD Corp.	Alkaline complex	466.8	3.2	1470	0.47
42		Grande-Vallée	Orbite Aluminae Inc.	Aluminous clay	1040	2.7	2808	0.89
							194373	**61.73**
Mine waste and tailings								
46	31G-08-0003	Mine SLC, scories	Ressources min. Augyva Inc.	Ferroniobium scories	0.065	815	53	0.02
47	22D-11-0012	Mine Niobec, scories	IAMGOLD Corp.	Ferroniobium scories	0.3	482	145	0.05
44		Phosphogypsum, Varennes	Rhodia Canada Inc.	Phosphate residues	2	300	600	0.19
45	21L-06-0021	Harvey Hill, residues		Mine waste	0.3	100	30	0.01
43		Boues Rouges, Jonquière	Rio Tinto ALCAN	Bauxite waste	50	30	1500	0.48
48	31G-08-0003	Mine SLC, tailings	Ressources min. Augyva Inc.	Mine waste	6.156	26	160	0.05
							2488	**0.79**
	Level of confidence:	NI43-101, or high degree of confidence	Medium	Low			**314851**	

Estimates based on public mining data, scientific articles and mineralogical data; all values are expressed as uranium metal (and not as U_3O_8 oxide).

5.7 QUÉBEC'S GLOBAL POSITION

Our inventory indicates that Québec's uranium resources are significant on the global scale. Table 5.3 shows that these resources mainly consist of intrusive deposits, unconformity-related deposits and conglomerate deposits. These last two deposit categories have long been mined in Canada. Table 5.4 demonstrates that there are low- and medium-grade deposits in Québec. In Canada, high-grade deposits have only been discovered at depth and following extensive exploration drilling campaigns. Given Québec's geological environments, there is the potential for comparable resources.

Table 5.3: Deposit types in Canada and abroad compared to Québec.

Deposit type	Production 2007 (t U)	N^{ber} deposits World IAEA	Global resources IAEA (t U)	N^{ber} deposits Canada IAEA	Canadian resources IAEA (t U)	N^{ber} deposits Québec (this inventory)	Québec resources 2013 (t U)
Sandstone deposits	**14,600**	575	**3,993,419**	7	17,286		
Proterozoic unconformity-related deposits	**14,100**	85	1,255,382	57	**757,880**	3	16,268
Breccia complex deposits	3,400	16	**2,309,497**	2	5,570	1	248
Volcanic deposits	3,200	114	555,385	9	53,274		
Intrusive deposits	2,600	78	1,094,545	23	62,681	28	**278,605**
Metasomatic deposits	1,150	54	952,437	1	680	3	877
Vein or unknown	830	277	1,145,212	14		2	160
Quartz-pebble conglomerate deposits	540	61	1,071,822	21	**434,732**	2	13,296
Surficial deposits	300	62	382,809	0			
Breccia pipe infill deposits	0	17	16,460	0			
Phosphate deposits	0	40	**12,898,130**	0			
Lignite and coal deposits	0	24	314,648	0			
Black shale/schist deposits	0	42	1,199,086	1	9,385	1	2,808
Total	**40,720**	**1445**	**27,188,842**	**135**	**1,408,752**	**41**	**314,851**

Sources: IAEA and UDEPO databases, Québec inventory as described in the text..

Table 5.4: Number of deposits inventoried in the world with proven uranium reserves, according to uranium grade and tonnage. For comparison purposes, the number of deposits in Québec with uranium resources is provided in parentheses. It should be noted that there are few medium- to high-grade deposits (> 0.1 %) in current exploration projects.

	Uranium reserves (t U)				
	< 1000	**1000 - 10,000**	**10,000 - 100,000**	**< 100,000**	**Total**
< 0.03 % U	12 *(7)*	65 *(8)*	32 *(7)*	6 *(1)*	115 *(23)*
0.03 - 0.10 % U	39 *(10)*	96 *(5)*	31 *(1)*	6	172 *(16)*
0.10 - 1.00 % U	139	282 *(1)*	89 *(1)*	7	517 *(2)*
1.00 - 5.00 % U	8	13	10	0	31
>5.00 % U	0	1	0	2	3
Total	**198** ***(17)***	**457** ***(14)***	**162** ***(9)***	**21** ***(1)***	**838** ***(41)***

Sources: UDEPO; IAEA.

6 LICENCING FOR URANIUM MINING PROJECTS IN QUÉBEC

Summary

- Mining is highly regulated by legislation in Québec.
- Many licences and authorizations must be obtained at every stage of a mining project in order to move forward.
- The main ministries concerned are the *ministère des Ressources naturelles* and the *ministère du Développement durable, de l'Environnement, de la Faune et des Parcs*.
- A claim holder has the obligation to disclose any discovered mineral substances with more than 0.1 % triuranium octaoxide (U_3O_8) within 90 days of its discovery.
- For uranium mines, there is also a federal agency involved in the licencing process: the Canadian Nuclear Safety Commission.
- Everywhere in Québec, uranium mining projects are subject to an environmental impact assessment following the procedure for the area in question.

6.1 INTRODUCTION

Regulatory and legal provisions that pertain to mining come under provincial jurisdiction. In Québec, these provisions are implemented by 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 regulates activities related to mining, such as the allocation of mining rights. Other laws and regulations are also applicable and pertain to the environment, land use and occupational health and safety, such as the Environment Quality Act (EQA), the Act Respecting the Ministère des Affaires Municipales, des Régions et de l'Occupation du territoire, the Act Respecting Land use Planning and Development, the Municipal Powers Act, the Regulation Respecting Standards of Forest Management for Forests in the Domain of the State, and the Regulation Respecting Occupational Health and Safety in Mines.

Uranium production falls under federal jurisdiction. As per the Nuclear Safety and Control Act (NSCA), the Canadian Nuclear Safety Commission (CNSC) (see inset) oversees regulations and authorizations for all current and future activities pertaining to mining and milling of uranium in Canada. The authorization procedure follows the steps set out in the Uranium Mines and Mills Regulations, which are: the preparation of a site, construction, operation, decommissioning and abandonment. As such, the CNSC issues a separate licence for each stage of the uranium mining and milling cycle. The CNSC closely monitors the implementation of regulations and ensures that all licence holders possess financial security for each piece of infrastructure – at all stages of the mining cycle – to cover future decommissioning costs. In accordance with the Canadian Nuclear Safety Commission Cost Recovery Fees Regulations, the Canadian Nuclear Safety Commission bills the licence holder for all costs related to regulatory activities. Furthermore, the CNSC must make sure that the requirements under the Canadian Environmental Assessment Act (2012) are met. Depending on the context, other federal laws or regulations could be applied to a project, such as the Metal Mining Effluents Regulations, the Navigable Waters Protection Act or the Fisheries Act (INSPQ, 2013).

The Canadian Nuclear Safety Commission (CNSC)

The federal agency charged with the implementation of the ***Nuclear Safety and Control Act,*** their *mandate can be summarized as follows*: "The CNSC regulates the use of nuclear energy and materials to protect the health, safety and security of Canadians and the environment and to implement Canada's international commitments for the peaceful use of nuclear energy. " (CNSC (2), 2013). Independent from government and from the nuclear industry, the CNSC members reach decisions on licence applications once public proceedings have taken place, to which all interested parties may take part. With more than 800 people in different fields of expertise, the personnel of the CNSC supports the work of members and implements the surveillance of licence holders. For uranium mines, successive licences are required based on the stage of project development. The CNSC also monitors medical and industrial equipment that use nuclear substances, as well as research reactors and reactors that produce electricity. It monitors compliance "from the cradle to the grave."

The mining rights approval process is a key component in controlling mining operations in Québec, 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 multiple agencies at many levels of government.

A detailed description of the approval process for all the licences is beyond the scope of this report. In the following pages, the approval process for the licences and authorizations required at the successive stages of a mining project is summarized, and some light is shed on the specific monitoring and control measures for uranium. Since the goal is to provide a general idea of the procedures involved, the laws and regulations relevant to each step are not cited. Information pertaining to consultations with Aboriginal nations are also included. Table 6.1 provides a summary of the main laws and regulations applied throughout the stages of uranium exploration and mining in Québec.

Table 6.1: Summary of the main laws and regulations applied throughout the stages of uranium exploration and mining.

Québec jurisdiction		**Federal jurisdiction**
MRN	**MDDEFP**	**CNSC**
Mining Act	**Environment Quality Act (EQA)**	**Nuclear Safety and Control Act**
Exploration stage (Prospecting, drilling, sampling, access roads)		
Acquiring 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 environmental impact.	
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. Where appropriate, authorization required in case of possible environmental impact and/or if activities take place in the James Bay and Northern Quebec territory.	Removal licence required.
Pre-construction and pre-mining stage (Site preparation and layout, construction of infrastructure, underground or open pit design)		
Request for a Mining Lease: Demonstration of the mine's viability; Approval of the rehabilitation plan; Submission of a feasibility study and of financial and market opportunity analysis.	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 assessment; 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		
Update to rehabilitation plan.	Request for a depollution attestation. Implementation of an impact surveillance program to monitor compliance with regulations and conditions of authorization.	Control measures to ensure compliance with regulations and conditions provided for in the licences.
Site closure, rehabilitation and monitoring stage		
Site security; Implementation of the rehabilitation plan.	Ongoing environmental monitoring for as long as waste is present; Implementation of a soil rehabilitation plan, if necessary.	Issuance of a decommissioning licence. Issuance of an abandonment licence.

6.2 PRIOR TO EXPLORATION

The aim of mineral exploration, or prospecting, is to discover mineral resources. The mining title that grants the exclusive right to explore for mineral substances is the claim. Some areas are closed to exploration, while others are subject to restrictions. The claim also gives its holder reasonable assurance that he will be able to mine mineral resources discovered within the claim's limits, if the holder obtains the required authorizations and licences. Claims are obtained by map designation or staking in the field by the holder of a prospector's licence. The prospector's licence is valid from the date of registration with the *ministère des Ressources naturelles du Québec*'s GESTIM system.

The Act amending the Mining Act, in force since December 10, 2013, states that the regional county municipalities (RCMs) will establish what land is not compatible with mining activities in their land use planning and development plan. Until then, it will not be possible to obtain new claims located on Crown land within an urban perimeter, where there were no claims.

The claim is valid for a period of two years. It can be renewed if work has been carried out and renewal fees have been paid. A fee schedule applies to determine whether the amount spent on work is sufficient (MRN, 2013). If the value of exploration activities is greater than the amount required for renewal, the portion left-over can be used to renew adjacent claims or toward future renewals. The expiry date for work credits is now set to 12 years.

Compliance with laws and regulations that apply to the property in question is mandatory. Exploration work is undertaken once the required licences have been obtained. For instance, if forestry work is required before exploration can begin, or if a non-removable construction is planned, a licence must be obtained from the MRN. If it is possible that planned exploration work might disturb the natural environment (forest, flora, fauna, lakes, streams, wetland), an authorization from the MDDEFP may be required.

6.3 EXPLORATION

Once the claim is granted (and other licences or authorizations, if applicable), the field exploration project can move forward. Several activities can, however, be done remotely, by remote sensing or airborne surveying (geophysics). Initial exploration work is typically limited to outcrop visits, mapping and rock sampling. Sediment sampling (lakes, streams, glacial sediments) may also occur at this stage. Ground geophysical surveys may also be carried out to better define the property's physical properties. Trenches may be excavated to map and sample the bedrock when the soil cover conceals areas of interest. Important outcrops may be stripped to perform detailed mapping. Channel sampling may be done inside trenches and excavations, which provides continuous data on the rock's surface composition. Trenches and excavations must be closed up upon completing exploration work. Drilling is undertaken to test the lateral and vertical continuity of mineralization, and samples are collected to measure the chemical composition of mineralized rocks.

Some exploration work can require a certificate of authorization in accordance with section 22 of the EQA, particularly when streams, lakes, ponds, marshes, swamps and peat bogs are affected by exploration work and the dimensions of trenches and excavations are greater than the limits set in the Directive 019 of the MDDEFP pertaining to the mining industry.

A claim holder must notify the landowner and local municipality of his claim within 60 days following registration. If the claim is located within the limits of a municipality, the claim holder must inform the municipality and the owner of the property on which work will be carried out, at least 30 days before the start of work. On private land, the claim holder must obtain the landowner's written authorization to access the property at least 30 days ahead of time.

The claim holder must declare to the *ministre des Ressources naturelles* and to the *ministre du Développement durable, de l'Environnement et des Parcs* any mineral substance discoveries with 0.1 % or more triuranium octoxide within 90 days of the discovery.

Furthermore, the presence of radioactivity within samples collected in the field (related or not to uranium) requires that they be packaged and transported in a specific way, under the Packaging and Transport of Nuclear Substances Regulations, which incorporate the International Atomic Energy Agency's (IAEA) regulations. These regulations apply to all subsequent steps of a mining project, and the CNSC oversees their implementation.

The CNSC considers that "Surface exploration for uranium is exempt from NSCA requirements because it poses low risks." Each province or territory is responsible for regulating and monitoring exploration activities within its jurisdiction and informing the public about those activities" (CNSC(3), 2013).

Moreover, an entire chapter of the *e3 Plus* guidelines for responsible mineral exploration is devoted to uranium exploration. In the e3 Plus document, which was developed by the Prospectors and Developers Association of Canada (PDAC), the security measures that must be taken to protect the health of people working in exploration and of those that oversee the transport and handling of radioactive samples are described.

6.4 ADVANCED EXPLORATION

Advanced exploration consists of precisely measuring the volume and composition of mineralized rocks. To do so, the portion of mineral resources occurring below the rock surface must be studied using diamond drilling. The number and density of drill holes increase as the project moves forward, until the geological continuity and grades have been determined with sufficient precision. The estimated deposit grade must usually be confirmed by collecting a bulk sample of more than 50 tonnes. The data obtained must be sufficiently precise such that a qualified person can determine if a future mine is feasible. The MRN issues a "bulk sampling authorization" after reviewing the documents requested from the project proponent (form, report and maps).

Extracting a bulk sample requires sinking a shaft or an exploration ramp. For old mines, this may involve dewatering a mine shaft. This type of work has a significant impact on the environment, since it involves stripping the site and setting out an area to pile waste rock and tailings. However, the waste generated must remain below applicable environmental standards, as set out in the Directive 019 on the mining industry, and a certificate of authorization from the ministry issued under section 22 of the EQA could be required. A site rehabilitation plan must be approved by the MRN, upon receiving a positive review from the MDDEFP. For advanced exploration projects located in the James Bay and Northern Québec territory, an environmental assessment could also be required under Chapter II of the EQA (see inset on the environmental assessment procedure in Québec).

The CNSC have to issue a licence to allow this type extraction of radioactive material. For the proponent, this involves submitting an application that will be reviewed by the personnel of the CNSC. The personnel will make recommendations to the CNSC members after having consulted other relevant federal ministries and agencies (Health Canada, Fisheries and Oceans Canada, Transports Canada, etc.) Furthermore, public hearings will be held such that the general public, Aboriginal groups affected by the project, and all other interested parties may voice

their opinion and submit briefs. The licence will be granted only if the panel deems that all the regulatory requirements have been met, as specified under subsection 24(4) of the Nuclear Safety and Control Act.

No licence shall be issued, renewed, amended or replaced — and no authorization to transfer one given — unless, in the opinion of the Commission, the applicant (...):

- *is qualified to carry on the activity that the licence will authorize the licensee to carry on; and*
- *will, in carrying on that activity, make adequate provision for the protection of the environment, the health and safety of persons and the maintenance of national security and measures required to implement international obligations to which Canada has agreed.*

The CNSC's licencing procedure must be repeated for every stage of a uranium mine. The licence granted will therefore contain particular provisions for the advance exploration stage.

Environmental assessment procedure in Québec

The *ministère du Développement durable, de l'Environnement, de la Faune et des Parcs* (MDDEFP) has overseen the procedure for environmental assessment in the northern regions of Québec since 1975, and in southern Québec since 1980. The principle goal of the environmental assessment procedure is to inform decision-makers as to what is at stake in authorizing certain projects that are likely to significantly disturb the environment, and to prompt questions from the general public. The Environment Quality Act sets out strict procedures for assessing and reviewing the environmental and social impacts of a project, with separate versions for the three jurisdictions concerned.

Southern Québec

The procedure that applies to the southern part of Québec is described under Division IV.1 of Chapter 1 of the EQA and in the ensuing Regulation Respecting Environmental Impact Assessment and Review (c. Q-2, r.23) (RREIAR). Division II of the RREIAR lists the projects that are subject to the procedure, including, for the mining industry:

- the construction of an ore processing plant for metalliferous ore or asbestos ore, where the processing capacity of the plant is 2,000 metric tons or more per day, for uranium ore, rare earth ore or any other ore, where the processing capacity of the plant is 500 metric tons or more per day;
- the opening and operation of a metals mine or an asbestos mine that has a production capacity of 2,000 metric tons or more per day, of a uranium mine, a rare earth mine or any other mine that has a production capacity of 500 metric tons or more per day.

The assessment procedure begins when the proponent notifies the MDDEFP of their intention to carry out one of the projects subject to the procedure. The Minister then produces a guideline indicating the information that must be included in the environmental impact statement, such as: project justification, project alternatives, a description of the biophysical and human environment, project impacts, mitigation measures planned, emergency measures and monitoring and follow-up programs.

Upon receiving the impact statement, the ministry makes sure that the guideline requirements have been met. They may then ask the proponent to provide clarifications or additional information regarding the impact statement before it is made public for information sessions and consultations, which are conducted by an independent agency, the *Bureau d'audiences publiques sur l'environnement* (BAPE).

During this 45-day period, a person, a group or a municipality may put in a request for a public hearing to the

Minister, who passes on this mandate to the BAPE for a period of up to 4 months. During public hearings, the general public can seek information on the project and make comments. The BAPE shares its findings and analysis in a report transmitted to the Minister, who then makes it public within 60 days following the receipt of the report.

Within the same period, specialists at the *Ministère*, in collaboration with other relevant ministries and agencies, analyze the project to advise the Minister on the project's environmental acceptability and the relevance of the project, and, if applicable, the conditions for authorization.

Based on the BAPE report and the environmental impact statement, the Minister makes a recommendation to the government. The government will then announce its decision by order-in-council in accordance with sections 31.1 and 31.5 of the EQA: the government authorizes the project with or without amendments, and on such conditions as it may determine, or refuses the project.

Northern regions - James Bay and Northern Québec Region

The assessment procedure that applies to the northern regions is described in Chapter II of the EQA, including schedules A and B which indicate, respectively, the projects that are automatically subject and automatically exempt from the assessment and review procedure, in accordance with the previsions set out in the James Bay and Northern Quebec Agreement (JBNQA) and in the Northeastern Québec Agreement (NEQA) reached with the Aboriginal nations in northern regions.

As such, under Schedule A, all mining developments, including the additions to, alterations or modifications of existing mining developments, are subject to the procedure whereas under Schedule B, all testing, preliminary investigation, research, experiments outside the plant, aerial or ground reconnaissance and survey or technical surveys prior to any project, are exempt. However, advanced exploration that does not come under schedules A and B may be subject to the procedure.

Furthermore, the Regulation Respecting the Environmental and Social Impact Assessment and Review Procedure applicable to the territory of James Bay and Northern Québec (chapter Q-2, r. 25) indicates the preliminary information that the project proponent must provide and indicates the content of the impact statement.

The environmental assessment procedures specific to these regions differ by the active participation of Aboriginals (Cree, Inuit and Naskapi) who inhabit them. Furthermore, the projects south of the 55th parallel are assessed and reviewed by the Evaluating Committee (COMEV) and the Provincial Review Committee (COMEX) and the projects north of the 55th parallel are assessed and reviewed by the Kativik Environmental Quality Commission (KEQC). Aboriginal administrations and the public can make presentations to the COMEX or KEQC, which may also hold public hearings or any other type of consultation. Finally, taking into account the recommendation from the COMEX or the decision of the KEQC, the Administrator, in this case the MDDEFP Deputy Minister, authorizes, or not, the project, in accordance with sections 164 and 201 of the EQA, respectively.

de Moinier region

The de Moinier region comprises the territory described in the second paragraph of section 31.9 of the EQA, which is the territory bounded on the west by the 69th meridian, on the north by the 55th parallel, on the south by the 53rd parallel and on the east by the eastern boundary described in the Québec boundaries extension acts of 1912 (II George V, chapter 7) and Statutes of Canada (II Georges V, chapter 45).

All projects listed in Schedule A of the EQA are subject to the Regulation Respecting the Environmental Impact Assessment and Review applicable to a part of the northeastern Québec region (c. Q-2, r.24). More specifically, this regulation indicates that for projects to increase, alter or modify an existing mining operation governed by subparagraph a of the first paragraph of Schedule A of the Act including changes to ore concentration process, the

establishment of a mining waste dump in a new drainage basin and the implementation of more advanced concentrate transformation.

The assessment procedure applied is described in Division IV.1 of the EQA pertaining to southern Québec, with a few amendments. As such, the projects subject to the procedure must obtain a certificate of authorization issued by the government under sections 31.1 and 31.5 of the EQA. In addition, they shall be subject to information and consultation sessions held by the BAPE, and eventually to public hearings. However, immediately after having made an environmental impact assessment statement public the Minister must transmit a copy to the Naskapi village of Kawawachikamach, which may then provide comments and request from the Minister that a public hearing be held. The content of any environmental impact statement must include the objectives and elements listed in sections 4, 5 and 7 of the Regulation Respecting the Environmental and Social Impact Assessment and Review Procedure applicable to the territory of James Bay and Northern Québec (Chapter Q-2, r. 25).

6.5 PRIOR TO CONSTRUCTION

Before beginning construction of the necessary mining infrastructure, the proponent must obtain a "mining lease" from the MRN. To do so, the proponent must demonstrate the presence of a mineable deposit (with a report certified by an engineer or a geologist), present a survey plan, a rehabilitation plan approved by the MRN, and pay the annual rent and a financial guarantee for rehabilitation work (following the established schedule). The lease may not be signed before the certificate of authorization, as set out in sections 22, 31.5, 164 and 201 of the EQA, has been issued, unless the delay involved is unreasonable. The lease application must also be accompanied by a feasibility study for the project and a financial and market analysis for transformation in Québec. These documents will be reviewed by the MRN. The *ministre des Ressources naturelles* can add provisions to the lease that aim to avoid conflicts with other users of the land. When granting a lease, the Government may, on reasonable grounds, require that the economic spinoffs within Québec be maximized. The mining lease covers a maximum of 100 hectares. It is valid for 20 years, and can be renewed up to three times, for a period of 10 years, subject to certain conditions. Afterwards, the lease may be extended for 5-year periods.

If some of the mine-related infrastructure (like the tailings facility or the ore processing plant) is located outside the mining lease, the proponent must obtain an authorization or a lease for public land from the MRN. A municipal building permit is also required for infrastructure located within a municipality's city limits.

The procedure for environmental assessment in Québec, described in the inset, is applied concomitantly. The environmental impact statement is prepared at this stage. Public consultations, if they were requested, will be held at this time.

Furthermore, certificates of authorization (CA) issued by the MDDEFP under section 22 of the EQA are required before undertaking construction or mining. As a guideline for the issuance of CAs and to ensure consistency in the way projects in the mining sector are analyzed, the MDDEFP published, in 1982, the *Directive 019* pertaining to the mining industry, which officially came into force in May 1989. A thorough update of the *Directive 019* was done in 2005, and again in 2012. This reference document is commonly used to determine the basic requirements that mine site operators must meet and the information that should be provided when submitting an application for a

CA. The *Directive 019* does not have the force of law, but it facilitates the implementation of section 22 of the EQA. As such, when the requirements set out in *Directive 019* are included in a CA, the operator must comply with them. The different versions of Directive 019, available on the MDDEFP's website, include strict requirements, particularly for mine waste management and liquid discharge.

Infrastructure related to access (roads, bridges, airports, ports), accommodations and water (collection, distribution, treatment), residual hazardous materials management, and contaminated soil management are also subject to strict regulations, and licences or other types of authorizations must be obtained. These are not necessarily specific to the mining industry; for instance, for storing and using explosives, a process supervised by the *Sûreté du Québec* is mandatory. Similarly, these licences and authorizations are not necessarily required at the construction stage, but can be mandatory throughout the mining cycle.

Moreover, the CNSC will ensure that the Canadian procedure for environmental assessment, updated in July 2012, is implemented. In fact, since this update, environmental assessments are no longer required as per the old CEAA. However, to avoid all unreasonable risks to the environment and to people's health and safety, the assessment of potential environmental impacts and mitigation measures for mining projects continues under the Nuclear Safety and Control Act, in the context of licence application reviews by the CNSC.

The application for a "licence to prepare site and to construct" submitted to the CNSC is comprised of a number of documents, including the programs and schedules for the recruitment and training of mine and maintenance personnel, as well as the information program for the general public on the effects of site preparation, and the effects of construction of infrastructure on public health and safety and the environment. A site decommissioning plan is also required to determine the amount the company must deposit as financial guarantee. This information will be updated at all stages of the mining process. Given the number of documents to prepare and the different steps involved in the approval process, delays are considerable before work can begin.

Finally, these projects continue to be subject to other relevant federal standards, laws and regulations such as the Fisheries Act and Metal Mining Effluents Regulations.

6.6 CONSTRUCTION AND SITE DEVELOPMENT

During construction, the agencies involved in issuing licences will carry out audits and monitor activities. The proponent must also transmit information to these various agencies, by carrying out different tests and inspections at regular intervals.

The regulations of the CNSC indicate that: "If the compliance activities identify a non-compliance or adverse trend, the CNSC can take various enforcement actions ranging from a request for corrective action up to and including recommending criminal prosecution" (CNSC, 2010).

Accountability is a fundamental aspect of retaining a licence and obtaining the next one. Deviations from the norm, incidents and, if applicable, accidents are the object of reports and follow-ups such that corrective actions be implemented as soon as possible. The CNSC can give out orders to licensees to remedy problems identified during inspections or when incidents are declared by the licensees. Investigation reports may also be produced at the CNSC's request.

6.7 PRIOR TO MINING

A CA issued by the MDDEFP under section 22 of the EQA, approval of the mine site rehabilitation plan, and a mining lease issued by the MRN are mandatory to start up mining operations. The CA includes an environmental impact monitoring and follow-up program, which the operator must implement throughout the mine's life.

Furthermore, an "operating licence" must be issued by the CNSC. Results for all the commissioning activities must be communicated to the CNSC and are part of the files that must be submitted to obtain an operating licence. If mining operations were not included in the previous environmental assessment, another assessment must be performed. The operating licence is valid for 2 to 5 years. It can be renewed if the operator fulfils his obligations satisfactorily. Safety management is of paramount importance.

6.8 MINING

One month after mine commissioning, the operator must, if applicable, file an application with the MDDEFP for a depollution attestation (DA), which is a regulatory tool introduced by the Québec government in 1988 under the *Programme de réduction des rejets industriels* (PPRI). The goal of this program is to gradually reduce discharge into the environment by issuing DAs. Because it is renewable (5 or 10 years) and specific to each industrial site, the DA allows the progressive tightening of environmental requirements based on new findings, the availability of technology and funds, and the particular protection needs of the environment. Furthermore, industrial site operators must cover the annual costs that are based on the amount of contaminants discharged in the environment, which encourages them to reduce their discharge volume.

The mining sector obliged to obtain a DA for all mine sites in Québec that:

- Annually process more than 50,000 metric tonnes of ore and mine waste (since May 2002);
- Have an annual ore extraction capacity of more than 2 million metric tonnes (since July 2013).

The DA groups all regulatory requirements and applicable mine site operating requirements contained in the authorizations issued under the EQA, such as in the certificates of authorization issued under section 22 of the EQA. It can include discharge requirements and prescribe additional follow-ups, specific studies or any other mining conditions for all types of discharge, whether wastewater, air emissions, noise emissions, odours or residual materials, including mine waste. It may also require the implementation of measures or equipment that protect against the presence of a contaminant in the environment. Finally, DAs may require that particular studies be carried out on the source of contaminants, or that the impacts of discharge on various environments be assessed and monitored. .

Furthermore, control over uranium mines is strict, and the CNSC ensures that regulations and conditions set out in the licences are complied with.

6.9 MINE CLOSURE

When a mine shuts down for a period of more than 6 months, the MRN must be notified and the premises must be secured. However, the environmental monitoring plan for the mine must be followed until a post-mining monitoring program is approved by the MDDEFP.

Finally, a "decommissioning licence" issued by the CNSC is required to close down a uranium mine. To obtain the licence, an environmental impact assessment must be completed, as required by federal law. The way in which some nuclear materials are managed on site, the volume of radioactive and hazardous waste and the work

schedule are some of the elements that must be addressed in the licence application. A long-term monitoring program is also triggered.

6.10 SITE REHABILITATION AND MONITORING

The rehabilitation plan approved by the MRN will have to be implemented. Completing rehabilitation work usually requires new authorizations under section 22 of the EQA. Site restoration must be done following best known practices. There are measures for continued mine site monitoring, particularly when contaminants are still in place and there is a risk for acid mine drainage which could affect the environment. The proponent will also have to ensure an environmental follow-up after restoration for a minimum of 5 years, or until contaminants are no longer discharged into the environment and the MDDEFP has issued a notice that is favourable to abandonment.

Land decontamination, other than in areas of mine waste accumulation, remains subject to Division IV.2.1 of the EQA concerning the land protection and rehabilitation. Land affected by mining operations must therefore be characterized and rehabilitated as per MDDEFP requirements. Once the work is complete, a certificate from an expert approved by the MDDEFP must be obtained in order to evaluate if the rehabilitation work conforms to guidelines.

Afterwards, the proponent may request to be released from this obligations pertaining to mine site restoration, as stipulated in the Mining Act. The mine site must have reached a satisfactory state according to the MDDEFP and the MRN. The MRN will issue, if applicable, a certificate of release after obtaining a favourable opinion from the MDDEFP. Once the certificate of release is emitted, the MRN can return to the proponent the sum paid as financial guarantee.

Moreover, when decommissioning is successfully completed as confirmed by long-term monitoring, an "abandonment licence" may be granted to the proponent, by the CNSC, which terminates the proponent's responsibility for the site. Regulatory surveillance and institutional control are then transferred to the provincial government.

6.11 ABORIGINAL CONSULTATIONS

Aboriginal nations are taken into consideration throughout the process. In fact, Canadian law recognizes the obligation to consult with Aboriginal communities when ancestral or treaty rights are established or claimed and when an activity may adversely affect these rights (refer to the Haida Nation (2004, CSC 73), Taku River Tlingit First Nation (2004, CSC 74), Mikisew Cree (2005, CSC 69) and Little Salmon/Carmacks (2010, CSC 53) judgements). When completing the environmental impact statement, Aboriginal consultations are an integral part of the process. Furthermore, the Mining Act provides new provisions specific to Aboriginals. The government will consult with Aboriginal communities separately, as required by the circumstances. Consideration of the rights and interests of Aboriginal communities shall be an integral part in reconciling mining operations with other possible uses of the land. The MRN will develop a policy for consulting with Aboriginal communities specifically for the mining sector.

Consultations may also be undertaken in parallel by the federal government. In fact, for uranium projects, the CNSC has clear rules when it comes time to solicit and encourage input from Aboriginal communities. However, Aboriginal consultations could be required at any stage of the project, such as if changes are made to the project or to the rights and claims of some communities.

In parallel with government consultations, which usually take place at the pre-mining stage, project proponents are increasingly consulting with neighbouring Aboriginal communities and negotiating with them directly to conclude

an Impact Benefits Agreement (IBA). There are different types of agreements that involve a long- or medium-term mutual commitment for the various steps of a mining project. These consultations help to limit the negative effects of the project on these communities and to maximize the benefits, all the while fostering a climate of trust. For companies, this is a way to manage risks and safeguard their investments. In fact, an Aboriginal community can sue the government if it deems that the Crown did not fulfil its obligation to consult with them, and if the community wins the case, the Crown may order the cessation of work, even if this affects a third party, in this case the company. By working to establish positive relationships with Aboriginal communities concerned by way of IBAs, the company can reduce this risk.

The content of IBAs is not usually made public, because they constitute mutual agreements. The government is not involved in negotiations and does not prescribe what subjects to discuss. We know however that most of these agreements contain provisions pertaining to jobs reserved for members of the community, training offered to future employees or to the community in general, business opportunities, the sharing of benefits with the community, financial or material aid for social and cultural activities and for economic development, the identification and protection of sacred sites and hunting, fishing and gathering areas, conflict management and environmental protection and management.

7 INVENTORY OF THE URANIUM INDUSTRY'S POTENTIAL IMPACTS

Summary

- The toxicity of natural uranium and its daughter elements results from their chemical toxicity and radiotoxicity.
- Natural uranium is weakly radioactive due to its long half-life. Its toxicity is mostly chemical and can lead to renal failure in animals and humans.
- Uranium is not easily bioaccumulated in plants, but it can bioconcentrate in some organisms of the lower trophic levels, such as algae and invertebrates.
- In Canada, uranium is mined in open pit or underground mines, and uranium is extracted from the ore by acid leaching.
- Uranium mining produces mine waste, effluent discharge and air emissions.
- Uranium mining is associated with potential environmental and health impacts. However, the risk of impact may be reduced by implementing environmental management strategies.

7.1 INTRODUCTION

The potential environmental and health risks posed by uranium mining are presented in this section, whereas environmental management measures that allow mitigating these risks are presented in the following section.

The radiotoxicity and chemical toxicity of uranium and its daughters are first discussed, with the help of examples. This is followed by a description of the possible types of transfer between radionuclides and living organisms, as well as the effects of bioaccumulation and toxicity observed in the microbial community, the fauna and plant species. Finally, the stages of uranium mining are presented, along with their associated sources of impact, and the effect of these impacts on the environment and organisms.

7.2 THE RADIOTOXICITY AND CHEMICAL TOXICITY OF URANIUM AND ITS DAUGHTER PRODUCTS

There are several mechanisms for transfer between radionuclides and living organisms. In humans, the two main transfer pathways are the digestive track (through ingestion) and the respiratory track (through inhalation of gas or aerosols). The skin (though injury or deposition) is also a transfer pathway, but is minor compared to the other two (CEA, 2013).

In plants, just like in animals and humans, the chemical toxicity of radioelements is only observed once the contaminant has been absorbed by the organism. In the case of radiotoxicity however, effects may be observed following internal or external exposure. An internal dose is received when radiation is emitted after the incorporation of a radionuclide in the organism's tissues through one of the many pathways (e.g. through the roots for a plant or through inhalation for humans). An external dose is received by the organism when radiation is from the external environment.

7.2.1 RADIOTOXICITY OF URANIUM

Natural uranium is weakly radioactive: it only emits a low amount of alpha radiation, since the half-lives of its isotopes are very long (Table 2.2a). For natural uranium, 97.8 % of its radioactivity is due to ^{234}U and ^{238}U (in equal proportions of 48.9 %) and 2.2 % is due to ^{235}U.

The specific activity of uranium is approximately 25,000 Bq per gram. This means that one (1) uranium atom out of every 1×10^{17} atoms decays per 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 negligible compared to its chemical toxicity.

Uranium in nonetheless classified as a human carcinogen by the United States Environmental Protection Agency (EPA) due to the established carcinogenic potential of alpha radiation (INSPQ, 2003).

7.2.2 CHEMICAL TOXICITY OF URANIUM

The International Atomic Energy Agency (IAEA) reports that the potential ecological impacts arising from the dispersal of radionuclides in the environment are typically related to the chemical toxicity of heavy metals and other non-metallic toxic compounds (sulfuric acid and kerosene from uranium milling, for instance). The damage caused by their chemical properties can be much more significant than the damage caused by the ionizing radiation they emit (CCME, 2007; IAEA, 2005). For example, in the 2003 version of Health Canada's summary of guidelines for Canadian drinking water quality, the maximum acceptable concentration for uranium is 20 µg/L (about 0.5 Bq/L) when considered as a chemical parameter, and about 323 µg/L (4 Bq/L) when considered as a radiological parameter. These values do not take into account the presence of daughter products. It should also be noted that

in the most recent version of this document, uranium is no longer listed as a radiological parameter. On the other hand, the maximum acceptable concentration for ^{210}Pb, a daughter of uranium, is 0.1 Bq/L (3.5 x 10^{-8} µg/L) when considered as a radiological parameter, and of 10 µg/L when considering the chemical character of all the stable isotopes of lead (Health Canada, 2003). The dominance of one character over another is determined by the specific activity of the radioisotope considered, among other things.

7.2.2.1 IN PLANTS

Several toxicity studies were carried out on plants consumed by humans. In plants, the chemical toxicity of uranium relies in large part on the soil's characteristics. In the soil the carbonate content, which dictates the formation of soluble carbonate compounds that can be assimilated by plants, as well as the presence of divalent cations like Ca^{2+} and Mg^{2+}, which compete with the uranyle ion UO_2^{2+} for absorption sites, will therefore have an impact on the amount of uranium that is assimilated, and consequently, on its level of toxicity. This level also varies from one species to the next and according to the plant's age at the time of exposure (CEAEQ (1), 2013).

The mechanisms of toxicity in plants typically involve enzymatic inhibition and interaction with nucleic acids. A reduction in the plant's biomass is commonly observed, as well as changes that impact its growth, development and survival.

7.2.2.2 IN ANIMALS AND HUMANS

In animals and humans, uranium's chemical toxicity varies according to the internal exposure pathway, either inhalation or ingestion. It also varies according to solubility and the chemical form of uranium compounds absorbed.

In the case of inhalation, soluble compounds are more toxic, due to the fact that once dissolved in lung secretions, they may reach the rest of the organism through blood circulation, and follow the same biological route as compounds entering the organism through gastro-intestinal absorption (CNSC (2), 2009). Some researchers believe that only the soluble form of uranium (UO_2^{2+}) causes chemical toxicity when ingested (Sheppard and coll., 2005).

In humans, the digestive track is the most common absorption pathway for radionuclides, given that uranium is present, albeit in trace amounts, in food and drinking water. In the case of ingestion, gastro-intestinal absorption of uranium is low, usually less than 5 % (INSPQ, 2003). Of this absorbed amount, 75 % is found in blood and soft tissues, i.e. the kidneys, lungs and liver. Kidneys are the target organ for bioaccessible uranium; the chemical toxicity of uranium leads to renal failure problems (INSPQ, 2003; IRSN (2), 2013). About 15 % of bioaccessible uranium is found in the skeleton, where it behaves like one of the components of bones, calcium.

The excretory system plays a critical role in eliminating uranium. For instance, in a study carried out on humans about 66 % of absorbed uranium was found to be excreted in urine after 24 hours, whereas another 10 % of absorbed uranium was excreted within the next three to four days (INSPQ, 2003).

Several studies on laboratory animals have shown that uranium is particularly toxic for kidneys and can cause renal failure for humans as well (CNSC (2), 2009). Effects on reproduction and development have also been observed in pregnant laboratory mice: a decrease in fetal weight and length, an increase in birth mortality rates, and a decrease in growth and development among young mice were observed after ingesting daily uranium concentrations of at least 2.8 mg/kg (INSPQ, 2003). This concentration is equivalent to a 50 kg person consuming about 140 mg of uranium daily, which is more than 5,000 times the average daily uranium intake for Canadians (the tolerable daily intake for uranium was set by the WHO at 0.6 µg of uranium per kg of body mass per day). It should be added that taking in 140 mg of natural uranium induces a dose of 40 mSv, which represents a cancer probability of 2 to 1,000;

this explains why the chemical toxicity of uranium is given greater importance than its radioactivity (LEDEN et EDP Sciences (1)).

Due to the natural background noise of naturally-occurring uranium, toxicity, at the environmental level, is rarely determined based on concentrations or fixed activities. Consequently, radiological risk assessment tools are often used. For instance, one tenth of the allowable dose limit of 1 mSv/year is used, which corresponds to 0.1 mSv/year, to determine drinking water guidelines for radionuclides (Table 7.1) (Health Canada, 2009). Health Canada estimates that the lifetime risk of developing a fatal cancer from 0.1 mSv is less than 1 in 100,000, therefore very low.

Published works on radionuclide concentrations in foodstuff are rare. The United Nations Scientific Committee has compiled such data (UNSCEAR, 2000; UNSCEAR, 2008); the concentrations measured in the United States are presented in Table 7.1 as an example.

7.2.3 RADIOTOXICITY OF RADIOACTIVE DUST AND RADON

For those working in the uranium industry, inhalation is the most common pathway for radionuclide absorption (Darolles, 2010). During uranium ore mining operations, radionuclides may be present in air emissions in the form of suspended particles or dust, and they may also enter the organism through the inhalation of radon.

7.2.3.1 RADIOACTIVE DUST

Dust inhalation leads to the deposition of particles in the lungs. On a mine site, dust may contain daughter products of natural uranium, such as thorium-230, radium-226 and polonium-210. Inhaled particles have different sizes, and their elimination from the body is based on their size and solubility. Soluble particles are dissolved in lung secretions and reach the rest of the organism through blood circulation before being eliminated by the kidneys. Insoluble particles, however, remain longer inside the lungs: they can reside there for long periods of time, and transmit higher radiation doses than those produced by soluble particles that are ingested then, for the most part, eliminated (CNSC (2), 2009).

7.2.3.2 RADON-222

Radon is a gas and is the most significant source of natural exposure to radiation for human beings. It rapidly decays (its half-life is 3.8 days) and it is an inert gas, i.e. devoid of chemical reactivity. This causes it to migrate readily from fissured bedrock in soil to the atmosphere, where it escapes from suspended dust particles in the air (Wilkening, 1990; BAPE, 2002). Radon however does not easily escape from solid, unfissured bedrock, where it remains confined.

When inhaled, radon that has not undergone decay while travelling though the lungs is completely expelled upon exhalation. On the other hand, radon atoms that have decayed via alpha emission during their stay inside the lungs will transform into solid elements that may settle in the respiratory track, where they will in turn emit ionizing radiation. These solid elements are the daughters of radon-222, i.e. polonium-218, lead-214, bismuth-214, polonium-214 and lead-210, the latter being the most stable (half-life of 22.2 years).

Alpha radiation emitted by radioactive dust and by radon and its daughters can cause damage inside certain lung tissues, and many studies have shown that prolonged exposure to high radon concentrations causes lung cancer.

Table 7.1: Radionuclide concentrations (uranium-238, thorium-232 and their daughter products) in water and certain foodstuff

	Activity concentration[a] (mBq/L)		Specific activity measured in foodstuff in the United States (mBq/kg) [b]				
	Drinking water: activity concentrations were calculated based on a dose of 0.1 mSv/year	Drinking water well, Nova Scotia: [c] activity concentrations measured	Dairy products (*reference value*)[d]	Animal products (*reference value*)	Cereal products (*reference value*)	Leafy vegetables (*reference value*)	Root vegetables and fruit (*reference value*)
Total uranium	20 µg/L	81 µg/L					
Uranium-238	3000	1000	0.7 (*1*)	0.8-2.3 (*2*)	3-23 (*20*)	24 (*20*)	0.9-7.7 (*3*)
Uranium-235	3000	50	0.05 (*0.05*)	0.02 (*0.05*)	0.1-1.3 (*1*)	1.2 (*1*)	0.1 (*0.1*)
Uranium-234	3000	1000					
Thorium-232	600	< 10	0.27 *(0.30)*	0.3-2 *(1)*	0.1-2.8 *(3)*	18 *(15)*	0.08-1.4 *(0.5)*
Radium-226	500	40	5.7 *(5)*	20 *(15)*	7-100 *(80)*	56 *(50)*	7-47 *(30)*
Polonium-210	100	120					
Lead-210	200	240	11 *(15)*	18 *(80)*	33-81 *(50)*	41 *(80)*	8-150 *(30)*

[a] Activity concentration is a measure of activity per unit of volume for the sample measured (Bq/L or Bq/m^3), whereas specific activity is a measure of activity per unit of mass (Bq/g); [b] UNSCEAR, 2000; [c] In Nova Scotia, significant uranium mineralization has led to an increase of radionuclide concentrations in a certain number of places, such as inside wells; averages for 52 wells are presented here (Health Canada, 2009); [d] Reference values in parentheses are also from the United Nations Scientific Committee.

Sources: Health Canada, 2009; UNSCEAR, 2000; UNSCEAR, 2008.

7.2.4 RADIOTOXICITY AND CHEMICAL TOXICITY OF OTHER ELEMENTS

7.2.4.1 THORIUM

Thorium has a chemical toxicity similar to that of uranium, whereas its radiotoxicity, which arises from the Th-232 decay series, is greater due to the fact that thorium's alpha- and beta-emitting daughter products have relatively shorter half-lives. It should be noted that the relative importance of one particular form of toxicity over another (to radiotoxicity with respect to chemical toxicity) has not yet been clearly established.

As with uranium, the studies show that thorium can be absorbed by most plants and other terrestrial and aquatic organisms. However, bioconcentration factors seem to indicate that thorium does not typically tend to bioconcentrate within organisms (CEAEQ (2), 2013).

Although absorption mechanisms are still poorly understood, laboratory studies have shown that high exposure to thorium can lead to slower growth rates in plants and an increase in mortality for some amphibians and mammals. Thorium, as a heavy metal and alpha emitter, causes damage to the DNA of living cells, as does uranium.

7.2.4.2 THE DAUGHTERS: RADIUM, POLONIUM AND LEAD

Radium-226 is the isotope most commonly found in the environment, and its half-life is 1,600 years (compared to 5.7 years, 3.6 days and 11.7 days for the other natural isotopes of radium, ^{228}Ra, ^{224}Ra and ^{223}Ra respectively).

When ingested by animals or humans, the metabolic behaviour of radium becomes similar to that of calcium. Consequently, the main site of deposition and retention of radium inside organisms is in bone structure. In the event of significant exposure to radium, the damage caused by ionizing radiation is related to bone cancer (IRSN (3), 2013).

As mentioned before, the specific activity of polonium-210 (the most abundant among the 29 isotopes of polonium even though it occurs as trace amounts in the environment) is very high (1.66 x 10^{14} Bq per gram of ^{210}Po). As such, its radiotoxicity is greater than its chemical toxicity. Because polonium-210 arises from the decay of radon-222, it is omnipresent in the air, with an activity concentration of about 50 mBq/m^3. Its specific activity may however be particularly high in uranium mine waste (15,000 to 22,000 Bq/kg compared to 10 to 200 Bq/kg in soil) (IRSN (4), 2013; IRSN (5), 2013).

Polonium-210 is transferred to terrestrial plants through the leaves without being absorbed, since it remains for the most part concentrated at the surface of leaves. For animals and humans, polonium-210 is transferred by means of ingestion or inhalation. It can accumulate and bioconcentrate within certain marine organisms, where much greater activities are observed than in ambient conditions (for instance in the digestive gland of molluscs, the liver of some fish or in plankton) (IRSN (4), 2013).

In humans, 10 to 50 % of ingested polonium is absorbed (depending on its chemical form), binding to red blood cells and being distributed between the liver, spleen, kidneys and bone marrow. Of the amount ingested, about half will be eliminated through urine within the first 50 days (IRSN (5), 2013). Not surprisingly, the lungs are among the organs impacted by polonium when inhaled (IRSN (4), 2013). In bone marrow, polonium-210 causes a decrease in white blood cells, which results in increased sensitivity to infections for the highly contaminated person (i.e. a weakened immune system).

Lead is a heavy metal. Unlike the elements discussed so far, lead possesses stable isotopes (which is to say non-radioactive), which are lead-204, 206, 207 and 208 (many being end products of the decay chains of ^{238}U, ^{235}U and ^{232}Th). Among the radioactive isotopes (^{210}Pb, ^{211}Pb ^{212}Pb, ^{214}Pb), only ^{210}Pb has a half-time of more than a few hours. However, because the stable isotopes occur at concentrations that are several orders of magnitude greater than their radioactive counterparts, their radiotoxic effects are generally overshadowed by their chemical toxicity, all the more so given that in the ecosystem, the chemical behaviour of radioactive isotopes and stable isotopes is the same. Only a small fraction of lead within the ecosystem is bioavailable. This fraction will mostly be absorbed by the cell walls of plant roots, where it will bioaccumulate. The phytotoxicity of lead will manifest itself as DNA damage, which could result in a reduced or inhibited rate for germination, plant development or chlorophyll production (Pourrut et al., 2011).

Other isotopes arising from the decay chains of ^{235}U and ^{232}Th behave in a similar way as their counterparts in the decay chain of ^{238}U (for instance ^{228}Ra and ^{226}Ra), but have variable levels of radioactivity.

Finally, radon-222 is an inert gas and therefore has a very weak chemical toxicity, since its electronic constitution makes it such that it is barely able to create chemical bonds with other atoms (except under very special circumstances created in the laboratory). It toxicity is therefore from the emission of alpha radiation as it decays.

7.3 BIOACCUMULATION AND BIOCONCENTRATION OF URANIUM IN FOOD CHAINS AND ITS IMPACT ON TOXICITY

Some organisms have the ability to bioaccumulate, which is the ability to absorb chemical substances found in the environment, such as radionuclides occurring in trace amounts. These organisms may be plants, animals, fungi or micro-organisms. Elements can be directly absorbed from the environment, such as from water, air or soil, or from the consumption of contaminated organisms (fish, for instance). The pathway is the route taken by a radionuclide to enter an organism. Knowledge of pathways makes it possible to anticipate the presence of radionuclides within various living organisms, and subsequently, estimate the potential impact of radionuclide discharges into the environment.

The parameters that determine the pathway of radionuclides are numerous (for instance, soil density or the presence of organic matter), and the processes are not always easy to predict. Mathematical models are used to more precisely estimate the movement and presence of radionuclides within an ecosystem. These models aim to reproduce actual conditions occurring in nature in order to predict the potential environmental impacts (Jeambrun, 2012). One of the parameters used in these models is the transfer factor (TF), which allows the estimation of radioelement concentrations in tissues.

TF = specific activity of a radionuclide in tissues/activity concentration of the radionuclide in the ambient environment

Studies that describe the pathways used by uranium in several species have been carried out, and the results pertaining to plant species are summarized in Table 7.2.

7.3.1 TRANSFER OF RADIONUCLIDES TO PLANTS

Transfer factor values range considerably from one plant to another, but the grounds on which mathematical predictions are based, lie in the hypothesis that the transfer of radionuclides to plants describes a linear relationship. In fact, published works have reported that radionuclide concentrations in certain plants varied linearly with increased concentrations in laboratory hydroponic solutions (Jeambrun, 2012). Natural processes for radionuclide migration, sorption and bioaccumulation, as they occur in the environment, are complex and cannot yet be perfectly replicated by mathematical models. The models do not always take into account the chemical form of radionuclides in the environment, nor their bioavailability. The models currently used are therefore not yet able to provide globally approved concentration limits for radionuclides such as uranium for environmental protection purposes (Schmidt et al., 2012).

Table 7.2: The main pathways for radionuclide transfer to plants.

Pathway	Description
Uptake of radionuclides in soil by roots (dominant pathway)	Radionuclides are transferred from the soil to the roots. Depends on parameters, such as: - soil chemistry (type of uranium mineral in soil, presence of the soluble UO_2^{2+} ion), biology (presence of micro-organisms); - soil physics (porosity) and hydrology; - plant physiology; - the presence of other elements (e.g. Ca^{2+} et Mg^{2+}) which may compete with the UO_2^{2+} uranyle ion for various absorption sites (Sheppard et al., 2005).
Air particle interception	Transfer occurs on the surface of leaves by intercepting air particles. Parameters like particle size and the chemical form of radionuclides will affect the extent of transfer.
Radionuclide translocation	Contaminants are redistributed to the parts of the plant that have not come into direct contact with radionuclides. Strong electrostatic interactions between the root surface of plants and radionuclides in their ion form can reduce the occurrence of translocation phenomena.
Re-suspension of soil particles	This phenomenon, mainly due to wind action, can be the main source of radionuclides for a plant when radionuclide concentrations in surface soil particles (that are re-suspended in the atmosphere) are greater than concentrations in roots.

Source: Jeambrun, 2012.

7.3.1.1 BIOACCUMULATION OF URANIUM IN CERTAIN PLANT SPECIES

Because uranium is omnipresent in soil, it can be detected in all plants. Normal concentrations observed in plants typically range from 0.5 to 2 mg per kilogram of plants ashes. Some researchers believe that uranium concentrations greater than 2 mg/kg (2 mg of uranium per kg of ash) are anomalous (IAEA, 1985). Nevertheless, there are some places, such as in northern Saskatchewan, where certain types of spruce trees have concentrations exceeding 10 mg/kg. Bioaccumulation of uranium in surface plants helps to determine if uranium ores are present below the sedimentary cover.

During a soil-root transfer, plant roots that absorb the most uranium are those which have a greater capacity to create electrostatic exchange, since absorption occurs through the transfer of ions between uranium compounds in solution and plant tissues (IAEA, 1985). Once absorbed, uranium mainly forms compounds with proteins and other molecules with a high molecular weight, by interacting with proteins located along cell walls. Consequently, the mobility of uranium is often reduced in the rest of the plant, and its concentration is greater on root surfaces than on other parts . In the environment, uranium is more readily absorbed by plants when it is dissolved in groundwater: absorption is on average 3,000 times higher in this case than when uranium occurs as a solid in soil (IAEA, 1985).

It is worth mentioning that several studies that look at the ability of plant species to absorb uranium are carried out in the laboratory, at uranium concentrations much greater than those observed in nature. Radionuclide concentrations in nature are very low; in order to precisely track their trajectory inside an organism and determine their effect in terms of toxicity it is sometimes necessary to increase their concentration. Furthermore, other parameters used in these studies, such as the chemical composition of irrigation water, can be far from natural conditions, since natural irrigation waters contain variable amounts of various salts and dissolved metals, which compete with uranium for activity sites along plant cell walls. Consequently, uranium absorption percentages obtained in the laboratory will not consistently reflect those in nature, but these studies nonetheless reflect general trends.

The capacity of living organisms to accumulate radionuclides is often expressed as a bioconcentration factor (BCF), which is similar to the transfer factor discussed above:

BCF = specific activity of U in an organism (Bq/kg) / total specific activity in an environmental medium (Bq/kg).

For sites with low uranium concentrations, BCFs range, on average, between 0.0002 and 0.01 (with some extreme values of more than 1) depending on factors such as soil type, are reported for a variety of fruits and vegetables (CEAEQ (1), 2013). Other BCF calculations were also done for plant species (spruce needles, Labrador tea, blueberries, etc.) occurring on sites slightly contaminated by uranium (1 mg/kg uranium). In this case, BCFs were higher, ranging from 0.026 to 4.5 (CEAEQ (1), 2013).

BCF calculations demonstrate that uranium does not naturally accumulate significantly in plant species found in the environment, with a few exceptions. Generally, the levels of bioaccumulation, bioconcentration and biomagnification for uranium are low, which explains why the Persistence and Bioaccumulation Regulations (CNSC (1), 2010) consider that uranium is not readily bioaccumulatable (BCF < 10) (CEAEQ (1), 2013; CCME, 2007).

7.3.1.2 IMPACT ON TOXICITY

Many studies on uranium toxicity were carried out in laboratories under controlled conditions whereby plant species were exposed to high uranium concentrations. Some of these studies have shown that the toxicity of uranium in plants manifests itself in many ways, such as a decrease in biomass.

These studies seem to demonstrate that impacts occur when plants are exposed to high uranium concentrations, well above the maximum recommended dose in Canada of 23 mg/kg for agricultural and residential soil (CCME, 2007). For instance, corn crops were exposed to soil containing 10, 25, 50, 100, 250, 500 and 1000 mg/kg of uranium. A decrease in the rate of survival was observed for crops exposed to concentrations greater than 250 mg/kg. It is worth mentioning that a stimulation of the roots' biomass was observed in crops exposed to low uranium concentrations (< 50 mg/kg) (CEAEQ (1), 2013).

However, the maximum allowable uranium concentration in Canada for soils in industrial areas is 300 mg/kg. Depending on soil type and mineral content, additional toxic effects could therefore be observed in these areas. A comprehensive review of the studies that investigate the toxic effects of uranium on plants is presented in the document prepared by the *Centre d'expertise en analyse environnementale* (CEAEQ (1), 2013).

7.3.2 TRANSFER OF RADIONUCLIDES TO ANIMALS

There are three ways by which radionuclides can be transferred to terrestrial and aquatic animals: the skin, ingestion and inhalation, the main pathway for animals and humans being ingestion (food, soil-sediment, water) (Jeambrun, 2012). Exposure scenarios for skin and ingestion are presented in Table 7.3.

Table 7.3: Exposure of various living organisms to radionuclides.

	Ingestion	Skin contact
Mammals and birds	• soil/sediment • surface water • plant	• soil/sediment • surface water
Fish and benthic invertebrates	• sediment • surface water	• sediment • surface water
Local populations around a mine site	• plant and animal food • drinking water	• exposure to waste rock piles

7.3.2.1 BIOACCUMULATION AND TOXICITY OF URANIUM IN ANIMALS

Many studies report the bioaccumulation of uranium in terrestrial and aquatic animals. The amount of radionuclides assimilated will vary according to the animal species, the species' body mass and the environment or breeding conditions. For instance, grain-fed hogs and poultry do not absorb the same amount of radionuclides as grazing cattle (Jeambrun, 2012). As for aquatic organisms, bioaccumulation will result from ingestion of contaminated sediments and water. A study to calculate bioconcentration factors (that are expressed as the ratio of the specific activity of uranium in organisms, in Bq/kg, to that of uranium in water, in Bq/L) on various freshwater species was recently published (IAEA (2), 2009). In this study, organisms of the lower trophic levels (algae: BCF = 210 L/kg, invertebrates: BCF = 170 L/kg) demonstrate a greater tendency to accumulate than organisms of higher trophic levels like fish (BCF = 0.86 L/kg of flesh). For comparison purposes, bioconcentration factors recommended by the International Atomic Energy Agency (IAEA) are of 1 L/kg for fish, 10 L/kg for crustaceans, 30 L/kg for molluscs and 100 L/kg for algae (Vandenhove, 2010).

The bioconcentration of various radionuclides arising from the decay chain of natural uranium (including uranium-238, lead-210 and polonium-210) in fish bones from lakes located close to the old Elliot Lake mine site in Ontario was examined (Clulow et coll., 1998). The ratios between radionuclide concentrations in bones and radionuclide concentrations in water indicated that lead-210 could be bioaccumulated and bioconcentrated in the bones of fish examined. It was also demonstrated that radionuclide concentrations were higher in fish bones than in flesh, as anticipated given the transfer mechanisms of numerous radionuclides (Mirka et al., 1996).

The consequences of uranium's chemical toxicity for animals exposed to high concentrations can affect species development or reproduction. However, renal failure seems to be the main effect observed.

7.3.2.2 TRANSFER OF RADIONUCLIDES TO MICRO-ORGANISMS

Micro-organisms have the ability to solubilize radionuclides and other heavy metals found in the environment, just as they possess the ability to immobilize them. This interaction occurs following various biological mechanisms: for soluble compounds being returned to the ecosystem, for instance, various mechanisms of chelation, autotrophic and heterotrophic salting out and methylation occur. Radionuclide immobilization occurs through intracellular absorption or precipitation of its inorganic insoluble forms (Gadd, 2002).

7.3.2.3 BIOACCUMULATION AND TOXICITY OF URANIUM IN MICRO-ORGANISMS

Compared to other heavy metals, uranium is thought to be less toxic for certain microorganisms in which it can accumulate and be highly concentrated in cell walls (CCME, 2007). Many species of bacillus occurring in uranium mine waste have demonstrated the ability to accumulate uranium and to extract about 90 % of uranium in contaminated waters (as they do for lead and many other metals) (Selenska-Pobkell et al., 1999; Selenska-Pobkell, 2002). Other aquatic fungi cultures have shown that, out of ten cultures tested, five bioabsorbed more than 90 % of uranium present in aqueous solutions (CCME, 2207). Several studies, however, have reported the harmful toxic effects of uranium on other microorganisms (CCME, 2007).

There are several transfer pathways between radionuclides and living organisms. One of the risks of uranium and its daughter products being introduced in living organisms is bioaccumulation, or bioconcentration. Depending on the living species and the isotopes absorbed, the impact on the biota's health may be moderate or significant, and effects on the reproduction and growth of the species could be observed.

7.4 THE MINERAL INDUSTRY AND SOURCES OF IMPACT

The following sections broadly describe the different stages of uranium exploration and mining and cite the potential sources of impact related to these stages. Examples that illustrate the relative impact of these stages are provided when available.

7.4.1 EXPLORATION

Exploration aims to locate uranium deposits using different techniques, some being non-intrusive (remote sensing, gamma-ray surveying), and others requiring minor or major excavation work, such as drilling and coring.

First pass exploration relies on geophysical and geochemical data and on geological observations, without any notable impact. Airborne geophysical surveys may temporarily inconvenience people or animals.

The next phase of work may comprise drill holes or blasting, and require the storage of core or excavated materials. Impacts on the biophysical environment related to the emanation of radioactive radiation or to the discharge of radiological contaminants may be observed (GA, 2008), such as:

- an increase in the air emission rate of radon from underground exhaust air, open holes or drill holes, excavated materials or surface waste;
- the contamination of water and air by radioactive emissions;
- the leaching of radioelements and other metals in surface waters, groundwater and soil;
- groundwater contamination due to exploration drill holes, which may intersect aquifers and put groundwater in contact with zones of uranium mineralization. Some aquifers may naturally be enriched in uranium due to the natural infiltration of groundwater in uranium-rich rocks and sediments.

7.4.2 SITE CONSTRUCTION

This step mainly consists of clearing the site of vegetation and erecting buildings, roads and other infrastructures, over a certain period of time (before and after the mining stage). The impacts related to this stage may result in increased rates of radon emission and radioactive radiation in the air. The sources of impact are discussed in the following paragraphs.

7.4.3 MINING

The method selected to extract uranium depends on various factors, such as the depth at which ore occurs in the bedrock, its uranium concentration (U_3O_8 weight percent) and geotechnical and hydrogeological parameters. The different extraction and transformation options for uranium ore are presented in Figure 7.1.

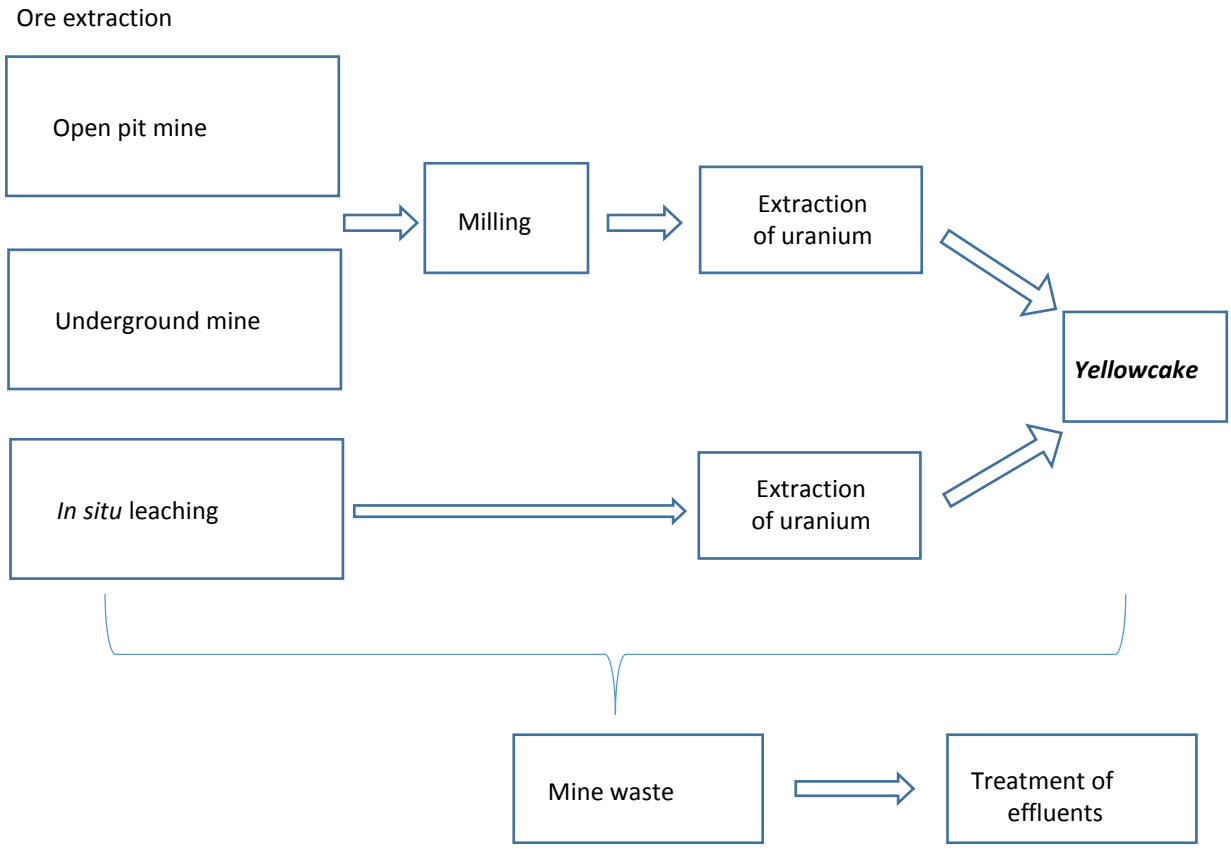


Figure 7.1 Conventional process for mining and transformation of uranium ore.

7.4.3.1 ORE EXTRACTION IN OPEN PIT AND UNDERGROUND MINES

Ore is mined by fracturing the rock using explosives. When the ore is located at depth within fragile rock structures, a form of mine support is required once the ore is excavated. In areas of permafrost, the frozen ground and bedrock conditions must be preserved to avoid groundwater infiltration. The use of remote-controlled mining equipment is necessary in hazardous areas, due to the potential instability of mine infrastructure or to high uranium concentrations. The ore is then milled at the mine and at the processing plant, until a pulp of adequate grain size to release uranium minerals is obtained. Yellowcake, a uranium concentrate, is produced in the processing plant, and subsequently shipped to an enrichment plant (Figure 7.1). Modern yellowcake is either brown or black, but its name comes from the colour and texture of the concentrates produced by early mining operations.

During mining operations, the rocks excavated to access the ore constitute mining rejects and are called waste rocks, which are stored in piles at the surface. These rocks do not contain any minerals in sufficient amounts to be considered ore (CNSC (1), 2012), and are not typically acid-generating (CNSC (6), 2012).

Tailings are derived from the ore following mechanical and chemical treatments designed to recover uranium. They may contain heavy metals in addition to unrecovered uranium and radioactive products (daughter products). Tailings must be stored according to the parameters set out in the certificates of authorization, either in areas of mine waste accumulation, or in abandoned mining pits converted for this purpose.

Potential sources of impact on the biophysical environment associated with mining of uranium ore are related to the presence of ionizing radiation, to the emanation of radon gas and to the chemical toxicity of radioelements. These sources include (GA, 2008):

- an increased rate of radon gas emissions to air from underground exhaust air (mine tunnels and ventilation shafts) or from surface waste (waste rock piles);
- gamma radiation from the surface disposal of mine waste and from underground openings (drill holes, levels, ramps);
- the emission of radioactive dust from ore crushing and milling, excavation work and tailing facilities;
- the management of waste rock that may generate contaminated drainage or release radionuclides and other heavy metals into the environment through leaching;
- the radioactive contamination of surface water, groundwater and soils, due to contaminated effluent.

7.4.3.2 ORE EXTRACTION THROUGH *IN SITU* LEACHING

To extract uranium using *in situ* leaching, an acid or basic solution, depending on the nature of the bedrock, is directly injected into the uranium-rich zone of permeable rock, along with an oxidizing agent. The solution is dispersed throughout the high-grade ore zone and oxidizes tetravalent uranium (U^{+4}) to form soluble hexavalent uranium (U^{+6}). Dissolved uranium is in the form of carbonate uranyle compounds $[(UO_2(CO_3)_3]^{4-}$ or sulfate uranyle compounds $[(UO_2(SO_4)_3]^{4-}$, and the solution is pumped to the surface through a network of wells which allow to control the percolation of the uranium-enriched solution. This technique makes it possible to extract uranium without extracting the rock, which reduces the environmental impact as it does not involve excavation nor waste rock and disposal of tailings. The potential impacts on the biophysical environment for this technique include (GA, 2008):

- aquifer contamination through leaching of chemicals used for extraction and by extracted and dissolved metals, such as uranium;
- the release of radioactive substances, including radon, and metals from the pumped extraction solutions;
- the accidental spillage of chemicals or radioactive substances;
- the disposal and treatment of solutions used for extraction (evaporation, burial);
- the monitoring and pumping of spent solution, which is done for a certain period of time after the stop of mining operations to prevent the infiltration of contaminated solutions in aquifers.

7.4.4 URANIUM CONCENTRATION: CHEMICAL ISOLATION OF URANIUM FROM THE ORE

Uranium concentration, which consists in extracting uranium from the ore after the milling stage, is generally done in a plant located on the mine site or in the surrounding area. Acids and bases, oxidizing agents and organic solvents are required at this stage.

a) Acid leaching:

1. Finely-milled ore containing uranium is dissolved using sulfuric acid in the presence of an oxidizing agent, such as hydrogen peroxide or dioxide or manganese chlorate. The uranyle ion (UO_2^{2+}) that forms reacts with sulfuric acid to form the $[(UO_2(SO_4)_3]^{4-}$ anion.

2. Uranium is extracted from this aqueous phase by an organic phase, which commonly consists of tertiary amines. Uranium may also be extracted using ion exchange resins.

3. Uranium typically precipitates as an ammonium diuranate compound ($(NH_4)_2U_2O_7$) using ammonium hydroxide solutions (NH_4OH). Uranium may also precipitate as magnesium diuranate, which reduces the risk of ammonia occurring in the environment. The product then undergoes calcination, and ammonium diuranate is transformed into uranium oxide (yellowcake) with a U_3O_8 grade of about 99 % (IAEA (1), 2009).

b) Base leaching:

The steps are the same as for acid leaching, except that uranium is dissolved in a basic aqueous solution using a diluted sodium carbonate solution with molecular oxygen as the oxidizing agent (EB, 2013), resulting in the formation of the anion $[(UO_2(CO_3)_3]^{4-}$.

The potential sources of impact on the biophysical environment for uranium concentration include:

- the emission of radioactive radiation and radon from radionuclides occurring in the milled ore;
- the management and treatment of spent solutions;
- solid waste derived from the concentration process, which contains uranium and other radionuclides;
- accidental spillage of chemicals containing radionuclides.

7.4.5 SITE RESTORATION AND DISMANTLING

At this stage, drill holes and excavations are grouted/backfilled, and surface infrastructure is dismantled. This stage can be undertaken from the very start of operations, by dynamic site restoration. As it does not involve any mining operations, there are typically no additional sources of impact. Radionuclides may however be redistributed regionally due to the transportation of infrastructure and waste.

7.5 ASSESSMENT OF THE SHORT-, MEDIUM- AND LONG-TERM POTENTIAL EFFECTS

The potential impacts presented below are divided into three sections: disposal of waste rock and tailings, effluents after their treatment, and air emissions. The impacts are discussed for all stages (exploration, ore extraction, uranium concentration) and according to their duration (short, medium, long term) where differences exist.

7.5.1 DISPOSAL OF WASTE ROCK AND TAILINGS

The environmental impacts related to mining are mainly due to the significant amounts of rock that must be removed and to their accumulation at surface (Arogunjo et al., 2009). Once the ore has been processed, the natural radioactivity of the rocks is concentrated in the tailings, which increases the risk of environmental dissemination.

Another significant concern related to mining operations is the risk of generating contaminated mine drainage. In some deposit, uranium is associated with metal sulphides, such as pyrite, an iron sulphide. Rocks excavated that contain metal sulphides tend to oxidize when in contact with air or water, and may release sulfuric acid, which has the ability to solubilize several metals, such as uranium. This process is referred to as acid mine drainage (AMD). This reaction may lead to acid runoff in the environment as well as the transport of radionuclides and other metals found in soil (IAEA (1), 2009), as was the case in the Elliot Lake area, in Ontario. AMD can also occur in underground rocks since the excavation and construction of underground facilities puts the underground in direct contact with the atmosphere, enabling the oxidation of metal sulphides (IAEA, 2005). Water pumped from open pits and underground excavations must therefore be recovered and treated at a plant before being discharged in the environment.

Contaminants that may be found in excavated materials and mine waste include radioelements that are part of the decay chain of uranium (including radium) and of thorium-232 (WNA, 2011). They also include radon and suspended particles (radioelements and metal dust), and are the source of gamma radiation.

7.5.1.1 SHORT- AND MEDIUM-TERM IMPACTS RELATED TO THE MINING STAGE

The main solid rejects produced during the mining stage are waste rock and tailings. They can be stored at surface, in underground cavities (WNA, 2011) or in man-made pits (GA, 2008).

The potential impacts associated with the disposal of waste rock and tailings pertain to the environmental dispersal of radioelements within them. The different modes of dispersal include (IAEA, 2005):

- the dispersal of radioactive dust and other chemically-toxic metals by wind: waste that is not covered or kept wet can dry up on the surface, and dust formed in this way is more readily dispersed;
- acid mine drainage: this type of runoff, if it is not contained and treated, increases the probability of environmental contamination, given the solubility of metals in acid waters;
- the migration of radionuclides and other toxic metals due to rain or melting snow (percolation), which may occur if process water and precipitation water on the mine site are not successfully separated from the solid fraction, recovered and treated as process water.

In the absence of adequate prevention methods, the aforementioned impacts could have medium- and long-term consequences on mammals, birds, fish and benthic invertebrates, as well as on humans. For instance, when leachate or contaminated effluents infiltrate surface waters, radionuclide absorption can decrease the reproduction rate of fish (Clulow, 2008).

7.5.1.2 LONG-TERM IMPACTS

Several studies report high radionuclide concentrations (in soil, sediments, surface water and underground water) and gamma radiation near old mine sites where little restoration work has been done (Aparin et al., 2012). These sites were mined under very different conditions than those prescribed by current regulations, some related to the military and strategic nature of uranium during the Second World War and the Cold War. Presented below are some results of studies conducted close to old mine sites where no restoration work is reported.

In Portugal, 60 sites were mined for radioactive ore (radium, followed by uranium) from the start of the XXTH century until 2001. As such, the industry generated 3 million tonnes of radioactive waste from uranium mining, for a total production of 4,000 tonnes of U_3O_8 between 1951 and 2001 (Carvalho et al., 2005). Solid and radioactive wastes were rarely left at the extraction sites, but rather at the sites for ore processing where radioactive waste piles were commonly found, particularly where ore was concentrated by acid leaching.

A study published by the International Atomic Energy Agency reported that in 2004, some of these piles contained traces of uranium-238 and its daughter products (radium, lead, bismuth, polonium), and surface radiation rates of 24 µSv/h were measured in some places (Carvalho et al., 2005). For comparison purposes, background radioactivity in the area ranges from 0.2 to 0.7 µSv/h, and the global background dose rate is about 0.09 µSv/h. In agricultural land next to mine sites, the specific activity of some radionuclides was occasionally found to be higher than in baseline soils (distances were not specified, but baseline soils are usually located quite far from the mining project and its surrounding area), resulting in the transfer of radionuclides to the food chain. For instance, the specific activity of uranium-235 in agricultural soil ranged between 6 and 70 Bq/kg, whereas the maximum value in baseline soils was of 35 Bq/kg (Table 7.4). The authors also noted the presence of acid waters (pH of 2-3) at the old mine sites, due to uranium extraction by *in situ* leaching. These waters had high activity concentrations for radionuclides and other metals, with values of up to 169.7 Bq/L for uranium. For comparison purposes, the activity concentrations of uranium in surface waters averaged 0.025 Bq/L (average concentration of uranium in surface waters = 1 µg/L (Vandenhove et al., 2010); the specific activity of natural uranium = 25,000 Bq/g (WNA, 2009)).

Table 7.4 : Radionuclide concentrations in contaminated areas, Portugal.

Location	Total U	^{235}U	^{234}Th	^{226}Ra	^{210}Pb	^{210}Po
Baseline soil (Bq/kg)	NA[(a)]	8 to 35	120 to 190	80 to 180	120 to 200	NA
Agricultural land next to sites (Bq/kg)	NA	6 to 70	210 to 340	150 to 260	290 to 320	NA
Mine waste from the Bica site [(b)] (Bq/kg)	NA	1290	3740	18 590	34,040	NA
Mine waste from the Vale da Arca site[(c)] (Bq/kg)	NA	635	6540	3530	7100	NA
Groundwater from the site Bica (pH = 3.1) (Bq/L)	8.6	NA	NA	1.5	1.8	0.23
Water stored on the site's surface Quinta Bispo (pH = 2.7) (Bq/L)	169.7	NA	NA	1.1	1.2	0.09

[a] Readings are not reported for these radionuclides; [b] The mine site that has among the highest values; [c] The mine site that has among the lowest values.

Data source: Carvalho et al., 2005.

In Kyrgyzstan, piles of waste rock from an old uranium mine site were stored over the course of mining and processing operations, from 1946 to 1968. Radioactive waste was accumulated in 23 waste piles, along with other piles of non-economic ore. Piles were covered with a 15- to 25-cm thick layer of soil. On the surface, the levels of gamma radiation ranged from values close to global background noise (0.09 µSv/h) to anomalously high values (0.877-4.385 µSv/h). The contamination of surface waters and sediments in radionuclides and other toxic elements, such as selenium, is also attributed to the waste rock piles (Aparin et al., 2012).

Modern-day mining projects have protective measures to reduce such impacts on the ecosystem, without however succeeding to completely prevent radionuclide dispersal. For instance, the Cluff Lake site that includes open pit and underground mines and a uranium processing plant in the Athabasca Basin of northern Saskatchewan generated more than 31,000 tonnes of uranium concentrate (U_3O_8) over the life of the project. Mining and processing operations began in 1980 and ended in 2002, and the resulting mine waste was covered with one metre of uncontaminated soil to reduce emission rates of radon and gamma radiation.

A comprehensive study of the Cluff Lake decommissioning project was completed by the CNSC in 2003 and provides radionuclide concentrations for various zones in the site area (CNSC, 2003). Groundwater radionuclide concentrations at monitoring stations located inside and along the perimeter of pits filled with solid waste were high compared to baseline values (Table 7.5), such that groundwater would represent a risk for humans and non-human biota if it were available as drinking water.

However, given the abundance of surface water in the local study area, the site's relative isolation and the presence of strict controls, it was deemed unlikely that this groundwater would eventually be consumed. On this basis, the authors classified the environmental effects of mining operations on groundwater as negative, but not significant. The site's restoration was completed in 2006, and the results for water samples from the site indicated that further treatment was not required (GA, 2008).

Some researchers believe that it is impossible to completely remove uranium and its daughter products from effluents after mining operations with current technology and at a reasonable cost (Schmidt et al., 2012).

Table 7.5: Radionuclide concentrations in groundwater from solid waste pits.

Radionuclide	Concentration close to solid waste pits	Baseline values
^{210}Pb (Bq/L)	0.300	0.037
^{210}Po (Bq/L)	0.080	0.034
^{226}Ra (Bq/L)	0.2	0.086
Total uranium (µg/L)	30	13.6

Data source: CNSC, 2003.

7.5.2 EFFLUENTS

Effluents may be composed of water from the areas of waste rock and the accumulation of tailings, various liquids generated by the milling process, and water from underground operations that is pumped back to the surface. The radioelements of uranium-238's radioactive family, various metals, suspended solids and dissolved salts are

potential contaminants, as are the chemical substances used to concentrate uranium. The on-site treatment of effluents is specific to each site, and depends on the techniques used for uranium mining and milling, as well as on various geological and biological factors like soil composition. Effluent treatment aims to reduce the concentrations of radionuclides, heavy metals and other potentially toxic elements by adding chemical substances that will bind with contaminants to form solid compounds, which will subsequently precipitate and be removed from water by processes such as filtration and sedimentation. For instance, when barium chloride is added to the effluents, it will combine with radium in the presence of sulfuric acid and form radium and barium sulphates, which will coprecipitate. Consequently, this process increases the amount of dissolved salts in the effluents, but this constitutes a medium-term impact since salt concentrations quickly return to pre-mining values once operations cease (SERM (2), 1997).

The treatment applied to effluents at the Cigar Lake mine in Saskatchewan is an example of the type of process commonly used in the uranium industry (GA, 2008). Effluents from the stockpiles and other waste are collected in staging ponds where radionuclides, heavy metals and other contaminants are removed from the water through several phases of precipitation (using flocculants, iron or barium compounds and lime) and filtration processes. The resulting waters are stored in secondary basins in order to collect samples for analysis, before being discharged in the environment. Resulting sludges are stored with tailings.

7.5.2.1 IMPACTS RELATED TO THE MINING STAGE

The potential impacts of mining effluent arise from the dispersal of radioelements in the environment, just as with solid waste. Because effluents are contained in purpose-built sedimentation basins, runoff, overflow, and accidental spills may occur. The mobility of radionuclides will depend on factors such as the chemical form of compounds present and the physicochemical character of the soils, streams and lakes affected. For instance, the migration of radioelements will be limited if the spill occurs in an aquifer with large amounts of absorbing materials or if they are discharged in a lake with a weak current (SERM (2), 1997). Species that are likely to be affected upon ingestion of sediments or surface water include fish and benthic invertebrates (MJ (1), 2013), birds and terrestrial animals.

Nowadays, several technologies used for the treatment of effluents make it possible to reach activity concentrations significantly below the maximum values set by regulatory agencies. As an example, in 2008, the government reported that prior to treatment, effluents from the McArthur River mine (Saskatchewan) contained on average 23 Bq/L of radium-226, the maximum allowable activity concentration for discharge into the environment being 0.37 Bq/L (MJ (1), 2013). However, the average activity concentration obtained after effluent treatment was of 0.063 Bq/L, which is well below the maximum value permitted (GA, 2008). Note that the Metal Mining Effluents Regulations provides for maximum harmful substance concentrations in effluents for various metals, but radium is the only radionuclide present in this regulation. For comparison purposes, according to Health Canada, the maximum acceptable concentrations for drinking water quality are 0.2 Bq/L for lead-210, 0.5 Bq/L for radium-226 and 0.02 mg/L for uranium (Health Canada, 2009).

Long-term ecological impacts resulting from inadequate effluent treatment have been observed in various environments, such as the uranium mine site near Elliot Lake (closed in 1996), in Ontario. After the start of mining operations in 1955, game fish populations downstream of the mine site rapidly declined following a decrease in their reproductive rate, and the lakes affected had high suspended solid and radionuclide concentrations, as well as acidic conditions (Health Canada, 2009). With the arrival of new effluent treatment technologies, treated waters achieved regulatory levels for drinking water toward the end of the 1960s, and the Ministry of Natural Resources of Ontario authorized the reintroduction of game fish in the lakes in question in the early 1980s. However, readings taken in 1998 showed the presence of residual radionuclides from the decay chain of natural uranium (such as

uranium-238, lead-210 and polonium-210) in sediments, fish and water from lakes close to the old mine site, at levels greater than those observed in control lakes. Examples of concentrations measured in water and sediments, and in the bones and flesh of fish are provided in Table 7.6.

Based on this data, the authors of the study concluded that the ingestion of radionuclides from eating one meal of fish per week (375 g) for a 1-year period represented less than 15 % of the annual recommended dose for the general public (reported as being 5 mSv/year in this study).

Several complimentary treatment methods can be used to reduce the uranium industry's contaminant emissions in the environment. Any approach must consider the mining method used and the particular characteristics of the affected aquatic environment.

Table 7.6: Lead-210, polonium-210, and natural uranium concentrations observed around the old uranium mine site near Elliot Lake, in Ontario.

Source	**Lead-210**	**Polonium-210**	**Total U**
Water from Quirke Lake	105 mBq/L	---	13 µg/L
Water from McCarthy Lake	1094 mBq/L	---	3.0 µg/L
Water from the control lake	**20 mBq/L**	**---**	**< 1 µg/L**
Sediment from Quirke Lake	425 mBq/g	---	24 µg/g
Sediment from McCarthy Lake	896 mBq/g	---	45 µg/g
Sediment from the control lake	**519 mBq/g**	**---**	**54 µg/g**
Trout bones from Quirke Lake	186 mBq/g	168 ± 34 mBq/g	4.4 µg/g
Trout bones from Whiskey Lake	180 mBq/g	208 ± 33 mBq/g	1.38 µg/g
Trout bones from the control lake	**< 50 mBq/g**	**20 ± 0 mBq/g**	**< 0.05 µg/g**
Trout muscles from Quirke Lake	< 50 mBq/g	26 ± 4 mBq/g	< 0.05 µg/g
Trout muscles from Whiskey Lake	< 50 mBq/g	< 20 mBq/g	< 0.05 µg/g
Trout muscles from the control lake	**< 50 mBq/g**	**< 20 mBq/g**	**< 0.05 µg/g**

Source: Clulow et al., 1998.

7.5.3 AIR EMISSIONS

A potentially significant impact of the uranium mining industry for workers arises from exposure to air emissions, i.e. exposure to gamma radiation, radon-222 gas and suspended particles in the air (dust) (IAEA (1), 2009). Mine

waste contains a large part of the radioactive material found in the original ore and is one of the sources for gamma radiation and radon. When uranium is extracted from ore (mainly ^{238}U and ^{235}U), 70 to 85 % of the original radioactivity is concentrated in mine waste, which contains all the radium produced from the decay of natural uranium (WNA, 2011). Radium decays to radon, and significant amounts of radon may be produced, particularly for high-grade uranium deposits (WNA, 2011). Natural uranium and its daughter products(such as ^{238}U, ^{235}U, ^{234}U, ^{230}Th, ^{226}Ra, ^{210}Pb and ^{210}Po), as well as thorium-232 (^{232}Th) and its daughter products may occur in suspended ore dust generated by ore crushing and wind erosion of uncovered mine waste.

The receptors most likely to be exposed to chemical or radioactive contaminants on the short, medium and long term are local communities and people working on the mine site, and to a lesser degree, animals and plants in the surrounding areas.

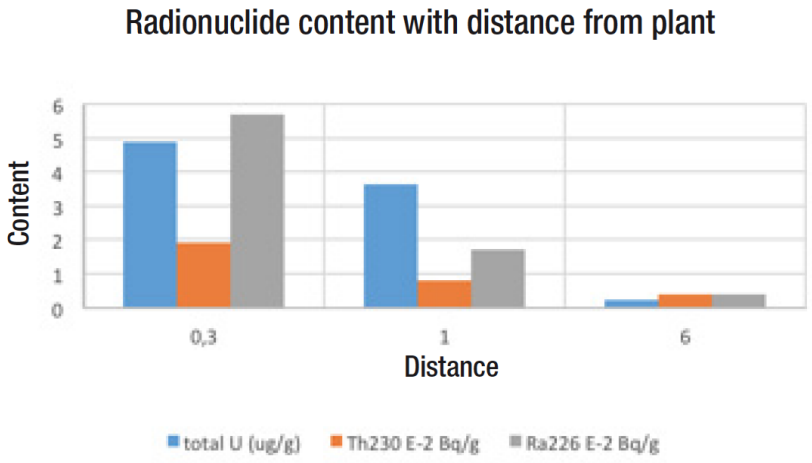
7.5.3.1 SHORT- AND MEDIUM-TERM IMPACTS RELATED TO THE MINING STAGE

Zones of waste rock and tailings accumulation may be a significant source of deleterious impacts, depending on their design. For instance, spreading the tailings over a large area promotes higher rates of radon emission and ionizing radiation. If the waste rock piles are not covered by a layer of water, for instance, or kept wet, surface materials may dry up and generate radioactive dust which, if exposed to wind, could be transported by air and dispersed in the environment, increasing the risk of interaction with surface waters (IAEA, 2005). After drilling and excavation activities, an increase in the radon emission rate may also be observed in the air inside underground facilities, and in exhaust air. An open pit mine promotes natural ventilation. For a particular mine site, the type of soil, the technology used and uranium concentrations in the ore may lead to varying radon concentrations being emitted into the atmosphere.

The CNSC's comprehensive study for the Cluff Lake mine decommissioning project reports that ambient radon levels at the Cluff Lake mine site (shut down in 2002) typically ranged between 15 and 160 Bq/m^3 during operations (CNSC, 2003). For comparison purposes, the maximum activity concentration authorized for radon-222 according to the Canadian Nuclear Safety Commission is 60 Bq/m^3, and Health Canada recommends that average annual activity concentrations in the occupied rooms of Canadian dwellings should not exceed 200 Bq/m^3.

Given the cumulative ionizing radiation from radionuclides in soil and suspended in the atmosphere, an increase in gamma radiation, mainly arising from stockpiles, could also be observed. For instance, in Portugal, radiation rates measured on the surface of uncovered mine waste located on old mine sites reached 24 µSv/h in some places (background radiation in the area ranged from 0.2 to 0.7 µSv/h) (Carvalho et al., 2005). In France, the dose rate reported for the same type of mine waste was about 10 µSv/h (LEDEN et EDP Sciences (2)). In the latter case, it should be noted that in order to receive a dose equivalent to the annual dose received from natural radioactivity, exposure to this mine waste for more than ten consecutive days would be required.

Tailings and waste rock piles and excavation activities may be sources of fine particles. With respect to radioactive dust, preliminary results presented in a report on uranium mining developments in Saskatchewan suggest that contaminant fallout from the atmosphere could occur within a 3-km radius from the source of emission, although many other studies suggest a much larger radius (SERM (1), 1997). To measure radionuclide and heavy metal fallout from suspended dust at its Cluff Lake facilities, Areva put a monitoring program in place to conduct chemical and radiological analyses on lichens. The analytical results have shown that the concentrations have a tendency to decrease with distance from the processing plant. The data compiled up to 1999 is presented in Figure 7.2, and demonstrates that stations closer to the plant had higher concentrations than the next station away. Uranium, thorium-230 and radium-226 concentrations at a six-kilometre distance were much lower than concentrations measured around the plant. The ratios between measured concentrations and baseline soils were 29.4 for uranium, 4.7 for thorium-230 and 7.4 for radium-226. Levels of lead-210, polonium-210 and other metals around the plant were on the same order of magnitude as baseline levels, or up to two times higher.



Data source: CNSC, 2003.

Figure 7.2: Total U, ^{230}Th and ^{226}Ra concentrations in lichens as a function of distance (in kms) from the Cluff Lake processing plant.

The Cluff Lake decommissioning report indicates that total suspended particles readings for 2002 (when mining operations ceased) returned values of 10 to 14 µg/m^3, which is well below allowable averages (Table 7.7). However, uranium concentrations in these suspended dust particles were slightly higher (0.024 µg/m^3, the highest value, was measured at the plant station) than regional baseline levels (0.001 µg/m^3 to 0.005 µg/m^3).

Table 7.7: Suspended particle concentrations on the Cluff Lake mine site and baseline levels.

	Maximum allowable concentrations
Ministry of the Environment of Ontario	120 µg/m^3 (for 24 hours)
Environment Canada	60 µg/m^3
Saskatchewan guidelines for air quality	70 µg/m^3
	Concentrations observed
Cluff Lake mine (2002)	10 to 14 µg/m^3

Source: CNSC, 2003.

The report on uranium mining developments in Saskatchewan indicates that the daughter products of radon (including polonium-210) could have a considerable cumulative impact in the medium- to long-term if high concentrations are measured within a 5 to 10-km radius from mine. Regional populations who source an important part of their food in the area are those who could be affected (SERM (1), 1997).

7.5.3.2 Long-term impacts

An increase of dust and radon levels in the atmosphere pose a health risk; among other things, it heightens the risk of developing a form of lung cancer. With respect to radon inhalation, it has been demonstrated that long-term impacts will affect workers if the protective measures are inadequate. In fact, many cohort studies done over the years on the health impact of radon on miners concluded that long-term exposure to radon concentrations above natural levels increased the risk of developing a form of lung cancer (CNSC (4), 2012). However, activity

concentrations for radon observed in the mining areas of northern Saskatchewan currently sit close to natural activity concentrations (1 Bq/m^3 to 20 Bq/m^3), which greatly reduces risks (CNSC (5), 2012). On uranium exploration, mining and processing sites, radon activity concentrations typically range between 1 Bq/m^3 and 50 Bq/m^3, except in areas where radon production rates were particularly high (e.g. close to stockpiles). Around waste rock piles, levels can reach 1000 Bq/m^3.

In ore dust, some deposits have, in addition to uranium, high concentrations of other toxic metals; for instance, the Midwest project site in Saskatchewan contains arsenic and nickel. Being chemically toxic (they are known carcinogens), arsenic and nickel can form toxic dust. The report on uranium mining developments in Saskatchewan indicates that there is a synergistic effect between exposure to ionizing radiation and exposure to arsenic (SERM (1), 1997). Consequently, mine sites with deposits that contain, in addition to uranium, significant concentrations of toxic heavy metals have a higher chemical and radiological risk if ore dust is inhaled or ingested, especially as the health of workers is concerned.

8 ENVIRONMENTAL PROTECTION MEASURES IN THE URANIUM SECTOR

Summary

- In the past, notable environmental and occupational health impacts related to the mining industry were observed. Procedures applied around the world were very different from today's standards, and the impacts of radioactive substances on health and the environment were poorly understood.
- Nowadays, the Canadian government and mine developers advocate prevention, planning and protection measures for the regulation of air emissions, effluents, waste rock and tailings and for the exposed populations.
- Environmental readings are taken (radionuclides, radon, radioactive dust and gamma radiation in air, water and soil) to characterize the biophysical environment of mine sites. Environmental monitoring can prevent contamination or reduce its impacts in a timelier manner.
- The current Canadian dose limit for exposure to ionizing radiation, which excludes radioactivity from natural or medical sources, is set to 1 mSv/year for the general public and to 100 mSv over 5 years, with a maximum of 50 mSv over one year for workers in the uranium sector.
- Current uranium mines have radiation protection programs and apply regulatory limits: mine developers must prove, before work begins, that their operations will not pose a threat to the security of humans or to the environment.
- 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 dose permitted for the general public (1 mSv/year).

8.1 INTRODUCTION

Uranium occurs naturally in the environment, but uranium exploration and mining activities pose potential risks to the biophysical environment. Standards and environmental protection measures have been developed in Canada and in many other countries, as described below. The goal of this chapter is to propose tools that will enable the implementation of preventive and safety measures in the uranium sector, from exploration to the last stages of mining. The first section provides general information on environmental management programs implemented at certain mining projects, and gives examples of application guides in Canada and abroad. The second section presents the mitigation measures used for air emissions, effluents, waste rock and tailings. The third section introduces the other chemicals that are emitted or used on mine sites, and the fourth section describes the radiological doses likely to be received by workers, populations and ecosystems close to industrial mining facilities

8.2 ENVIRONMENTAL MANAGEMENT PROGRAMS IN CANADA AND ABROAD

Extractive operations, such as uranium mining, have an impact on the environment and on local communities, and the implementation of strict environmental management measures reduces this impact. These measures are tied to concepts of "sustainable development" (Falck and Coetzee, 2012) or "balanced development" (Waggitt, 2011), the latter term being more appropriate in some cases given that, although mining has an impact on the environment, it occurs over a specific period, and mine site rehabilitation, once mining operations have ceased means the land can eventually be reused (such is the case for the South Alligator Valley site in Australia, Waggit, 2004). When rehabilitation work is complete and site analyses indicate that radionuclide concentrations are below maximum allowable concentrations set by authorities, the site may again be considered “natural”, or be reused for various applications. For instance, some old mine site properties in France and in Germany were transformed into solar farms (examples are provided at the conclusion of this chapter).

As for other metal mines, several examples of long-term ecological impact caused by the lack of adequate control measures and treatment were reported in the past. In Germany the mining company Wismut produced more than 230,000 tonnes of uranium between 1946 and 1990, making East Germany the fourth uranium producer in the world, but left over more than 100 km^2 of the mining properties in a heavily damaged state, due to the lack of appropriate environmental management programs; as a Crown Corporation their priorities focused exclusively on uranium production during the Cold War. The German federal government after acquiring the company in 1991 undertook decommissioning and rehabilitation work and the end of rehabilitation is planned for 2015, the investment of about 8.3 billion dollars (Paul, 2008).

Today, in order to avoid this type of damage and the associated costs mining companies along with several governments, including those of Québec and Canada, advocate an approach based on prevention, and planning of mine site rehabilitation activities. Increasingly, site rehabilitation is often undertaken during the mining operations, in order to reduce the environmental footprint. Progressive restoration allows for the protection against long-term contamination effects, and also allows the adaptation of new methods developed by scientific study. Several international agencies and mining companies support sustainable development, like the International Atomic Energy Agency (IAEA) and member companies of the International Council on Mining and Metals (ICMM). In Canada, the Prospectors and Developers Association of Canada (PDAC), which brings together industries in the mining sector, has developed a framework for best practices in mineral exploration and promotes responsible exploration (e3plus), in terms of social responsibility, environmental management and the health and safety of workers and local communities.

8.2.1 ISO 14001

Cameco, and Areva, two mining companies specialized in uranium exploration and mining, have implemented environmental management systems and obtained ISO 14001 certification for many of their mining projects. ISO certification is granted by the International Organization of Standardization and is the reference for implementing environmental management systems in companies. More precisely, the ISO 14001 standard provides a framework for the management and prevention of environmental impacts related to a company's activities, based on continuous improvement (ISO, 2013; SMA (1), 2013). The company must periodically undergo an independent audit and renew its certification every three years. It is worth mentioning that the ISO 14001 standard does not set out performance requirements; the company must strive to reach its own goals. In Saskatchewan, most active uranium mines are certified to ISO 14001 (McClean Lake, Key Lake, McArthur River, Cluff Lake and Rabbit Lake) (Wollenberg 2012). Most mining projects in Australia (the third uranium-producing country, behind Kazakhstan and Canada) are also certified to ISO 14001. This is the case for the Ranger mine, which is audited every six months by an independent firm (WNA, 2011). Mining operations in Australia are subject to government regulations, which define a code of practice (*Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing*). Like the CNSC in Canada, this code provides standards for concentrations of element of potential concern, radiation protection and environmental assessment (ARPNSA, 2005).

8.2.2 GOVERNMENT REGULATIONS

In Canada, regulations pertaining to radioactive element concentrations that pose a potential risk, and to environmental assessments are set out by the CNSC, which oversees uranium mining, and by the provincial government where mining operations are taking place (WNA, 2012; CNSC (3), 2012). The CNSC also oversees radiation protection measures, i.e. the set of procedures that aim to ensure the protection of workers and the general public against the potentially harmful effects of ionizing radiation.

In conjunction with government authorities, mining companies in the uranium sector must establish protection measures and long-term environmental monitoring. For instance, to monitor and restore 210 old uranium mine sites, the French ministry of Ecology and Sustainable Development (*ministère français de l'Écologie et du Développement durable*) and Areva are responsible for the implementation of an action plan designed to restore old mine sites. Areva, who are responsible for about half of the old mine sites, are committed to environmental reporting (rehabilitation and monitoring) for all 210 sites (Areva (1), 2013). One of the strategies in the action plan developed by the French government consists of making available all the information pertaining to the old sites' location, history and current state. The four main tenants of the action plan are (MEDDE, 2009):

1. Managing the old mine sites;
2. Furthering knowledge on the health and environmental impacts related to old uranium mines and monitoring;
3. Managing waste rocks: better understanding their applications and reducing the impact, if necessary;
4. Disseminating knowledge and consulting with people.

8.2.3 EXAMPLES OF PROTECTION AND ENVIRONMENTAL CODES

Environmental impacts related to mining are mainly attributed to the significant volume of rock and soil that must be excavated and to their accumulation on the surface, as well as to the presence of mine tailings and effluents. The protective measures applied to mining projects where an environmental management system is in place can be summarized as follows (GA, 2008; SERM (2), 1997):

- Burial of mine waste in an open pit or underground mines;
- Long-term confinement and monitoring measures for solid waste with a potential for mine drainage that exceeds the composition provided for in the regulations;
- Ongoing site rehabilitation during mining operations, including the treatment of effluents;
- Radionuclide and other heavy metal concentration analyses in fish and macrophytes (aquatic plants visible to the naked eye) that inhabit nearby waters, as well as stream sediments.

Government authorities establish regulations pertaining to protective measures and mitigation measures. These authorities require detailed management plans for the control of radioactive mine waste and ionizing radiation.

A guide for developing environmental protection procedures at uranium mines and mills was published by the CNSC (CNSC, 2006). According to this guide, the environmental management systems implemented by proponents must meet regulatory requirements established by the CNSC. These systems must contain complete data pertaining to radioactive waste that will be produced, including:

- the nature of waste;
- the composition and origin of waste;
- volumes anticipated;
- types of treatment;
- their management and disposal;
- the risks associated with the supply of new water to the site (for example: precipitations, percolation, infiltration, runoff, flooding) and measures taken to divert or control it.

Environmental management systems must also include health and safety programs to protect people working on site, and emergency environmental measures to prevent or mitigate the effects of accidental radionuclide discharge (CNSC, 2006). In fact, accidental leaks or spills from stockpiles or staging ponds may occur despite protective measures being implemented. In such situations, appropriate response measures will limit the volume of spilled products that could reach surface waters or groundwater aquifers or avoid this contamination entirely.

The CNSC's radiation protection regulations stipulate that the permit holder must implement a radiation protection program; as part of this program, he must make sure that the level of exposure to radon daughter products, as well as the doses received by workers, are maintained at the lowest achievable level, given economic and social factors (CNSC, 2006). Such a program implies:

- in depth knowledge of the work methods by the management team;
- skilled training of personnel;
- controlling exposure of personnel and the general public to radiation;

- planning for unusual situations.

For its part, the Australian government's code of practice includes the following items, which coincide with the CNSC's radioactive waste management plan (ARPNSA, 2005):

- Assessing and describing the waste that will be produced;
- Describing the environment in which effluents will be discharged after treatment and where mine waste will be stored. This includes an assessment of the environment's radioactive background noise prior to the start of mining operations. For radioactivity, background noise refers to radiation from unaltered natural sources, such as cosmic rays and radiation from the soil and surrounding materials, before the start of industrial activities;
- Developing a waste management system (handling, disposal, treatment and elimination of radioactive waste);
- Estimating the radionuclide concentrations and radiation doses received by workers;
- Committing to compliance to protection codes;
- Developing an environmental monitoring program for radionuclide concentrations;
- Developing response plans (in case of accidental spills, uncontrolled dispersal of mine waste with a radioactive component, etc.);
- Developing a decommissioning plan for operations and facilities related to waste management and a site rehabilitation plan;
- Developing a system for regular assessments.

Its ionizing radiation management plan comprises the following items:

- Demonstrating a close collaboration between radiation protection professionals;
- Elaboration of a surveillance program for radiation exposure and evaluation of the doses received by employees;
- Using appropriate equipment and facilities, trained employees and mining procedures;
- Implementing introductory courses and training;
- Developing response plans in the event of accidents, incidents and emergencies related to exposure to ionizing radiation, and developing a system to assess the effectiveness and accuracy of procedures provided for in the plans.

Nowadays, protective measures and environmental management measures are typically implemented by uranium-producing countries like Canada.

8.3 PREVENTIVE AND MITIGATION MEASURES

The sources of environmental impacts associated with excavation and the surface accumulation of waste rock and tailings include the risks of exposure to gamma radiation and inhalation of air emissions, as well as the risk of tailings being dispersed in the environment. The preventive measures and mitigation measures implemented in Canadian mining projects are presented n the following sections.

8.3.1 AIR QUALITY

8.3.1.1 SOURCE AND COMPOSITION OF AIR EMISSIONS

As described above, air emissions comprise:

- radon released in the atmosphere from ore and mine waste;
- gamma radiation from radionuclides in ore, for which the quantity depends on the original uranium grade (if the uranium concentrations are high, the concentrations for uranium daughter elements will also be high);
- uranium dust generated by ore blasting and crushing operations, or by wind erosion of fine waste.

8.3.1.2 PREVENTION: INDIRECT CONTACT WITH AIR EMISSIONS

According to the federal government's recommendations for Saskatchewan mines (SERM (2), 1997):

- Mining methods must be designed as to avoid the direct exposure of miners to ore and its dust;
- the safety of employees relies on the confinement of ore during milling, sludge transport, treatment and the surface disposal of waste rock and tailings.

To this end, the proponents of high-grade uranium mines, such as the Cigar Lake and McArthur River mines, have implemented mining techniques that ensure minimum contact between workers and ore: remote-controlled mining equipment is used and ore is confined in underground shielded conduits throughout the different extraction processes, such as milling. The use of shielded conduits reduces the emission of atmospheric radiation and dust. These emissions are also controlled inside the yellowcake production plants of Saskatchewan, where confinement measures, dust collectors and wetting agents (which limit dust dispersal) are used. All potentially radioactive material is confined and handled in rooms with a negative air pressure, such that air transfers occur from outside inwards, which prevents environmental dispersal (GA, 2008). It should be added that yellowcake, which is the final product, is very weakly radioactive as it only contains uranium, the radionuclide daughters having been removed during ore processing.

Another commonly used confinement method in Canada consists of covering up significant emission sources, such as soil or water, or isolating them inside concrete spaces, as dense material absorbs gamma radiation.

8.3.1.3 PREVENTION: MINE SITE VENTILATION

Negative health impacts on workers related to the presence of radon and dust may also occur if underground ventilation is inadequate.

For workers, open pit mines and *in situ* leaching operations reduce radionuclide exposure, as natural ventilation alone is enough to reduce radon concentrations to acceptable levels (GA, 2008).

In underground mines, particularly in high-grade uranium mines, exposure to radon must be controlled. Radon can be evacuated by adequate ventilation. For instance, the activity concentrations of radon-222 were measured at

several points at the Midwest underground mine in Saskatchewan, in the early 1990s (CNSC (6), 2012). Readings taken at the mine's ventilation shafts showed that activity concentrations were close to 27,000 Bq/m^3. These were rapidly diluted by natural ventilation, and activity concentrations of about 32 Bq/m^3 were obtained for the rest of the site, which is comparable to those measured off site (22 Bq/m^3). For comparison purposes, the maximum activity concentration for radon-222 above background noise authorized by the CNSC is 60 Bq/m^3. The exposure limits recommended by Health Canada for exposure to radon in Canadian dwellings is 200 Bq/m^3, whereas the World Health Organization (WHO) recommends a maximum activity concentration of 400 Bq/m^3. The significant difference between concentrations obtained near ventilation shafts and elsewhere on the site indicates that high radon concentrations near the mine's ventilation shafts are successfully dissipated in ambient air, such that it is can be stipulated that exposure of workers and the general public to radiation is reduced to a minimum.

In Canada, CNSC regulations impose the installation of backup ventilation systems in case of failure of the main ventilation system. As such, underground mines are equipped with powerful ventilation units that can reach the same ventilation levels as in open pit mines and when combined with strict industrial hygiene procedures (cleaning of equipment and work uniforms) also protect workers from exposure to dust. The ventilation system in place at the underground Olympic Dam mine in Australia (low-grade uranium mine) permits an average exposure of less than 1 mSv/year for workers, whereas the doses received in Saskatchewan mines (high-grade uranium) are less than 2 mSv/year (GA, 2008). For comparison purposes, the annual exposure limit for employees of nuclear power plants in the U.S. is 50 mSv/year, and the average dose received by the general public and by flight crews from exposure to ionizing radiation is about 2.4 and 5 mSv/year, respectively (Sievert, 2013).

Below are four examples of mitigation measures applied to uranium mine sites in Canada to reduce dust fallout and air emissions (CNSC (6), 2012). It should be noted that some mitigation measures apply to all mining facilities, and not only to uranium mines:

- The use of controlled blasting methods and monitoring to ensure slope stability in open pits;
- The use of measures to limit dust production;
- The use of ventilation systems designed to replace exhaust air, which allows for the regulation of concentrations of radioactive dust with long half-lives and radon in air;
- The use of wet scrubbers (which control dust) in various chimneys receiving regular maintenance.

Ongoing monitoring of underground air quality is also part of the mitigation measures favoured by mine proponents (Strateco (2), 2009).

These control measures apply to all mining operations.

8.3.1.4 MONITORING AND ANTICIPATED EVOLUTION OF THE BIOPHYSICAL ENVIRONMENT

Measuring the radioactive background noise and the activities of radon and suspended particles in the atmosphere on a regular basis from the start of operations makes it possible to track their evolution over the course of mining operations. During mining, readings are taken at the surface of tailing facilities, at tunnel entry points and at various stations on and off site, on a regular basis.

By monitoring various atmospheric constituents on mine sites the concentration as a function of distance from the course and the cumulative impacts of varying concentrations of daughter products of radon, such as polonium-210, can be evaluated. Radioactive dust can settle on surrounding vegetation by means of gravity or precipitation, and if concentrations are high, impacts could be felt by regional communities which source an important part of their food in the area.

Radionuclide fallout from dust in suspension was monitored on lichens around the Cluff Lake mine in Saskatchewan (CNSC, 2003). These analyses made it possible to determine the activity of various radionuclides (uranium, thorium-230, radium-226) as a function of distance (see section 7.5.3.1).

8.3.1.5 AIR CONCENTRATIONS FOR VARIOUS RADIONUCLIDES

Maximum allowable concentrations for radionuclides in the air, calculated based on the maximum allowable dose (in addition to the dose received from natural and medical sources) for the general public (1 mSv/year), are presented in Table 8.1. These calculations were performed assuming continuous exposure for one year.

In comparison, activity concentrations observed at the Cluff Lake mine site during mining operations are provided below. For radon, typical activity concentrations between 15 and 160 Bq/m^3 were obtained between 1994 and 2002, with a median of less than 40 Bq/m^3 at most of the stations sampled (CNSC, 2003). These values are on the same order of magnitude as regional baseline values measured in the eastern part of the province, which is also rich in uranium resources.

A uranium concentration of 0.024 $\mu g/m^3$ represents the highest concentration obtained in 2002 for the entire mine site. This reading was obtained from the station located at the ore processing plant, and is greater than values obtained at other stations at surface at various locations on the site. It is relatively higher than regional baseline levels of 0.001 $\mu g/m^3$ to 0.005 $\mu g/m^3$, but is well below the maximum allowable concentration (0.56 $\mu g/m^3$ based on the maximum allowable dose of 1 mSv/year (Strateco, 2009)). Thorium-230, radium-226, lead-210 and polonium-210 concentrations at this location were also the highest obtained for the entire mine site.

Average annual uranium concentrations in the air were measured around the uranium ore processing plant in Port Hope, Ontario. During a follow-up in 1997, concentrations from < 0.00006 $\mu g/m^3$ to 0.076 $\mu g/m^3$ were measured within 2 km radius of the processing plant. The lower concentrations observed when the operations ceased for the summer indicate that the presence of uranium in the air is related to processing operations, and not to a cumulative effect involving the re-suspension in the air of uranium-bearing soil particles (CCME, 2007).

An association of federal ministries (including the CNSC and Natural Resources Canada) examined the issue of ambient air quality close to uranium mine sites and prepared a detailed report based on monitoring data collected on the Midwest and McClean Lake mine sites in Saskatchewan (CNSC (6), 2012). According to this report, all the total suspended particle (TSP) readings obtained from the Midwest and McClean Lake mine sites were less than Saskatchewan's annual standard for ambient air quality (*Saskatchewan Ambient Air Quality Standard*), which is 70 $\mu g/m^3$. Measured metal and radionuclide concentrations were representative of background concentrations.

Table 8.1: Baseline values for atmospheric radioactivity and values observed.

Radionuclide	Allowable activity concentrations in (mBq/m^3)[a] (in addition to background concentrations)	Highest activity concentrations [g] at Cluff Lake in 2002 (mBq/m^3)[a]	Background atmospheric concentrations measured at various North American locations
Natural uranium	0.56 $\mu g/m^3$ (14 mBq/m^3)	0.024 $\mu g/m^3$	0.001-0.005 $\mu g/m^3$ [e]
			0.000025-0.0001 $\mu g/m^3$ [e]
Thorium-230	8.5	~ 0.1	0.0006[c]
Radium-226	13	~ 0.1	0.0006[c]
Radon-222	60 Bq/m^3	40 Bq/m^3	5-15 Bq/m^3 [f]
Lead-210	21	2.3	0.1-1 [c]
Polonium-210	28	0.6	0.010-0.040 [c]
TSP[b]	70 $\mu g/m^3$	10 to 14 $\mu g/m^3$	---

[a] In $\mu g/m^3$ for natural uranium and TSPs; [b] TSP: Total suspended particles; [c] Measured in the U.S. (UNSCEAR, 2000); [d] Typical concentration in Canada (CCME 2007); [e] Regional baseline value for Cluff Lake (CNSC, 2003); [f] WHO, 2009; [g] except for TSPs, which are medians.

Data sources: UNSCEAR, 2000; CCME, 2007; CNSC, 2003; WHO, 2009.

The report also presents radon activity concentrations measured between 1988 and 1990 at various places on the Midwest mine site, including ventilation shafts. At the ventilation shafts, measured activity concentrations were between 7,570 and 26,932 Bq/m^3. These high concentrations are not surprising given that ventilation shafts are where radon-enriched air from extraction operations is expelled at surface. Activity concentrations measured at other sampling stations on the site averaged 32 Bq/m^3 and were similar to those measured off site (22 Bq/m^3), demonstrating that air-borne emissions are diluted rapidly by natural ventilation.

8.3.2 WASTEWATER TREATMENT AND PHYSICOCHEMICAL CHARACTERISTICS

Contaminated natural waters are the main pathway for the dissemination of radionuclides in the environment. All the water used on site is therefore recovered, sampled and treated as required, such that effluents meet applicable standards. Let us note that the Metal Mining Effluents Regulations prescribe maximum harmful substance concentration standards in effluents for various metals and solids in suspension, but radium is the only substance presented as a radionuclide (maximum average monthly activity concentration permitted: 0.37 Bq/L) (MJ (1), 2013).

8.3.2.1 SOURCE AND COMPOSITION OF WASTEWATER

Wastewater includes precipitation and water used in mining processes. Wastewater is collected from surface runoff on the mine site or from percolation in the waste rock piles, and is not reused. Effluent treatment on mine sites depends on the presence and nature of the contaminants generated by the methods used for uranium mining

and concentration, on the geological and biological characteristics of soils, and on the characteristics of the affected aquatic environment in need of protection.

Potential contaminants found in effluents include radioelements of the uranium-238 family and various metals, such as nickel and copper, or metalloids such as arsenic, for which the presence and concentration depend on the type of uranium ore found in the uraniferous district. It should be noted that the presence of these metals in effluent is not specific to uranium mines, but concerns all types of mines. Suspended solids and dissolved salts, chemical compounds such as ammonia used in uranium concentration, or metallic complexes formed during neutralization processes, all constitute contaminants that may occur in the effluents (GA, 2008).

8.3.2.2 WASTEWATER TREATMENT

The wastewater treatment procedure for Canadian mines aims to reduce radionuclide, heavy metal and other element concentrations by adding chemical compounds that will bind with contaminants to form solid compounds. These will precipitate making it possible to remove them from the water, through processes such as filtration or sedimentation. For instance, adding barium or lead compounds will precipitate radium and lead, adding lime will precipitate metals such as nickel and copper, and adding flocculants will precipitate suspended solids, whereas the toxicity related to the presence of compounds such as ammonia will be reduced by adjusting the pH. Classic procedures are used in Canada, such as at the Cigar Lake mine processing plant, in Saskatchewan, which is the deposit with the second highest uranium grade (GA, 2008). Treated waters are collected in a second holding basin, and the quality is verified before they are discharged into the environment.

This type of process increases the concentration of dissolved salts in effluents, which constitutes a negative environmental impact, even though it is preferable to the impact caused by the presence of heavy metals. This is a medium-term impact since salt concentrations quickly return to pre-mining values once operations cease (SERM (2), 1997). Adding certain elements could however result in more harmful effects for the environment. For instance, at high concentrations and depending on the compound's solubility, barium could have significant effects on mammals. The intentional or accidental ingestion of soluble barium compounds can lead to acute barium poisoning, which can cause convulsions and even paralysis (CCME, 2013). The behaviour of barium in terrestrial and aquatic ecosystems has not been extensively studied, but we estimate that barium behaves essentially like strontium in soils and plants, and that its mechanism of toxicity is related to its ability to substitute for calcium (IRSN, 2002; CCME, 2013). Most of the toxicity data for barium comes from studies that study its soluble forms, such as barium chloride, yet its most commonly occurring form in the environment is barium sulphate, which is insoluble (CCME, 2013). During effluent treatment, soluble barium chloride is typically used to precipitate radium. Part of the added barium coprecipitates with radium sulphate under sulfuric conditions, as insoluble barium sulphate.

The effectiveness of water treatment processes is reflected by a significant decrease in the percentage of radionuclides measured. Prior to treatment, effluents from the McArthur River mine (Saskatchewan) contained on average 23 Bq/L of radium-226, the maximum allowable activity concentration for discharge into the environment

being 0.37 Bq/L (Metal Mining Effluents Regulations, Government of Canada). However, the average activity concentration after treatment was of 0.063 Bq/L, which is well below the maximum accepted value (GA, 2008).

8.3.2.3 POSSIBLE TYPES OF WASTEWATER TREATMENT

New technologies for the treatment of uranium mine effluents have been documented. Some processes make it possible to reduce the volume of effluents treated by reducing the amount of water used in underground operations and by reusing water.

These new technologies include treatment in artificial wetlands and the use of evaporation tanks (Vandenhove, 2010). Artificial wetlands are ecosystems designed to treat, among other things, mining effluents using biological methods such as phytoextraction. The principle behind phytoextraction is the use of accumulator plants to absorb and concentrate, within their harvestable parts (leaves, roots, etc.), soil contaminants that occur in trace amounts. Contaminants are transferred from contaminated soil to plants, reducing contaminant concentrations in soil when plants are harvested. The plants may then be incinerated and the ashes are kept for certain metallurgical applications, or stored (Hedhli, 2010).

A study carried out over three years in a German mine showed that the wetland treatment effectively removed radium from wastewater (Vandenhove, 2010). On the other hand, evaporation tanks make it possible to reduce the mass and volume of waste by evaporating water, which facilitates transport and treatment. The most commonly used technology is inverse osmosis, a very fine filtration system that allows only water molecules through a membrane but which may only be used when total dissolved salt and metal concentrations are low (GA, 2008). These low concentrations are observed, for instance, in groundwater pumped by wells installed around the site, which are used to hydraulically isolate the mine site from the surrounding environment.

8.3.2.4 QUALITY OF GROUNDWATER AND SURFACE WATER

Effluent treatment brings radionuclide and heavy metal concentrations well below the maximum concentrations set by the authorities for aquatic biota protection. However, trace concentrations remain which leads to the accumulation of contaminants in sediments (Vandenhove, 2010). During mining operations, groundwater and surface water quality is monitored at intervals determined in the environmental monitoring programs developed by the mine proponents, subject to the approval of regulatory bodies (e.g. the Ranger mine). These programs assess the actual environmental risks affecting the environment and to measure radionuclide concentrations in living organisms such as fish and aquatic plants in nearby waters, and sediments. In Québec, results of environmental monitoring carried out by mining companies are disclosed annually by the MDDEFP.

In France, audits of old mine sites are overseen by the company Areva, the operator in part. Monitoring results are also published by the *Institut de radioprotection et de sureté nucléaire* (IRSN). At a site such as La Crouzille, the most important uranium district in France where operations ceased in 1990, streams are monitored on a monthly basis. The average concentrations for samples collected in 2006 in streams and ponds on the site are presented in Table 8.2 (IRSN, 2006). Average concentrations in aquatic plants and sediments from an old mine site (DuCellier,

sampled every two years), as well as baseline concentrations for effluents and drinking water are also presented in Table 8.2.

Table 8.2 : Results of analyses done in 2006 on the old French mine sites of La Crouzille and Du Cellier, and baseline concentrations.

		Radionuclide								
		Radium 226	Uranium Total	Uranium 238	Uranium 234	Thorium 232	Thorium 230	Lead 210	Polonium 210	Global alpha activity
La Crouzille mine site	Average low and average high values in nearby waters (Bq/L)	0.038-0.218	---	0.080-0.357	0.082-0.60	---	---	---	---	0.14-0.93 (0.)[(c)]
Baseline values for water	Maximum acceptable concentration for drinking water in Canada (Bq/L)[(a)]	0.5 0.37[(e)]	20 µg/L (0.02 µg/g)	NA	NA	NA	NA	0.2	NA	---
	Allowable concentration in drinking water according to the WHO (Bq/L)[(b)]	1	NA	10	1	1	1	0.1	0.1	---
Du Cellier mine site	Sediments (Bq/kg sec)	1100	---	7100	7100	110	300	---	---	---
	Aquatic plants (Bq/kg sec)	150	---	650	650	---	6.6	---	---	---
National recommendations for sediment quality, baseline values from the CNSC [(d)]	Minimum concentration with effects (Bq/kg)	900	104 µg/g	---	---	---	---	600	800	---
	Concentration with serious effects (Bq/kg)	21,000	5874 µg/g	---	---	---	---	14,400	12,000	---

[a] Health Canada 2009; [b] Based on an annual dose of 0.1 mSv and a daily water consumption of 2 litres (WHO, 2011); [c] Global alpha activity in areas affected by mining; [d] CNSC (6) 2012; [e] Metal Mining Effluents Regulations, Government of Canada (these regulations prescribe maximum harmful substance concentrations in effluents for various metals, but radium is the only substance presented as a radionuclide).

Data sources: Health Canada, 2009; WHO, 2011; CNSC (6), 2012.

The MDDEFP and the International Atomic Energy Agency recommend that surface water and groundwater on mine sites be sampled and controlled before the start of operations in order to measure background concentrations for various elements, including radionuclides, and that the analytical procedure be implemented over the course of operations. Surface water and groundwater that is in contact with uranium ore will naturally have higher radionuclide concentrations, but mining operations may promote an increase in metal concentrations by increasing the rate of natural processes (redox reactions, ion exchanges and microbial activity). By monitoring the quality of natural waters, a database may also be set up for use by protection services to detect and prevent contamination, or to quickly reduce the impact of such contamination (IAEA, 2009). The Ranger mine in Australia is an example of a mining project where water management programs include the installation of monitoring stations (both at surface and underground) that continually sample natural waters (ERA, 2012).

8.3.2.5 ANTICIPATED EVOLUTION OF THE BIOPHYSICAL ENVIRONMENT

The risks of impacts associated with uranium mining are related to the presence of radionuclides in mining effluents, but also to various processes and mechanical activities pertaining to the capture or discharge of water in the environment. These processes, which disturb the biophysical environment, are not specific to uranium mining but to mining operations in general. In the comprehensive study on the Midwest uranium mine site in Saskatchewan, the mitigation measures that must be implemented to reduce impacts on the aquatic environment are described. Here are some examples (CNSC (6), 2012):

- A fish habitat compensation plant to compensate for the loss of waterbodies. A fish capture and transfer program. The program is based on best practice to minimize consequences at stream crossings and to ensure that fish can cross at certain points;
- Monitoring of water levels and baseline nutriment levels. Increasing the water volumes in lakes, as needed, by adding water obtained through inverse osmosis;
- Water intake are designed to prevent fish from getting stuck and suspended particles from being carried away in diverted waters;
- No construction activities near stream crossings during periods of fish spawning or migration in spring and fall;
- Work in streams only done during periods of low flow, when possible, to reduce erosion to a minimum;
- Erosion and sediment control measures to prevent the discharge of sediments in streams populated by fish;
- Hydrodynamic confinement to prevent the discharge of contaminants into the environment during mining operations.

8.3.2.6 WATER REMEDIATION

When waters are contaminated, the risk for the ecosystem and for humans is high, and remediation is necessary. Aquifer remediation can be done by pumping groundwater to the surface for treatment. This technique is not very efficient since only part of the contaminated system is treated.

Contaminated environments may be decontaminated by a process called *in situ* bioremediation (or biological remediation) which utilizes biological processes occurring on site, thereby reducing the anthropogenic pressure on the environment. The biological systems used take advantage of the activity of living organisms such as plants or micro-organisms (GA, 2008). Rhizofiltration, for instance, is the accumulation of water contaminants in plants by absorption through the roots. The contaminants are transferred from the water to the roots, which are subsequently harvested and incinerated. The ashes are reused or stored (Hedhli, 2010). A pilot study was carried out at an old uranium enrichment plant (Ashtabula, in the United States) where contaminated waters had uranium concentrations between 21 and 874 µg/L. The study showed that sunflower roots could reduce uranium concentration (VI) to concentrations close to or below regulatory concentrations (20 µg/L, U.S. Environmental Protection Agency) within 24 hours (Dushenkov et al., 1997).

Other bioremediation technologies were tested in the laboratory and in the field with high success rates (U.S. NRC, 2008). For instance, studies have shown that uranium can be immobilized *in situ* by indigenous micro-organisms in the presence of simple organic molecules, such as acetates (diluted vinegar) or ethanol. The micro-organisms occurring in the natural environment enable the precipitation of uraninite (mainly UO_2) by reducing uranium (VI) to uranium (IV), leading to lower dissolved uranium concentrations in groundwater. Uranium therefore remains in the environment, but in a form that cannot be bioassimilated by living organisms. This remediation technique generates less mine waste than pumping and subsequent surface treatment because radionuclides are immobilized *in situ*. This also reduces the exposure of workers to mine waste. Given the low cost of the organic molecules used, this technique is also much more economical compared to pumping and surface treatment.

It should however be noted that the long-term immobilization of uranium (IV) depends on many factors and that uraninite may again be oxidized in the presence of oxidizing agents (dissolved oxygen, nitrates, substances containing oxidized iron or manganese atoms). The presence of minerals such as iron sulphides (FeS_2), precipitates when uranium is bioreduced, can help maintain uranium in its reduced form by slowing down the oxidation process.

Reactive, permeable barriers can also be set up *in situ* within aquifers through which groundwater passes. The depollution techniques used can be chemical, biological or physical: water from the aquifer passes through a barrier containing the active treatment agent (iron, activated carbon, bacteria, compost, chemical compounds or clay), which retains the radionuclides by various chemical or biological means of transformation, sorption, reduction, or precipitation (Vandenhove, 2010).

For water remediation, the potential use of a substance called hydrotalcite was assessed at the Beverley mining project (Australia, *in situ* leaching). Layers of hydrotalcite, characterized by the presence ofwater molecules and anions, allow for electrostatic exchanges. Field experience has shown that after adding two compounds, MgO and $NaAlO_2$ (magnesium oxide and sodium aluminate), hydrotalcite forms and can retain a range of contaminants, such as uranium and other rare earth elements (Douglas et al., 2012). Adding sodium promotes a neutral pH (the pH is about 2 during operations) by forming sodium sulphate ($NaSO_4$), a salt that naturally occurs at high concentrations in the environment.

8.3.3 Acid-generating, radioactive, high-risk waste rock and tailings

8.3.3.1 Source and chemical composition of mine waste

The environmental impacts related to the presence of waste rock and tailings depend on the chemical composition of waste, the volume of excavated rocks and the method used for surface disposal. As a reminder, waste from extraction, called "waste rock" does not contain sufficient metal concentrations to be considered ore (CNSC (1), 2012). Waste rock is excavated to access the ore and its potential for acid generation is typically low. Mine tailings are the material left over after uranium has been extracted from the ore using mechanical and chemical methods of treatment. Tailings may contain various substances such as radionuclides and metals. According to various studies, they possess 70 % to 85 % of the original radioactivity (MEDDE, 2009).

8.3.3.2 Mine waste management

Waste rock and tailings are not usually stored at the surface without some form of protection against precipitation and oxygen in the atmosphere. They are placed in piles equipped with means of confinement. In a joint federal-provincial report on uranium mines in Saskatchewan, one of the prevention options consists of using mine waste as infill material for abandoned open pits, re-engineered for this purpose (SERM (2), 1997). This mode of disposal is used in Australian uranium mines (Ranger and Jabiluka). This option becomes especially relevant when the waste rock possesses relatively high iron sulphide concentrations, which may generate sulfuric acid when exposed to oxygen in the atmosphere or precipitation; this process is termed acid mine drainage (AMD). Radionuclides and other heavy metals are soluble in acid and can therefore be transported in the environment. Consequently, the best way to reduce AMD consists in limiting the exposure of waste rock to oxygen, which can be done by placing them in underground excavations or below a layer of material with low permeability.

In Canada, waste stored on the surface occasionally contains minerals such gypsum (calcium sulphate) and jarosite (hydrated iron sulphate). When uranium ore is treated chemically, certain processes lead to the coprecipitation of gypsum and jarosite minerals and radium contained in the ore, and in some cases, activity concentrations of 200 to 3000 Bq per gram of sludge, may be observed if radium concentrations in soil are high. In comparison, average activity concentrations of 100 to 200 Bq/g were observed in French mine waste (MEDDE, 2009). However, gypsum and jarosite readily solubilize during percolation and as such, radium rapidly goes into solution in stockpiles, which facilitates its potential dispersal in the environment. To reduce these risks, mitigation measures are applied: waste rock and tailings piles are paired with collection basins fitted with protective membranes, which collect all percolation and runoff liquids (rainwater, pore water in waste, etc.). These liquids are then sent to the treatment plant.

A layer of waste rock or clay that can withstand erosion can be put in place to form a low-permeability shield between waste and the atmosphere. Waste with a potential for AMD is submerged beneath a layer of stagnant water which reduces oxygen input, the diffusion coefficient of oxygen in water being 100,000 times less than in air. However, the water layer must be permanent to ensure long-term protection. Installing protective layers also reduces external radiation, which results in a decrease of radon concentrations and gamma radiation (WNA, 2012).

The residual radioactivity measured on mine sites varies from one site to the next and is influenced by factors such as the chemical composition of the soil. In some cases, the radioactivity measured may be less at a mine site than in areas that are naturally radioactive due to geological factors, or parameters such as altitude. In comparison, the dose rates measured at various places around the world and the dose rates received by living organisms are presented in Table 8.3.

Table 8.3: Example dose rates.

Dose rate	
Location/context	**Rate measured (µSv/hour)**
Cluff Lake mine site: natural baseline levels of gamma radiation, in areas not affected by mining operations (1999)	0.01 to 0.5[a]
Global background noise	0.09[b]
Granitic areas removed from the influence of mining	0.15[c]
Cluff Lake mine site: highest levels of gamma radiation, observed in the waste management area, close to the processing plant and waste disposal areas (1999)	≥ 5 [a]
Natural dose at the geographical poles, at an altitude of 12,500 m	7.5 [d]
Rate measured 1 m away from a patient after being administered 0.74 GBq ^{99m}Tc	10 [e]
Natural dose at the geographical poles, at an altitude of 18,000 m	20 [d]
Beach sand from the seaside resort of Guarapari (Brazil)	20 [h]
Threshold above which it becomes necessary to protect the environment for terrestrial animals	42 [f]
Dose measured in April 2011 at 1.5 km away from the Fukushima Daiichi nuclear power plant	112 [g]
Threshold above which it becomes necessary to protect the environment for aquatic animals and terrestrial plants	400 [f]

[a] CNSC, 2003; [b] IRSN, 2011; [c] IRSN, 2009; [d] ref; [e] UNSCEAR, 2000; [f] DOE, 2002; [g] Nuclear Regulatory Authority, Japan, 2011; [h] ULB, 2009.

8.3.3.3 MITIGATION MEASURES THAT AIM TO PREVENT CONTAMINATION FROM MINE WASTE

Mining companies carry out field analyses before the start of operations in order to characterize the site's biophysical environment, including the chemical composition of soils. These analyses allow the selection of appropriate uranium mining and milling techniques. Like the characterization of hydrological sites, the characterization of minerals, rocks and soil types allows for the determination of background radionuclide concentrations on the mine site. Monitoring makes it possible to build a database which will be used to assess and prevent the risks to the environment (ERA, 2012). Federal and provincial regulations for uranium mines in Saskatchewan indicate that for all mining properties in northern Saskatchewan, waste must be monitored on an ongoing basis, from the start of operation to several years after they end. The effectiveness of waste burial

methods can only be confirmed several decades after burial, when environmental analyses demonstrate that waste has remained contained and that radionuclide dispersal is very low. Saskatchewan and federal regulations impose ongoing control of decommissioned mine sites, including the implementation of new waste disposal measures in the event of acid mine drainage.

Examples of monitoring and mitigation measures are presented below as reported in a comprehensive study for Saskatchewan's Midwest mine site (CNSC (6), 2012):

- Sampling of waste rock generated by the re-engineering of pits;
- Installing a dike around the ore stockpile to collect runoff water; the dike is fitted with a waterproof membrane;
- Hydrodynamic confinement to prevent the discharge of contaminants into the environment during mining operations;
- Installing dewatering wells to stop groundwater from coming into contact with interstitial water in waste rock;
- Adding reactive agents to waste rock to reduce the concentrations of resistant contaminants;
- Ongoing controls and sampling such that concentrations of elements of interest remain as close as possible to their natural concentrations.

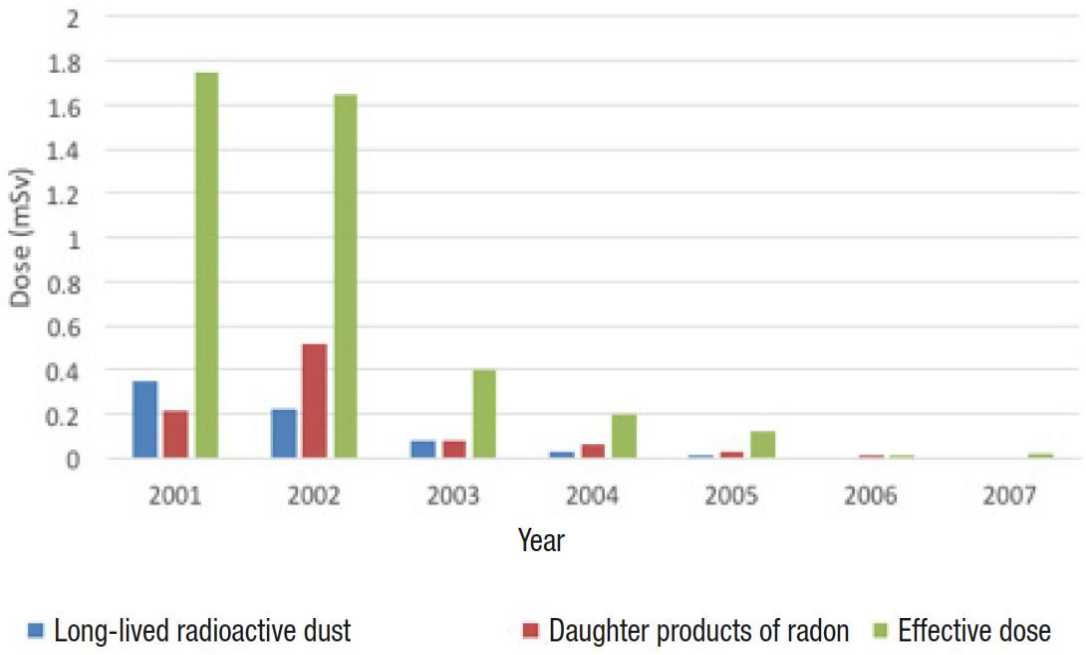
8.3.3.4 SITE REHABILITATION: EXAMPLES

Various methods may be used to rehabilitate land affected by mining depending on the type of mine (underground or open pit), the volume of waste produced and where waste will be buried. For instance, when an old mine site in Colorado was rehabilitated, mine waste was stored inside underground cavities made of low-permeability rocks and natural materials resistant to water and geological erosion. Once filled, the cavities were sealed using layers of erosion-resistant rocks (CDPHE, 2001).

Once restoration work is complete, government authorities like the CNSC in Canada determine whether the site can be decommissioned. In northwestern Saskatchewan, the Cluff Lake mine site was mined by Areva Resources Canada for more than 20 years, before its closure in 2002 after reserves were exhausted. The site included three open pits, two underground mines, one mill and one waste management facility. The restoration plan was developed at the beginning of mining operations, and restoration was completed in 2006 once the site was re-vegetated and secured. The CNSC decommissioned the mine in 2003 and concluded that decommissioning would not have significant harmful effects on the environment, except for a deterioration in the quality of groundwater in the areas affected by mining (CNSC, 2003). Radionuclide concentrations with activities greater than baseline values were measured at some of the underground stations (Table 8.1), but the CNSC came to the conclusion that the environmental effects on groundwater could be classified as not significant.

A surveillance and environmental monitoring program was implemented at the old mine site in compliance with provincial and federal regulations (Areva (3), 2013; GA, 2008). A report by the CNSC published in 2009 presented data for the doses received at the Cluff Lake mine between 2001 and 2007. The information is presented in Figure

8.1 is based on graphical data provided by the CNSC. The diagram shows that the average doses received after exposure to radioactive dust and radon radically decrease after the stop of mining operations (2002), becoming negligible as of 2006.



Source: CNSC (1), 2009.

Figure 8.1: Trend for the average dose received at the Cluff Lake mine.

Old uranium ore mining and processing sites in the Elliot Lake region in northern Ontario were also restored. These sites were in operation since the 1950s, when environmental regulations were very different than current standards. Consequently, the environment suffered considerable damage, manifested by the presence of radionuclides from the decay chain of natural uranium (including uranium-238, lead-210 and polonium-210) in sediments, fish and water from lakes located close to the old mine sites, at concentrations greater than in control (unaffected) lakes (see section 7.5.2). Since the last uranium mine closed in 1996, decommissioning and restoration projects have been undertaken (decommissioning work by Rio Algom and Denison Mines Inc. started in 1992), and the CNSC monitors the sites' environmental performance and maintenance (CNSC (7), 2012):

- it reviews monthly data on water quality;
- it reviews annual reports and reports on the state of the environment that are produced every five years;
- its inspectors visit the sites regularly and give particular attention to water treatment facilities and to maintenance activities that are either completed, underway or planned;
- it makes sure that a review of all geotechnical work is carried out every seven years by a third party, as recommended by the Canadian Dam Association;
- it looks over the results of radiation protection and public information programs and makes sure that financial guarantees in place are adequate, which are subject to a strict, ongoing regulatory review.

Old uranium mine sites have been restored, and the CNSC reports that the quality of the environment is constantly improving. Thanks to the monitoring program put in place by the CNSC, the current discharge of radionuclides in the environment is observed to be very low. The CNSC also reports that outside the impact areas covered by operating licences, measurable impacts are negligible.

It is not always possible to reduced residual radionuclide concentrations to background levels at old mine sites given technological limitations, economic factors and the risks of collateral environmental damage. Several documents report that old mine sites must be put under the control of authorities, and that environmental monitoring of rehabilitated mining properties must be maintained over an indefinite period of time.

It should be noted that progressive site rehabilitation during mining operations reduces the total cost associated with rehabilitation measures. Old mine sites must be perceived as land for eventual reused, and not as land requiring maintenance by future generations (Waggitt, 2011). It is with sustainable development in mind that old uranium mine sites are today reused such as in the following examples.

Solar energy - United States (Waggitt, 2011)

In the Rifle area (Colorado), an old uranium mine site was restored in 1996. Because the site was classified as a contaminated site, the long-term environmental monitoring program was implemented for the site's entire area of 22 ha (13 of which contained mine waste). In 2004, town council decided to reuse part of the site to install a water treatment plant. To supply the treatment plant in energy, photovoltaic cells were installed over 4.8 ha. Today, the water treatment plant is in operation and auto-generates 60 % of its electricity.

Solar energy - France (Areva)

The old Ecarpière uranium mine site (end of operations: 1991) was completely restored between 1989 and 1996. Certified to ISO 14001, it is now under surveillance: a team from AREVA oversees environmental monitoring and water treatment. In 2011, Areva and a firm specialized in renewable energy signed an agreement for the installation of a photovoltaic farm on the old mine site. The thousands of solar panels installed will be able to supply clean energy to a community of 3500 inhabitants.

Golf course (Waggitt, 2011)

Waste rock piles in Germany were re-engineered and transformed into a golf course. This operation required significant investments, and detailed risk analyses took place over several years. The original idea, which came from a local group of golfers, dates back to 1997; the 86 ha site was then acquired in 2004 and risk analyses were completed in 2007. In 2009, a nine-hole course (Schlema Golf Club) welcomed golfers.

8.3.4 PRESENCE OF OTHER CHEMICALS ON MINE SITES

Uranium mills represent sources of air emissions, these emissions being composed of, among other things, sulphur dioxide (SO_2), suspended particles (which were addressed in previous sections) and nitrogen oxides. Hazardous

materials, like various types of fuel, are also present and are stored on mine sites. Sulphur dioxide and nitrogen oxide emissions and the use of various chemicals are not specific to uranium mining: they occur on all types of mine sites.

Air emission reduction systems are in place in mining facilities such as those of McClean Lake and the Midwest deposit in Saskatchewan. On the McClean Lake project site, readings taken since 1999 show that the lowest average annual concentration in SO_2 is 0.79 µg/m^3 (2004) and that the highest, 11.5 µg/m^3 (1999). The provincial standard is set at 26.2 µg/m^3. Concentrations measured close to the Midwest site are comparable to regional data and representative of background values. The maximum desirable annual SO_2 concentration determined by the Saskatchewan government is 30 µg/m^3, whereas the maximum acceptable annual concentration is 60 µg/m^3 (CNSC (6), 2012).

Nitrogen oxides (NOx) may also be observed on site. These oxides are mainly emitted by diesel engines, but can also be from the use of ammonia in uranium milling. However, the catalytic reduction of nitrogen oxides into molecular nitrogen (N_2, a non-toxic molecule that naturally occurs in the air) and water, which is an effective control measure for NOx, is applied in the Canadian mining sector (Health Canada, 2004), such that NOx concentrations observed are low (GA, 2008).

Many hazardous substances, such as fuel and reactive agents (explosives, compressed gases, flammable liquids and solids, oxidizing agents, toxic and corrosive substances), are stored on mine sites. However, their disposal is such that they cannot come into direct contact with the environment under normal mining conditions, given their conditions of storage (CNSC (6), 2012). The storage and management of residual hazardous materials comes under the Regulation respecting hazardous materials (R.L.R.Q., chapter Q-2, r. 32).

8.3.5 Risks of impact for exposed populations and organisms

The potential effects of uranium mining operations on the health of exposed populations do not differ from the effects related to other types of mines. The effects common to both types of mines comprise the risks associated with the contamination of water by various toxic metals and with the presence of suspended particles that may be inhaled by miners or nearby communities. The health risks specific to uranium mines are related to the presence of ionizing radiation emitted by uranium ore and its daughter products, and of gaseous radon and its daughters products (Health Canada, 2004).

8.3.5.1 Radiological doses likely to be received by workers

Exposure to ionizing radiation has a risk of biological damage. Even though the risk related to natural radiation is minimal for the general public, it becomes higher in certain sectors of the industry, for instance in the mining sector where employees are exposed to increased natural radiation or in the medical or industrial sectors where employees may be exposed to artificial radiation. Consequently, maximum doses of exposure to ionizing rays, excluding radioactivity from a natural or medical origin (for a personal treatment), were determined by the CNSC. The current Canadian dose limit for exposure to ionizing radiation excluding radioactivity from natural or medical

sources is set to 1 mSv/year for the general public and to 100 mSv over 5 years, with a maximum of 50 mSv for a single year for workers in the uranium sector (Health Canada, 2008).

Today, workers of the mining sector are exposed to concentrations that are well below these legal limits. For instance, employees of the Olympic Dam mine in Australia (low-grade uranium mining) receive an average exposure of less than 1 mSv/year, whereas the doses received by employees in Saskatchewan mines (high-grade uranium) are less than 2 mSv/year (GA, 2008). The CNSC reports that the total radiation doses received by uranium mine employees average 0.5 mSv/year. In 2011, the average annual dose received by workers in the uranium mining sector in Saskatchewan, including contractors, was about 0.72 mSv, which represents 0.72 % of the average allowable annual dose over 5 years (100 mSv). The doses received by employees were all below this limit, the maximum annual dose recorded being 10.75 mSv (this dose represents 21.5 % of the maximum allowable dose for one year, i.e. 50 mSv) (SMA(2), 2013). It should be noted that the type of job and method of mining (underground or open pit) will affect the average dose received (see Table 8.4) by workers of the mining sector.

For comparison purposes, the average annual doses received by workers of different sectors in Canada in 2008 are presented in Table 8.4 (Health Canada (2), 2008).

Table 8.4 : Annual doses by type of employment for all of Canada

Employment type	**Average annual dose (mSv)**
Office personnel	0.04
Dental hygienist	0.01
Industrial radiologist	2.06
Nuclear medicine technologist	1.60
Uranium mine: underground miner	2.43
Uranium mine: open pit miner	0.37
Uranium mine: nurse	0.13

Source: Health Canada (2), 2008.

For information purposes, the effects related to various doses for different periods of exposure are presented in Table 8.5.

Table 8.5: Different radiation doses received according to the period of exposure

Dose (millisieverts, mSv)	Period of exposure	Observations
10,000	Short	Immediate effects on health, death in the short term
2000 - 10,000	Short	Significant immediate effects on health
1000	Long	5 % increase in the incidence of cancer
1000	Short	Nausea, decrease in white blood cells
50	Per year	The lowest potential cancer-causing dose
20	Average per year over 5 years	Upper limit tolerated for workers of the nuclear industry and uranium mines
2 – 3	Per year	Average background noise in North America (including radon)
2	Per year	Caused by radon in the North American atmosphere (this value is included in the background noise value cited above)
1- 10	Per year	Global natural background noise
1	Per year	Dose received by a person who spends 90 % of his time in a house with 50 Bq/m^3 of radon
0.3 – 0.6	Per year	Artificial sources, especially medical applications
0.2	Per year	Average dose due to outdoor radon
0.05	Per year	Target limit around the perimeter of nuclear power plants
0.001 – 0.1	Per year	Industrial and mining sources

Source: BAPE, 2002.

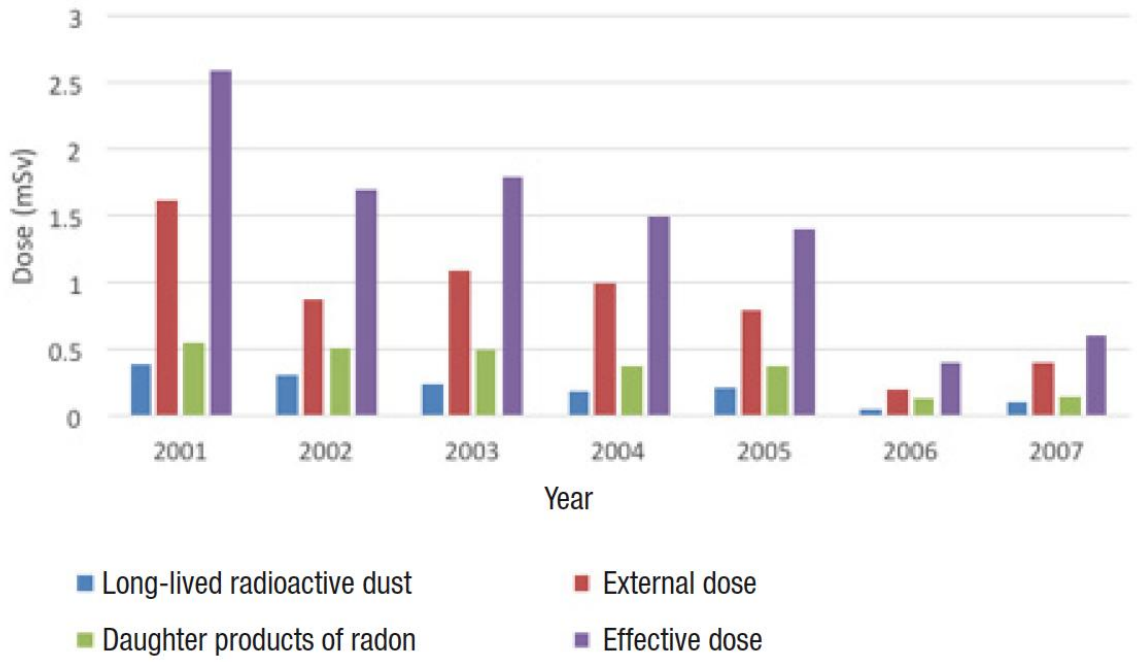
The doses received by workers are mainly from radon and its decay products. The low levels of exposure observed today result from the efforts made to reduce risk, following the ALARA principle (As Low As Reasonably Achievable). However, these types of measurements have not always been taken to ensure the protection of workers. The CNSC conducted a study on 17,660 workers of the Eldorado uranium mines, who worked at the Port Radium (Northwest Territories) and Beaverlodge (Saskatchewan) mine sites, and at the Port Hope facility in Ontario between 1932 and 1980 (CNSC(2), 2012). The study reports that for the most part, with the exception of some reported cases of lung cancer (see below), the employees in charge of uranium mining and processing were as healthy as the Canadian male population. A decrease in the risk of some cancers and in the death rates due to diseases such as heart disease was even observed. This phenomenon could be explained by the "healthy worker effect", as reports the CNSC (being a miner requires being healthy, in good shape and a lot of stamina (Emploi-Québec, 2013)). On the other hand, the study showed that lung cancer rates and related mortality rates were much higher for the employees of uranium mines than for the rest of the population, and were due to the inadequate ventilation in mines and to the lack of radiation protection programs.

It should however be noted that for this study, data on smoking was not available. Smoking is responsible for more than 85 % of lung cancer cases in Canada. Exposure to radon and its decay products is the main cause of lung

cancer for non-smokers, but this risk is increased for smokers. It is therefore important to take smoking into account when interpreting the results of such studies (CNSC(2), 2012).

The implementation of regulations and radiation protection measures results in gradually decreasing exposure rates. For instance, the Canadian workers' exposure to radon went from more than 400 working level months (400 WLM) in the early 1940s to an average exposure of about half of (1) working level month (0.5 WLM) per year in 1970 (CNSC, 2010). The working level month is sometimes used for exposure resulting from the inhalation of air containing alpha particles. One (1) working level month received annually is equivalent to 5 mSv per year, if we assume 2000 work hours per year.

Exposure continues to decrease. Figure 8.2, which is based on graphical data presented by the CNSC in 2009 (and which are presented here as approximations), illustrates the various doses received by employees of the McClean Lake site in Saskatchewan between 2001 and 2007 and shows the tendency of doses to slightly decrease from one year to the next.



Source: CNSC (1), 2009.

Figure 8.2: Trend of the average doses received at the McClean Lake mine.

Today's miners are therefore exposed to low levels of radon. Important factors such as the time of exposure and a lower dose debit reduce the risk of developing lung cancer. The CNSC reports that by 2030, about 24,000 people will be employed for various periods of time in Saskatchewan mines. Of this number, probabilities indicate that 142 miners are at risk of developing lung cancer (CNSC, 2010). According to the CNSC, 141 out of the 142 miners are at risk of developing lung cancer due to the use of tobacco and one (1) miner could develop lung cancer due to workplace 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 (CCS, 2013).

8.3.5.2 PREVENTIVE MEASURES FOR THE HEALTH OF WORKERS

As previously mentioned, 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 additional protection against ionizing radiation is provided for. Radioactivity management programs include the monitoring and surveillance of workers' exposure to such radiation.

Employees in the mining sector use shielding equipment that minimizes exposure to ionizing radiation. Protection against alpha radiation is minimal because a single sheet of paper blocks this type of radiation, but beta radiation requires protective materials such as a sheet of plywood, aluminium or glass. The hazard associated with exposure to these types of radiation is therefore related to the risks of inhalation or ingestion, alpha radiation being more harmful health-wise when alpha-emitting elements are incorporated within the organism. Gamma radiation is very penetrative, and more imposing forms of shielding such as thick layers of concrete or lead are required.

In Saskatchewan, regulations require that each worker wear a dosimeter (SMA(2), 2013). The dosimeter is a device that records and calculated the total radioactive doses received from external radiation. Dosimeters are subject to monitoring by independent agencies, which transmit the results to Health Canada (SMA(2), 2013). Health Canada keeps a central register, the contents of which are available to workers and the Canadian Nuclear Safety Commission. CNSC employees carry out inspections and assess programs designed to protect workers against radiation (CNS (3), 2012). Other dosimeters may be worn in addition to the basic dosimeters when real time radiation levels must be known. Furthermore, workplaces can be equipped with devices that measure the ambient radiation level.

Government reports indicate that controlling workers' exposure to ionizing radiation also involves rapid decontamination of spills, strict maintenance of underground ventilation systems and minimizing the period to which workers are exposed to ore (SERM (2), 1997).

The time of exposure is one of the key factors of the ALARA principle. Tied to the precautionary principle in the field of toxicology and radiation protection, when the "dose-response" relationship for an element of potential concern is somewhat uncertain, the ALARA principle indicates that an absorbed dose may be reduced by decreasing the time of exposure to the source of radiation. It implies that a given approach cannot be taken if a safer approach exists, even if the dose limits would not be exceeded.

As such, current uranium mines implement radiation protection programs, regulatory limits and programs that comply with the ALARA principle, and the companies must demonstrate beforehand that their mining operations will not pose a threat to the safety of humans nor to the environment. The CNSC, which inspects and controls the doses absorbed in the mining sector, has come to the conclusion that the doses are well below regulatory limits

and that the risk for uranium workers of developing lung cancer is comparable to that of the general public (CNSC(3), 2012).

8.3.5.3 WORKERS AT THE MINERAL EXPLORATION STAGE

During mineral exploration, workers may be intermittently exposed to low radiation levels compared to radiation levels observed during the mining stage. Table 8.6 presents the dose limits and the steps to follow based on the level of radiation exposure during uranium mineral exploration.

Table 8.6: Action levels for radiation protection controls (cpm = counts per minute; EPD = electronic personal dosimeter; TLD = thermoluminescent dosimeter)

Monitored parameter	Action level	Action
Radiation dose rate at 1 m	1 µSv/h (10 µSv/h on contact)	Initiate radiation protection controls
	10 µSv/h	Restrict time
Daily dose as measured with an EPD	10 µSv	Review, restrict time
Quarterly TLD dose rate	100 µSv	Investigate, restrict time
Contamination meter reading	> 300 cpm	Swipe
	100cpm above background level	Decontaminate

Source: e3 Plus, 2009.

Dosimeters are used to monitor the parameters. Daily dose readings taken with an electronic personal dosimeter (EPD) aim to inform workers on the dose received during their work shift, in real time. Radiation readings appearing on the screen as well as visual and sound alarms enable the ALARA principle to be applied on an ongoing basis, by allowing workers to control and reduce their time of exposure. The dosimeter consists of an electronic box with a display screen.

Thermoluminescent dosimeters (TLD) are also used for higher action levels. They may be worn on different extremities of the body, for instance on the arm, leg or finger as a ring. They are meant to record individual equivalent doses received by the extremities, which are most exposed to ionizing radiation. The dose is determined based on the light produced when the dosimeter is heated, the pulse being proportional to the radiation dose received.

Contamination meters are used to measure radioactive contamination in certain places or work areas. Efficient and portable equipment makes it possible to measure alpha, beta and gamma contamination. Contamination meters record counts per minute (cpm), which is the number of radioactive decays (counts) per unit of time (minute). When the signal is greater than 300 cpm for instance, a swipe check must be done. This technique consists in swiping a potentially contaminated surface with a fine, wet piece of paper that will be analyzed using instruments that can detect contamination. If contamination is confirmed, decontamination (through cleaning) is performed. Table 8.7 provides examples of precautionary measures that should be taken at the different stages of exploration.

Table 8.7: Precautionary measures to take at each step of uranium mineral exploration to avoid occupational and environmental contamination

Activity	Precautions (e3 plus)	Additional Saskatchewan requirements
Exploration licence application		- Uranium exploration is subject to an application procedure, which must be submitted to Ministry of Environment's Ecological Protection Specialist. Verification by the Heritage Resources Branch and a map from the Conservation Data Centre must accompany the application.
Sampling	- Workers must be trained, have received a training certificate in accordance with the TDG Regulations for WHMIS (Workplace Hazardous Materials Information System) Class 7 goods or carry out these activities in the presence of and under the supervision of a trained person - Workers must wear their TLD inside their jacket during their shift - Workers must wear gloves, safety glasses and a dust mask - Workers must remove their work gloves before eating or smoking - Areas where radiation is greater than 1 µSv/h at a distance of 1 m must be marked - Samples must be placed in plastic bags - Workers must monitor their hands, soles of shoes and clothing with a contamination meter prior to boarding a vehicle - Sample bags must be stored at least 1 m away from personnel - Field clothing and equipment must be stored in change facilities and not in the office or living quarters and must be washed in designated washing machines	- During exploration, a gamma survey must be done to make sure that gamma radiation levels are less than 1 µSv - If radioactivity levels exceed this threshold, the Ministry of Environment must be notified
Drilling	- Workers must be trained, have received a training certificate in accordance with the TDG Regulations for Class 7 goods or carry out these activities in the presence of and under the supervision of a trained person - Prior to drilling, a site check must be performed, and background radiation levels should be measured on a grid pattern - Workers must wear their TLD inside their jacket - Field clothing and equipment must be stored in change facilities and not in the office or living quarters and must be washed in designated washing machines - Mineralized core must be stored 10-20 m away from the drill platform - When diamond drilling in mineralized zones, a closed circuit facility should be used to recycle water - When RAB drilling is employed in a mineralized zone in dry soil above the water table, appropriate dust suppression techniques should be employed - In wet drilling, once the cuttings settle out, the water can be recycled and drained into a sump located down slope from the drill and 50 m from streams - After a drill hole is completed, residues must be monitored using a gamma meter and any residues with a gamma reading greater than 1 µSv/hr at a 1 m distance should be either covered with soil in a pit, or returned down the drill hole - After the drill hole is complete, the upper 30 m of bedrock should be grouted; grouting of mineralized sections is highly recommended - If ore is encountered, grouting the entire hole is strongly recommended	- A hole with a uranium concentration greater than 1.0 % over more than 1 m with a metre-concentration percentage factor greater than 5.0 must be grouted 10 m above and below the mineralized intersection - Any residue with a U_3O_8 concentration that is greater than 0.05 % should be returned down the hole and grouted - Drill sites must be restored such that the maximum radiation be less than 1 µSv/h at a 1 m height (excluding natural outcrops)

Activity	Precautions (e3plus)	Additional Saskatchewan requirements
Core splitting	- Workers must be trained, have received a training certificate in accordance with the TDG Regulations for Class 7 goods or carry out these activities in the presence of and under the supervision of a trained person - Workers must wear their TLD, safety glasses, gloves and coveralls - Workers must wear a respirator for splitting mineralized core - If necessary, self-monitoring must be done - Workers must refrain from eating, drinking or smoking in the core shack - Clothing must be placed in a plastic bag and washed in designated washing machines - Workers must thoroughly clean themselves - Proper disposal of any radioactive rock chips or grinds is mandatory	
Core logging	- Workers must be trained, have received a training certificate in accordance with the TDG Regulations for Class 7 goods or carry out these activities in the presence of and under the supervision of a trained person - Intervals with uranium content of >1 % U_3O_8 must be stored in a separate and clearly marked area, preferably outdoors to avoid radon accumulation - Workers must wear their TLD when working - Workers must wear gloves, coveralls and glasses - Mineralized core must not remain in the core shack for more than 48 hours - Signs warning of radiation must be clearly visible - There must be no eating, drinking, or smoking in the core facility - Dust control must be exercised - There must be a core shack monitoring program which includes radiation monitoring - Contaminated areas must be clearly marked until they are cleaned up - A lead apron may be worn when examining the core - Dust must be reduced by wetting the area - If the 1 µSv/hr action level has been exceeded in the drill core, field clothes must be checked periodically; if the reading is greater than 100 cpm above background level, clothes must be bagged on-site for laundering. - Always work in a well-ventilated environment or monitor periodically for radon build-up; if the 1 µSv/hr action level has been exceeded, monitor work areas on a regular basis	
Core storage	- Radioactive core must be stored at least 30 m away from the main camp area and downwind from the main wind direction - Core must be stored at least 30 m away from any body of water - A minimum number of core boxes should be stored inside the core shack - Signs warning of radiation must be in place - Core with greater mineralization should be separated physically from core with lower gamma fields - Core must be appropriately identified and store and must be handled following the relevant protocol	

Sources: Selection from the e3plus Guidelines for Radiation Protection during Exploration for Uranium, 2009; Saskatchewan Labour: Radiation Protection Guidelines for Uranium Exploration and Mineral Exploration Guidelines for Saskatchewan.

8.3.5.4 WORKERS OF THE MINING SECTOR

Regulated dose limits are based on the guides published by the IAEA and by the International Commission on Radiological Protection (ICRP), and must be adjusted for each case. In general, a material or substance with an activity greater than 1 Bq/g uranium or thorium, 10 Bq/g potassium-40 (IAEA, 2011) or 1000 Bq/m^3 radon-222 (ICRP, 1993; IAEA 2004) must be regulated. Doses to which workers of the nuclear sector are exposed are compared to the dose limits received by the general public in Table 8.8:

Table 8.8: Dose limits for workers of the nuclear sector, a comparison between Canada and Australia.

	Dose limits	
	Canada	**Australia**
Nuclear energy worker	50 mSv per year and 100 mSv over 5 years	20 mSv per year without exceeding 50 mSv per year
Lense of an eye	150 mSv per year	150 mSv per year
Skin	500 mSv per year	500 mSv per year
Hands and feet	500 mSv per year	500 mSv per year
During a crisis	The effective dose cannot exceed 500 mSv, and the equivalent dose received by the skin, 5000 mSv	
Pregnant worker	4 mSv for balance of the pregnancy	The same as the public
General public	1 mSv per year	1 mSv per year
Lense of an eye	15 mSv per year	15 mSv per year
Skin	50 mSv per year	50 mSv per year
Hands and feet	50 mSv per year	-

Data source: MJ (2), 2013; MJ, 2014; Health Canada, 2008; ARPANSA, 2005; ARPANSA, 2011.

8.3.5.5 LOCAL COMMUNITIES

The intensity of radiation decreases exponentially with distance from the source. Reported values indicate that the doses received by the Canadian overall population, in general, related to ionizing radiation originating from uranium mining represents only a small fraction (0.001 to 0.100 mSv/year) of the admissible effective dose for the general public due to mining operations (1 mSv/year).

Among local communities, the dose received may come from eating food (vegetables or meat) or from drinking water. Uranium concentrations varying between 1 and 15 µg/L were measured in lakes located near the old Elliot Lake mine site in northern Ontario. These values are equal to or less than the maximum concentrations established by Canadian and international agencies for drinking water (15, 20 and 30 µg/L for the WHO, Canada and the Unites States, respectively). Compared to regulatory values, surface waters generally have uranium concentrations inferior to 1 µg/L.

The authors of a German federal government report estimate that the single act of drinking 350 litres of water with a uranium concentration greater than 240 µg/L per year would lead to the maximum annual dose permitted by German federal regulations to be reached, which is 0.1 mSv/year for an adult (Schmidt et al., 2012). Only the radioactive character of uranium was considered, its chemical toxicity being ignored. However, this report, along

with another report on the presence of uranium in drinking water published by the WHO, indicates that epidemiological studies or tests on animals were not able to demonstrate that uranium ingestion from drinking water could lead to cancer development. Moreover, studies done in Finland and Sweden showed the absence of harmful effects in individuals who drank well water with close to 100 µg/L uranium. No carcinogenic effects were observed in animals that consumed soluble uranium compounds, although bone cancer was observed after they were injected or inhaled (WHO, 2011).

Studies demonstrate that there is a lack of evidence for chemical toxic effects that could be observed after drinking water containing 30 µg/L uranium, which is the maximum concentration allowed in the United States (WHO, 2011). The effects on kidneys, which constitute a target for uranium that can be bioassimilated by organisms, occur at much greater concentrations. Effects related to uranium radioactivity are anticipated at concentrations greater than 100 µg/L (WHO, 2011).

The report entitled *Bilan de la qualité de l'eau potable au Québec (2005-2009)* (Drinking water quality in Québec for the 2005-2009 period) indicates that the Québec standard of 20 µg/L uranium is exceeded in 4 to 10 municipalities every year. The maximum uranium concentration measured during the time period considered is 116 µg/L, which is about six times the standard value.

With respect to the quality of agricultural soil in Canada, allowable uranium concentrations for various types of soil were established by the Canadian Council of Ministers of the Environment (CCME, 2007) and take into account the chemical toxicity of uranium. Concentrations of up to 23 mg uranium per kg of soil are permitted in agricultural soils. However, the maximum allowable concentration for industrial soils is of 300 mg of uranium per kg of soil. These values should serve as reference for the rehabilitation of mine sites. Depending on the type of soil, the composition and the ability to provide uranium species that can be bioassimilated, plants (such as berries consumed by local communities and animals) could contain uranium concentrations and contribute to the dose resulting from ingesting this radionuclide. It should be specified that the tolerable daily intake for uranium is set by the WHO at 0.6 µg of uranium per kg of body mass per day.

As previously mentioned, the authors of a study looking at fish in lakes close to the old Elliot Lake mine site reported that eating 375 g of fish per week (which corresponds to one meal per week) represented an effective dose of less than 0.75 mSv/year (based on the radionuclide activities presented in Table 8.9) (Clulow et al., 1998). Uranium mining was carried out without adequate control measures for mine waste and effluents, from the onset of operations in 1955 and for the several years that followed. The lack of environmental management procedures resulted in an increase in radiological activities in nearby lakes and as a result fish, as presented in Table 8.9.

Table 8.9: Various radionuclide activities in fish from the Elliot Lake area, Ontario.

Fish	Radionuclides	Activity or DL[a] (mBq per g of fresh flesh) [c]	Effective annual dose[b] (mSv)	Total effective annual dose (mSv)
Trout	Lead-210	12.6	0.3194	**0.6078**
	Polonium-210	6.5	0.0786	
	Thorium-230	5.0	0.0341	
	Thorium-232	5.0	0.1755	
	Total uranium	0.0126 µg/g	0.0002	
Whitefish	Lead-210	15.2	0.3853	**0.7155**
	Polonium-210	6.1	0.0737	
	Thorium-230	6.1	0.0416	
	Thorium-232	6.1	0.2141	
	Total uranium	0.0365 µg/g	0.0007	

[a] DL: Detection limit [b] Based on dose conversion factors (Clulow et al., 1998) [c] In µg/g for uranium

With respect to radon inhalation, readings taken on the Midwest mine site demonstrate that radon emitted from underground cavities was quickly diluted by natural ventilation and that the activity concentrations measured on the very site (32 Bq/m^3) were comparable with those measured off site (22 Bq/m^3). These values suggest that in general, local communities are exposed to very low doses of radon, which are close to the average activity concentrations in the air of 5-15 Bq/m^3 (WHO, 2009). Radioactive dust concentrations, measured at various locations on the Cluff Lake mine site, also showed a tendency toward dilution, decreasing concentrations were observed with increasing distance from the processing plant (CNSC, 2003).

The potential effects of uranium mining on the health of exposed communities therefore mainly results from the presence of ionizing radiation and radon gas. Exposure may occur when contaminated water or food is consumed, such as fish or plants found in the area, or when ambient air is inhaled. Although it has not been proven that low doses of radiation have an adverse impact on health, such as an increased risk of developing cancer, we consider that any dose received, regardless of its order of magnitude, represents a risk. We may however question the significance of the risk associated with exposure to low doses. According to the International Commission on Radiological Protection (ICRP), an international non governmental organization that makes recommendations on how to measure exposure to ionizing radiation and on safety measures for such facilities, the risk factor for mortality is 1 to 10,000 per dose of 10 mSv (CECCV, 1984). In other words, if a person is exposed to 10 mSv, his risk of dying due to cancer increases by 1 in 10,000.

A study carried out by the government of Virginia, USA compared this risk factor to one associated with the exposure to natural radiation in the uranium mining area of Swanson, Virginia. The levels of gamma radiation and radon concentrations were measured at various locations in the area, and the annual risks associated with their presence were calculated. For instance, average annual doses from ambient gamma radiation received by the population were about 0.9 mSv in 1984. The results of calculations showed that exposure to gamma radiation and radon represented risks of 9×10^{-6} and 12×10^{-6}, respectively, for a total annual risk of 21×10^{-6}. This signifies that the risk for the area's inhabitants of developing cancer after having been exposed to gamma radiation and radon was about 21 in 1,000,000.

For comparison purposes, Table 8.10 provides activities for which the annual risk of dying is about one in one million.

Table 8.10: Scenarios with a mortality risk of 1 in 1,000,000

Scenario	Cause of death
An 80-km drive or 16-km bicycle ride	Accident
Living for 2 years inside a house made of bricks or stones	Cancer resulting from the radioactivity in construction materials
Being struck by lightning within a 2-year interval	Electric shock
Death from air pollution within a 2-day interval	Variable causes
Living for 2 months under the same roof as a smoker	Cancer, heart diseases
Drinking 0.6 ounces of beer every day for one year	Alcohol-related cancer
Drinking 2 ounces of milk every day for one year	Cancer related to the presence of aflatoxin
Living for 20 minutes at the age of 60	All causes

Source: CECCV, 1984.

8.3.5.6 FAUNA AND FLORA

The effects of ionizing radiation on the environment must also be taken into consideration because plants and animals are exposed to the same internal (ingestion of inhalation of radionuclides) and external (radiation from contaminated environments) sources of radiation as humans. In most cases where living organisms are exposed to additional radiation, the additional exposure does not cause any noticeable effects on plants and animals in the wild (Linsley, 1997). Additional exposure occurs during the authorized (and controlled) discharge of radioactive materials in air, soil, and natural waters, such as during uranium mining operations.

Given the diversity of organisms inventoried in ecosystems, it is impossible to consider each one separately for the purposes of environmental radiation protection. As such, with respect to the doses received and likely to have a negative impact on organisms other than humans, there is only consensus as to the absorbed dose. The absorbed dose is defined as the amount of energy that is transferred by ionizing radiation to a given amount of tissue, and is expressed in grays (Gy). The weighing factor for various types of radiation is not typically considered (for instance, the fact that an alpha particle emitted inside an organism is much more damageable than a beta particle) except in the case of specific sensitivity studies. The varying degrees of tissue sensitivity to ionizing radiation are also not considered (IRSN, 2011), whereas the effective dose for humans, expressed in sieverts (Sv), takes these variations into account.

Several international agencies have sought to evaluate the effects associated with exposure to ionizing radiation in order to determine acceptable limits, i.e. a baseline value for living organisms. Experimental radiation studies were carried out, and the dose rates in μGy/h are reported for different organisms are presented in Table 8.11.

Table 8.11: Dose rates measured at various locations and the consequences for different organisms.

Living organism or location	Dose rate (µGy/h)	Effect
Terrestrial organism	0.01 to 0.09 (herbaceous: 1.1).	Natural background exposure[(a)]
Freshwater plant	0.7 to 4.2	Natural background exposure[(a)]
Aquatic marine organism	0.08 (fish) 27 (crustacean) 57 (macrophyte)	Natural background exposure[(a)]
Non-human living organism	10	Baseline value [(d)]
Old mine in Portugal	24	Dose measured in mine waste [(e)]
Freshwater bottomfish	31	Natural background exposure[(a)]
Mammal	40-100	Potentially radical change in the population's reproductive rate[(b)]
Mammal	400	Potentially radical change in the population's mortality rate[(b)]
Aquatic organism	400 for a low proportion of individuals	Lack of adverse effects for the population [(b) (c)]
Plant	400	Minimal impact on sensitive plants[(b)]
Plant	1000-3000	Impact of chronic radiation[(b)]

[a] (IRSN, 2011); [b] (Linsley, 1997); [c] The radiation doses required to cause significant adverse effects are, however, difficult to estimate due to several factors such as long-term monitoring (natural revegetation, migration of individuals, etc.); [d] (CEAEQ (3), 2013); [e] (Carvalho, 2005)

The tools used for assessing the environmental risk associated with radionuclides, ERICA (Environmental Risk for Ionising Contaminants: Assessment and Management), makes it possible to update the database on the effects of ionizing radiation on non-human organisms (IRSN, 2007). Using this database allows for the definition of ecosystem protection criteria and the characterization of the ecological risk by analyzing the effects of exposure to ionizing radiation on fauna and flora. To ensure adequate protection of all ecological receptors in case of chronic exposure to ionizing radiation, this tool uses a baseline value of 10 µGy/h. This values applies to the terrestrial, freshwater aquatic and marine environments (CEAEQ (3), 2013), and is used by the CNSC in Canada and by the *Institut de recherche en sûreté nucléaire* in France (IRSN).

The results of radiation experiments show that mammals are the species most sensitive to ionizing radiation, followed by birds, fish (which overlap with upper level plants), reptiles, insects and viruses (Linsley, 1997).

Environmental monitoring of the aquatic fauna and flora must be undertaken by proponents to check for the presence of potential contaminants. Environmental studies carried out in the Elliot Lake area in Ontario measured the magnitude of ecological impacts resulting from the inadequate treatment of effluents prior to the 1980s (Clulow et al., 1998). Monitoring also makes it possible to gather information on the number of animals and to determine the biota that is most at risk (CNSC, 2003).

8.3.6 TRANSPORT OF RADIOACTIVE SUBSTANCES

The transport of radioactive substances is regulated by Transport Canada and the CNSC's Packaging and Transport of Nuclear Substances Regulations (MJ, 2011). The IAEA defines a radioactive substance as a substance with a

radioactivity that is greater than 70 kBq/kg (IAEA, 2012 and Health Canada, 2000). These substances must have labels that contain, among other things, the UN number.

If the transported substance's radioactivity is less than 5 µSv/h, the package containing the substance is considered by the IAEA as an "excepted package": the substance is not deemed to be dangerous, and can be shipped normally. The following instructions must however be followed:

- A label marked “Radioactive Samples” must be placed inside the package so that the label is visible to the person opening the package
- Removable radioactive contamination on the outside of the package must not exceed 0.4 Bq/cm^2 averaged over 300 cm^2 or must not be detectable above background;
- The UN number “UN2910” must be attached to one vertical side of the shipping container;
- Both the senders and receiver’s addresses must be displayed on exterior of the package;
- If the weight exceeds 50 kilograms, the weight must be shown on exterior of the package;
- If transported by air, the package must be able to withstand a temperature range of -40 °C to -55 °C and withstand without leakage a reduction of ambient pressure to 5 kPa;
- The way bill requires the shipping name (Radioactive Material, Excepted Package – Limited Quality of Material) and the UN number;
- Three copies of the documentation are required – one each for the shipper, the carrier, and the receiver;

(e3 Plus, 2009)

If the dose rate on the exterior of the package is >5 µSv/hr, then the package will be shipped as a Low Specific Activity-I (LSA-I) shipment. "Most geological samples shipped for analysis from an exploration camp are of this type" (e3 Plus, 2009). The rules for shipping LSA-I packages are:

- Both the sender and receiver’s addresses must be displayed on exterior of the package;
- If the weight exceeds 50 kilograms, the weight must be shown on exterior of the package;
- The shipping name (Radioactive Material, Low Specific Activity) and the UN Number “UN2912” must be attached to two vertical and opposite sides of the shipping container;
- Three copies of the documentation are required; one each for the shipper, the carrier and the receiver;
- Radioactive Yellow II labels are attached next to the shipping name and UN number labels;
- On the Radioactive Yellow II labels the following must be written:
    - “LSA-I” in Radioactive Contents section,
    - The activity level in the package, estimated in Bq,
    - The Transport Index. This index is the gamma radiation field in mSv/hr at a distance of 1 m from the exterior of the package multiplied by 100. For example, the Transport Index for 0.005 µSv/hr will be 0.5;

- The package for an LSA-I Shipment must satisfy the IAEA Requirements for Type 1 Industrial Packages (Type IP-1), which are the same as for an Excepted Package, plus:
    - The smallest external dimension of the package cannot be less than 10 cm
    - The container must be durable and legally marked on the outside “Type IP-1”.

The packaging is also subject to protocols and must be prepared by a person with the appropriate training. The packaging rules are from the CNSC's Packaging and Transport of Nuclear Substances Regulations and the IAEA's Regulations for the Safe Transport of Radioactive Material (TS-R-1). Packages designed for the transport of high-risk nuclear substances must be put through thorough tests that simulate normal and extreme conditions. CNSC experts examine the packaging and the test results to make sure they comply with regulatory requirements.

An application for package certification typically contains information on:

- structural design;
- thermal and shielding evaluation;
- containment of the nuclear substance in the package;
- the operation of the package;
- the maintenance program;
- the quality assurance program followed for the design, manufacture and maintenance of the package

(Source: CNSC, Fact Sheet, Regulating the Packaging and Transport of Nuclear Substances in Canada).

At the exploration stage, samples are shipped to the laboratory for chemical composition analysis. These samples must be packed in approved containers such that they do not exceed the limit for a LSA-I type package.

For certain mining operations, it may be necessary to transport the ore to the nearby mill. For instance, at the McArthur River mine (Saskatchewan), uranium is crushed and returned to the surface as pulp. The pulp is placed in type-II industrial packages (Type IP-II). The packages are filled to 50 % of their capacity with pulp that contains 30 % U_3O_8 (Rosner et Edwards, 1998) and are shipped by truck, four packages at a time (5.55 t), over a distance of 80 km to the Key Lake processing plant, where the pulp is converted to U_3O_8 uranium oxide or yellowcake (Chadwick, 1997; Thomas et Lenail, 1998). Truck drivers need to be trained in case of an accident, and an emergency response plan must be provided.

9 CONCLUSIONS

Uranium is a radioactive metal that occurs naturally in the environment (bedrock, water, biosphere). Its unstable atomic nucleus decays slowly, emitting ionizing radiation resulting in lighter atoms, its daughter elements/atoms, , following a decay chain that ends with the formation of a stable atom. The transformation of uranium and its daughter products has multiple applications in civilian society, such as the production of electrical energy, agricultural uses, and in the medical sector.

Canada is the second largest uranium producer in the world. In Québec, many uranium exploration projects are at various stages, but there is currently no uranium being produced. Known uranium resources total 315,000 tonnes. Less than 30 % of uranium resources are in deposits in which uranium is the main product, and about 60 % are located in deposits in which uranium is a secondary product that could be developed. Other uranium resources are located in mine and industrial waste.

In Québec, mineral resource exploration and mining is mainly regulated by the Mining Act and the Environment Quality Act, which are under the jurisdiction of the MRN and MDDEFP, respectively. Furthermore, in the case of uranium, Canadian legislation also applies because radioactive substances come under exclusive federal jurisdiction. This is governed by the Nuclear Safety and Control Act, under which the Canadian Nuclear Safety Commission (CNSC) was established, which supervise mining, decommissioning and site rehabilitation at the end of operations. The commissioning of uranium mines must be authorized by the MRN, the MDDEFP and the CNSC.

Applicable laws and regulations in Québec and Canada concerning environmental aspects and radiation protection serve as international references and are based on proven scientific concepts. Respecting and applying these laws and regulations remains the best way to reduce the potential negative impacts of exploration and mining of uranium resources in Québec.

Uranium and its daughter products have a potential toxicity due to their chemical and radioactive properties. Uranium radiotoxicity is negligible compared to its chemical toxicity, the latter depends on the accumulation and mobility of uranium in the environment. In uranium-rich regions, it is imperative to quantify, in the most comprehensive way possible and prior to the commissioning of a uranium mine, the natural concentrations in the environment (air and water) and in plants that are part of the food supply for living organisms of the upper trophic level. Given the number of physicochemical parameters that will affect the mobility of uranium and its daughter products, prior characterization of the biogeochemical mechanisms specific to a mine site allows to better define these parameters, thus enabling adequate rehabilitation, if applicable. This type of analysis should be proposed and supervised by an independent environmental management agency.

Negative environment impacts related to the uranium exploration stage are low, yet can increase with more advanced stages of exploration. These impacts vary according to the type of uranium mineralization and to modern methods of mining, ore processing and waste treatment.

During uranium mining and site rehabilitation, controlling dust emissions and applying confinement measures for effluents and mine waste prevent the dispersal of uranium and its daughter products in the environment, 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, which also prevents radioactive elements from being dispersed in the environment. Maintaining radioactive dust and radon concentration at levels comparable to regional levels is possible through the ventilation of confined spaces.

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APPENDIX 1 – OVERVIEW OF CANADIAN AND INTERNATIONAL LAWS PERTAINING TO URANIUM EXPLORATION AND EXPLOITATION

Jurisdiction	Title of Law or Regulation	Internet Address
Canada	Lignes directrices canadiennes pour la gestion des matières radioactives naturelles (MRN)	http://www.hc-sc.gc.ca/ewh-semt/alt_formats/hecs-sesc/pdf/pubs/contaminants/norm-mrn/00ehd245.pdf
	Règlement sur la radioprotection	http://laws-lois.justice.gc.ca/PDF/SOR-2000-203.pdf
	Règlement sur les mines et les usines de concentration d'uranium	http://laws-lois.justice.gc.ca/eng/regulations/sor-2000-206/index.html
	Règlement sur l'emballage et le transport des substances nucléaires	http://laws-lois.justice.gc.ca/PDF/SOR-2000-208.pdf
	Loi de 1992 sur le transport des marchandises dangereuses	http://laws-lois.justice.gc.ca/fra/lois/T-19.01/
	Règlement sur les effluents des mines de métaux	http://laws-lois.justice.gc.ca/PDF/SOR-2002-222.pdf
	Loi sur Investissement Canada	http://laws-lois.justice.gc.ca/fra/lois/I-21.8/index.html
	Loi sur l'énergie nucléaire	http://laws-lois.justice.gc.ca/fra/lois/A-16/
	Loi canadienne sur l'évaluation environnementale (2012)	http://laws.justice.gc.ca/fra/lois/C-15.21/index.html
	Loi sur la responsabilité nucléaire	http://laws-lois.justice.gc.ca/fra/lois/N-28/index.html
	Loi sur les dispositifs émettant des radiations	http://laws-lois.justice.gc.ca/fra/lois/R-1/index.html
	Loi sur la sûreté et la réglementation nucléaires	http://laws-lois.justice.gc.ca/fra/lois/N%2D28.3/
	Loi sur les déchets de combustible nucléaire	http://laws-lois.justice.gc.ca/eng/acts/N-27.7/
	Loi sur le terrorisme nucléaire	http://www.parl.gc.ca/HousePublications/Publication.aspx?Mode=1&DocId=6246171&Language=F
	Règlement sur les sanctions administratives pécuniaires de la Commission canadienne de sûreté nucléaire	http://laws-lois.justice.gc.ca/fra/reglements/DORS-2013-139/TexteComplet.html
	Règlement sur les installations nucléaires de catégorie I	http://laws-lois.justice.gc.ca/fra/reglements/DORS-2000-204/page-1.html
	Règlement sur les installations nucléaires et l'équipement réglementé de catégorie II	http://laws-lois.justice.gc.ca/fra/reglements/DORS-2000-205/
Saskatchewan	Radiation Protection Guidelines for Uranium Exploration	http://www.lrws.gov.sk.ca/radiation-protection-guidelines-uranium-exploration
	The Occupational Health and Safety Act, 1993	http://www.qp.gov.sk.ca/documents/English/Statutes/Statutes/O1-1.pdf
	The Radiation Health and Safety Act, 1985	http://www.qp.gov.sk.ca/documents/English/Statutes/Statutes/R1-
	The Mines Regulations, 2003	http://www.qp.gov.sk.ca/documents/english/Regulations/Regulations
	Mineral Exploration Guidelines for Saskatchewan, 2012	http://www.environment.gov.sk.ca/mineralexploration
	Règlement d'exclusion des mines d'uranium et des usines de concentration d'uranium de la Saskatchewan	http://laws-lois.justice.gc.ca/fra/reglements/DORS-2001-115/index.html
Ontario	Règlement sur la santé et la sécurité au travail dans les mines d'uranium de l'Ontario	http://laws-lois.justice.gc.ca/PDF/SOR-84-435.pdf

Australia	Safety Guide, Monitoring, Assessing and Recording Occupational Radio Doses in Mining and Mineral processing	http://www.arpansa.gov.au/pubs/rps/rps9_1.pdf
	TR Radiation protection in the mining and milling of radioactive ores part 1-10	http://www.arpansa.gov.au/pubs/technicalreports/arl095_vol1_pt1.pdf
	Code of Practice for the Near Surface Disposal of Radioactive Waste in Australia	http://www.arpansa.gov.au/pubs/rhs/rhs35.pdf
	Code of Practice on the Management of Radioactive Waste from the Mining and Milling of Radioactive Ores 1982 (CoA 1982)	http://www.arpansa.gov.au/pubs/rps/rps9.pdf
	Technical Report: Classification and Disposal of Radioactive Waste in Australia	http://www.arpansa.gov.au/pubs/technicalreports/tr152.pdf
	Environmental protection: Development of an Australian approach for assessing effects of ionising radiation on non-human species	http://www.arpansa.gov.au/pubs/technicalreports/tr154.pdf
	RPS No. 9 Code of Practice and Safety Guide for Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing (2005)	http://www.arpansa.gov.au/pubs/rps/rps9.pdf
	TR: Dose Calculations for intake of ore dust	http://www.arpansa.gov.au/pubs/rps/rps9_1.pdf
	RPS No. 9.1 Safety Guide for Monitoring, Assessing and Recording	http://www.arpansa.gov.au/pubs/rps/rps9_1.pdf
	Radiation Protection and Radioactive Waste Management in Mining and Mineral Processing (2005)	http://www.arpansa.gov.au/pubs/rps/rps9.pdf
	Australian Radiation Protection and Nuclear Safety Act 1998	http://www.austlii.edu.au/au/legis/cth/consol_act/arpansa1998487/ et http://www.pir.sa.gov.au/minerals/licensing_and_regulation/mining_operations/uranium_mine_incident_reporting
South Australia	Occupational Health, Safety and Welfare Act 1986	http://www.legislation.sa.gov.au/LZ/C/A/OCCUPATIONAL%20HEALTH%20SAFETY%20AND%20WELFARE%20ACT%201986.aspx
	Environment Protection Act 1993	http://www.legislation.sa.gov.au/LZ/C/A/ENVIRONMENT%20PROTECT
	Dangerous Substances Act 1979	http://www.legislation.sa.gov.au/LZ/C/A/DANGEROUS%20SUBSTANC
	Radiation Protection and Control Act 1982	http://www.legislation.sa.gov.au/LZ/C/A/RADIATION%20PROTECTION
Western Australia	NORM series 1-7	http://www.dmp.wa.gov.au/6745.aspx
United States	Health and environmental standards for uranium mill tailings	http://www.law.cornell.edu/uscode/text/42/2022
	U.S. EPA: 40 CFR Part 141 - National Primary Drinking Water Regulations	http://www.law.cornell.edu/cfr/text/40/141
	U.S. EPA: 40 CFR Part 144 - Underground Injection Control Program	http://water.epa.gov/type/groundwater/uic/regulations.cfm
	U.S. EPA: 40 CFR Part 145 - State UIC Program Requirements	http://water.epa.gov/type/groundwater/uic/regulations.cfm
	U.S. EPA: 40 CFR Part 146 - Underground Injection Control Program Criteria and Standards	http://www.gpo.gov/fdsys/pkg/CFR-2012-title40-vol24/xml/CFR-2012-title40-vol24-part146.xml
	U.S. EPA: 40 CFR Part 147 - State Underground Injection Control Programs	http://www.gpo.gov/fdsys/pkg/CFR-2012-title40-vol24/xml/CFR-2012-title40-vol24-part147.xml
	NRC Regulatory Guides Division 7 Transport	http://www.nrc.gov/reading-rm/doc-collections/reg-
	49 CFR Part 171-177 (Transport)	http://www.law.cornell.edu/cfr/text/49/171

	Uranium Mill Tailings Radiation Control Act (UMTRCA) 1978 (92 STST. 3021; 42 U.S.C. 7901)	
	U.S. EPA: 40 CFR Part 61 - National Emission Standards for Hazardous Air Pollutants	http://www.ecfr.gov/cgi-bin/text-idx?c=ecfr&tpl=/ecfrbrowse/Title40/40cfr61_main_02.tpl
	U.S. EPA: 40 CFR Part 264 - Standards for Owners and Operators of Hazardous Waste Treatment, Storage, and Disposal Facilities	http://www.wbdg.org/ccb/EPA/40cfr264.pdf
	U.S. EPA: 40 CFR Part 440 - Effluent Guidelines and Standards - Ore Mining and Dressing Point Source Category	http://www.gpo.gov/fdsys/pkg/CFR-2013-title40-vol9/pdf/CFR-2013-title40-vol9.pdf
	U.S. NRC: 10 CFR Part 40 - Domestic Licensing of Source Material	http://www.gpo.gov/fdsys/pkg/CFR-2013-title10-vol1/pdf/CFR-2013-title10-vol1.pdf
	U.S. EPA: 40 CFR Part 192 - Health and Environmental Protection Standards for Uranium and Thorium Mill Tailings	http://www.gpo.gov/fdsys/pkg/CFR-2013-title10-vol1/pdf/CFR-2013-title10-vol1.pdf
	U.S. DOE: Order 5400.5 - Radiation Protection of the Public and the Environment	
	U.S. NRC: 10 CFR Part 20 - Standards for Protection Against Radiation	http://www.gpo.gov/fdsys/pkg/CFR-2013-title10-vol1/pdf/CFR-2013-title10-vol1.pdf
Oregon	DIVISION 92 : Standards for the sitting of uranium mills in Oregon	http://arcweb.sos.state.or.us/pages/rules/oars_300/oar_345/345_092.html
	DIVISION 95: Construction, Operation , and Decommissioning rules for Uranium Mills	http://arcweb.sos.state.or.us/pages/rules/oars_300/oar_345/345_095.html
	Division 60 : Transportation of Radioactive Material	http://arcweb.sos.state.or.us/pages/rules/oars_300/oar_345/345_060.html
	Division 50 : Radioactive Waste Materials	http://arcweb.sos.state.or.us/pages/rules/oars_300/oar_345/345_05
	DIVISION 110: Radiation Safety Requirements for Radioactive Tailings and Ponds	
Washington	WAC, Title 246, Chapter 246-252	http://apps.leg.wa.gov/wac/default.aspx?cite=246-252
	Title 70, Chapter 70.99 Radioactive Waste Storage and Transportation Act of 1980	http://apps.leg.wa.gov/RCW/default.aspx?cite=70.99
	Title 70, Chapter 70.121 Mill Tailings - Licensing and Perpetual Care	http://apps.leg.wa.gov/RCW/default.aspx?cite=70.121
	Title 70 Public Health and Safety, Chapter 98 Nuclear Energy and Radiation	http://apps.leg.wa.gov/rcw/default.aspx?Cite=70
Texas	Chapter 331 Underground Injection Control	http://info.sos.state.tx.us/pls/pub/readtac$ext.ViewTAC?tac_view=4&ti=30&pt=1&ch=331
Nebraska	Title 122 Rules and Regulations for Underground Injection and Mineral Production Wells	http://www.deq.state.ne.us/RuleAndR.nsf/Pages/122-TOC
Colorado	Part 17 - Transportation of Radioactive	http://www.colorado.gov/cs/Satellite/CDPHE-
	Part 18: Licensing Requirements for Uranium and Thorium Processing	http://www.ehs.colostate.edu/WRad/PDF/Part18_Uranium_Thorium_Processing.pdf
AIEA	IAEA Safety Standard Series, Radiation protection and safety of radiation sources: International Basic safety standards	http://www-pub.iaea.org/MTCD/publications/PDF/p1531interim_web.pdf

	IAEA Safety standards series No. RS-G-1.6, Vienna 2004. 95 p. (supersedes IAEA Safety Series No. 26)	http://www-pub.iaea.org/MTCD/publications/PDF/Pub1183_web.pdf
	Best Practice in Environmental Management of Uranium Mining	http://www-pub.iaea.org/books/IAEABooks/8122/Best-Practice-in-Environmental-Management-of-Uranium-Mining
	Security in the transport of Radioactive	http://www-pub.iaea.org/MTCD/publications/PDF/pub1348_web.pdf
	Fundamental Safety Principles	http://www-pub.iaea.org/MTCD/publications/PDF/Pub1273_web.pdf
	Regulations for the Safe Transport of Radioactive Material	http://www-pub.iaea.org/MTCD/publications/PDF/Pub1384_web.pdf