Preliminary Radon Assessment for a Used Fuel Deep Geological Repository

NWMO-TR-2019-09 December 2020

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ABSTRACT

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Abstract
The Nuclear Waste Management Organization (NWMO) is implementing Adaptive Phased Management (APM), Canada's plan for the long-term management of used nuclear fuel. The APM approach encompasses centralized containment and isolation of the used fuel in a Deep Geological Repository (DGR) in a suitable rock formation, such as crystalline rock or sedimentary rock, in an informed and willing host community.

Radon is a radioactive atom produced by the radioactive decay of uranium, thorium and actinides. It is naturally produced from the uranium and thorium present in the host rock of any repository site, and also from the decay of the used nuclear fuel.

An initial assessment of the radon hazard during construction and operation of the DGR was performed to determine whether there is health hazard to workers, and a need for radon monitoring or development of any action levels in order to be in compliance with the applicable regulatory requirements. These results were for a generic crystalline or sedimentary rock site.

The results of the assessment indicate that there is no significant radon hazard to the workers or the general public during construction and operation of the DGR. For workers, the highest radon concentration in an area where workers may be present is in the ventilation exhaust shaft. The concentration of radon in all worker locations is less than the Derived Working Limit of 200 Bq/m^3, based on the Canadian Guidelines for Management of Naturally Occurring Radioactive Materials (unrestricted classification). For members of the public, even those very close to the facility, the dose contribution from radon during construction and operation of the facility is much less than from natural sources.

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1. INTRODUCTION

The Nuclear Waste Management Organization (NWMO) is implementing Adaptive Phased Management (APM), which has as its endpoint the centralized containment and isolation of Canada's used nuclear fuel in a Deep Geological Repository (DGR). The APM repository reference design is based on the reference used fuel container (UFC) and the repository could be located in a suitable crystalline or sedimentary rock site, in an informed and willing host community.

1.1 Objectives

Radon is a radioactive atom produced by the radioactive decay of uranium, thorium and actinides. It is naturally produced from the uranium and thorium present in the host rock of any repository site. Radon is also generated from the decay of the used nuclear fuel. Radon is a gas under normal conditions, and can be present as a gas or dissolved in groundwater. At surface, it is primarily present as a gas.

The objectives of this report:

- Assess the potential hazard due to radon emanation from the surrounding host rock, the waste rock pile, and from the used nuclear fuel during construction and operations; and
- Recommend whether radiation protection (action level) and radiation monitoring will be required for radon during these periods.

This operational safety aspect is being considered jointly with design development. It is intended that this report provides feedback into future design updates.

1.2 Radon Characteristics

The most abundant and longest-lived form of radon is Rn-222, with a half-life of 3.82 days. Rn-222 is a decay product of radium (Ra-226), and a member of the U-238 decay chain (the most common isotope of uranium). It is widely present at low levels due to the natural presence of low levels of uranium throughout the environment.

Radon decay products are divided into two groups: the short-lived radon progeny Po-218 (3.05 minutes), Pb-214 (26.8 min), Bi-214 (19.7 minutes), and Po-214 (164 μs) with half-lives below 30 minutes; and the long-lived radon decay products Pb-210 (22.3 years), Bi-210 (5.01 days), and Po-210 (138.4 days).

Two of radon's progeny in particular, Po-218 and Po-214, decay rapidly and emit alpha particles. When alpha particles hit an object, their energy is absorbed by the surface of the object. Human skin is thick enough to not be affected, but if alpha particles enter the human body through inhalation, they can damage bronchial and lung tissue and can lead to lung cancer (CNSC 2011).

In open air, the concentration of radon gas is very small. However, radon released from soil beneath a building gives rise to an average indoor background air concentration of about 45 Bq/m^3 (Health Canada 2011). Across Canada, the average internal public dose from inhalation of natural radon is about 1 mSv/a, but the dose varies greatly with the geological composition of the environment. For example, the average dose from radon in Vancouver is 0.2 mSv/a, but in Winnipeg it is 2.2 mSv/a (Health Canada 2011).

In confined underground spaces, such as a mine, radon gas can accumulate and reach relatively high concentration levels, and become a health hazard.

Radon progeny concentration in air in mines is reported in Working Level (WL) or Working Level Month (WLM). One Working Level is any combination of short-lived radon progeny in one liter of air that has the potential to release 1.3×10^5 MeV of alpha energy. One WLM is defined as an exposure of one WL for a period of one month. Based on an average of 170 working hours per month, the cumulative exposure of any individual may be calculated as (Section 13.3.3, McPherson 1993):

$$\text{WLM} = \frac{\sum(WL \times hours\ of\ exposure)}{170} \tag{1.1}$$

As per the Canadian Guidelines for Management of Naturally Occurring Radioactive Materials (NORM) (Health Canada 2011), a radon progeny concentration of 0.25 WLM is equivalent to a radon concentration of approximately 200 Bq/m^3 and gives a dose of 1.4 mSv/a, based on occupational exposure (2000 hours per year).

1.3 Regulatory Context and Radon Assessment Criteria

The Canadian Nuclear Safety Commission (CNSC) regulatory dose limits for the public and Nuclear Energy Workers (NEWs) are shown in Table 1.1 (CNSC 2017).

Table 1.1: CNSC Effective Dose Limits (CNSC 2017)

Person	Period	Effective Dose (mSv)
Nuclear energy worker, including a pregnant nuclear energy worker	One-year dosimetry period Five-year dosimetry period	50 100
Pregnant nuclear energy worker	Balance of the pregnancy (after the licensee is informed of the pregnancy)	4
A person who is not a nuclear energy worker	One calendar year	1

To assist in the assessment of the NEW doses, Derived Working Limits (DWLs) are determined based on the annual dose limits (Health Canada 2011). The guideline implicitly accounts for the presence of radon decay products (radon progeny), which are responsible for virtually all the dose and risk of exposure to radon.

The radon criterion for NEWs adopted for this study is a DWL of 200 Bq/m^3 (Health Canada 2011), corresponding to the unrestricted classification (upper limit). This criterion is used for this study to determine if radiation monitoring and specific action levels are required for radon during construction and operation of the DGR.

1.4 Analysis Approach

The methodology used to assess the potential hazard due to radon for both workers and the public is outlined in Figure 1.1. The approach comprises the following basic steps, with each step described in detail in subsequent sections of this report:

- The context of the assessment is defined, including a description of the study objectives (Section 1.1), background information on radon (Section 1.2), the regulatory context and criteria (Section 1.3), and the treatment of uncertainties (Section 1.5).
- Key input data is compiled, including current information on the conceptual design of the various surface handling facilities and underground repository (Section 2), information on the radon concentration in the used fuel (Section 3.5), and information on the properties of the host rock (Section 4.1).
- The methodology is developed for calculation of radon concentration at various locations of interest, including radon concentration in the underground repository, in the Used Fuel Packaging Plant (UFPP), and adjacent to the waste rock pile (Section 3).
- The results are analyzed, interpreted and compared with dose criteria and the natural background radon concentration to inform on the performance of the system, and the nature and role of key uncertainties (Sections 4, 5, and 6).

1.5 Treatment of uncertainties

Uncertainties are addressed through the adoption of conservative scenarios, models and data.

Conservative assumptions have been incorporated into this analysis in the source term parameters. Radon emanation coefficients used in this analysis are selected to be conservative. Values are selected based on the average of experimental data for similar rock types. Diffusion coefficients are also calculated to be conservative. In particular, the effective diffusion coefficient for radon in the host rock is calculated assuming that the rock surfaces in the DGR are completely dewatered (i.e., saturation is 0%), resulting in a higher value compared to saturated or partially saturated host rock. Finally, ventilation rates used in this analysis are selected to be conservative. Values are selected based on the lower end of the range of planned ventilation rates, as this will provide the highest calculated radon concentrations.

Conservative values have also been incorporated into the calculation of Atmospheric Dispersion Factor (ADF)s. ADFs used for this assessment are based on long-term average values resulting from a continuous release at a generic site (Canadian Standards Association (CSA) 2014 and references therein). The uncertainties of using generic site ADF values are addressed by utilizing conservative default values for this analysis. The frequencies assumed for Classes E and F are generally representative of conditions in Canada, but Class D is overestimated and the unstable classes (A, B, and C) are underestimated (CSA 2014). Assuming a more stable atmospheric condition is conservative in this study, because downwind radionuclide concentrations are highest when the atmosphere is highly stable. As well, the ADFs are calculated conservatively neglecting plume depletion processes, such as dry and wet deposition, and buoyancy and momentum of the effluent, which would increase the effective stack height due to the heat content of the plume or the vertical momentum of the release.

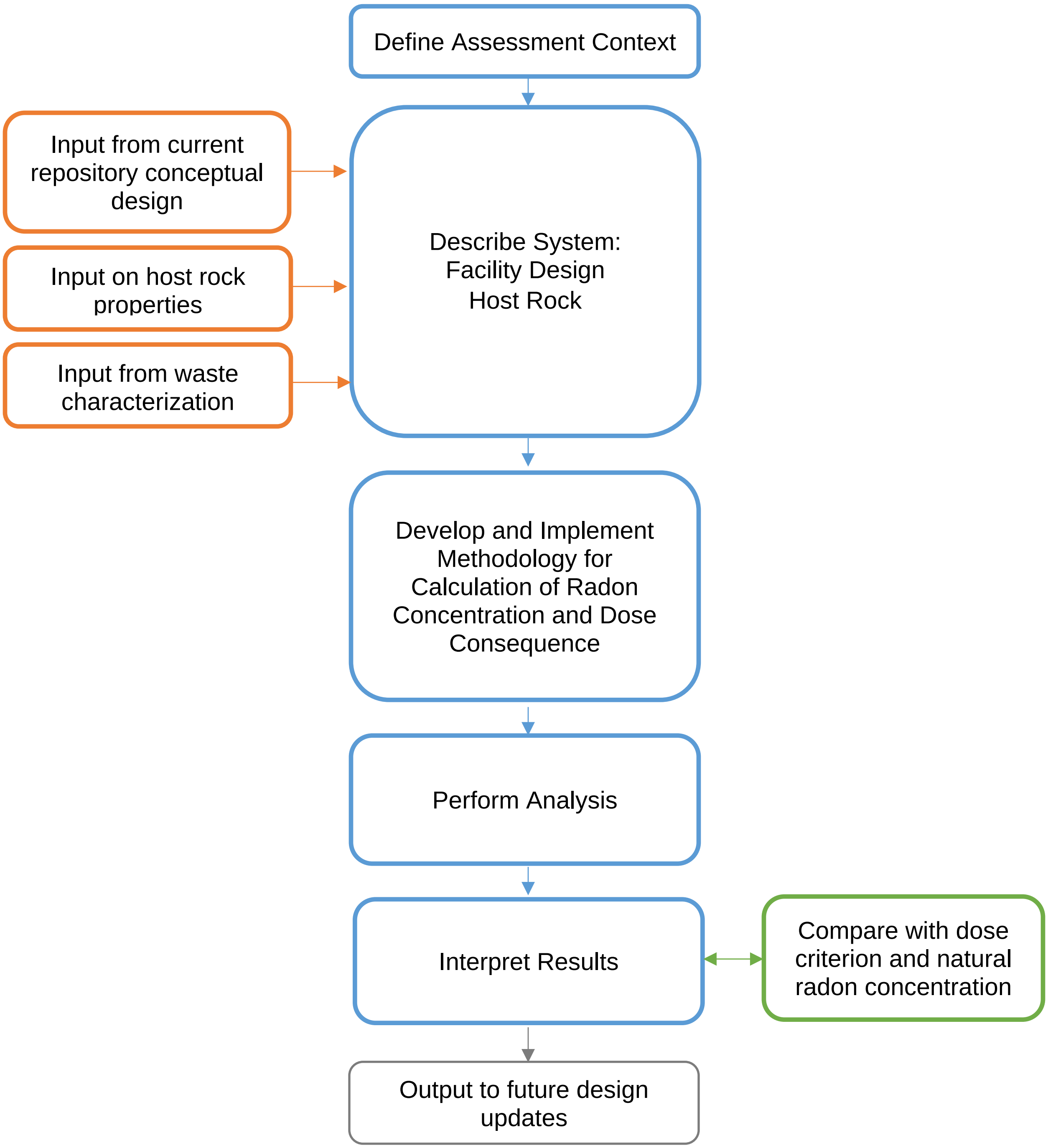

Figure 1.1: Approach used in the Preliminary Radon Assessment Analysis

2. APM FACILITY CONCEPTUAL DESIGN

The APM conceptual design consists of various surface handling facilities and an underground repository (Noronha 2016). The underground DGR is located approximately 500 m underground in a hypothetical generic geology – crystalline rock or sedimentary rock. The reference used fuel container is a copper coated steel container handling 48 used fuel bundles. The underground engineered barrier system (EBS) is illustrated in Figure 2.1.

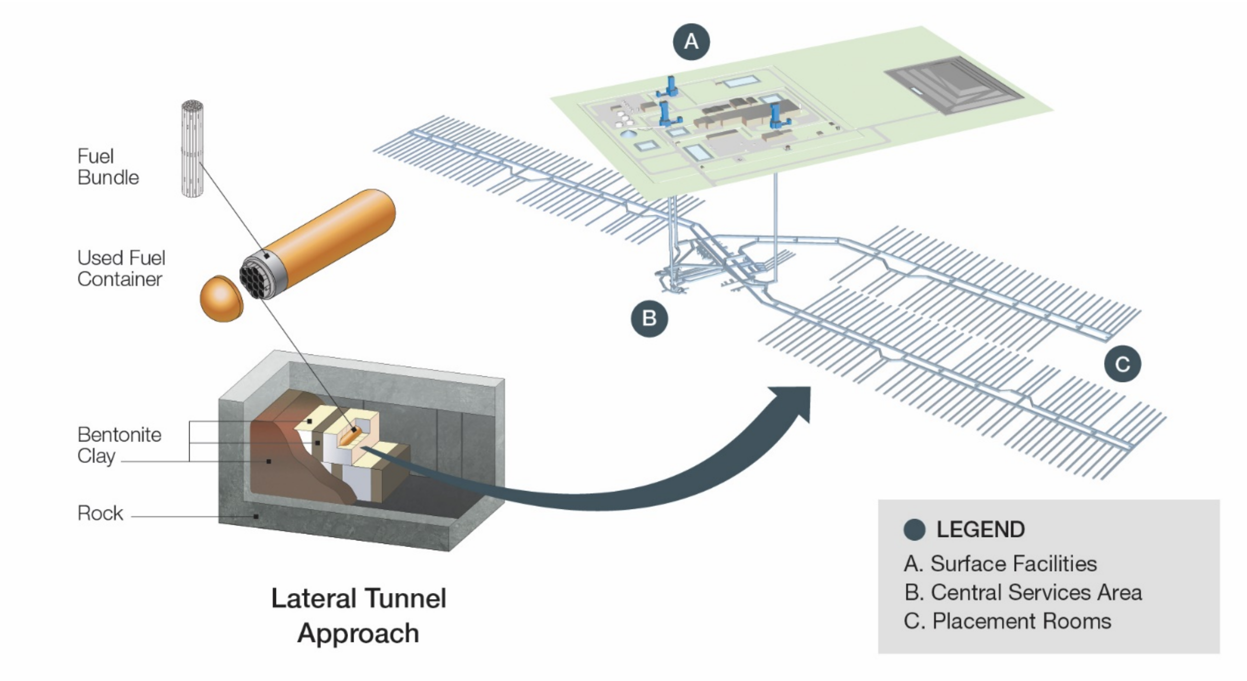

Figure 2.1: Schematic Illustration of the APM Conceptual Design in Crystalline Rock

2.1 Surface Facilities

The surface facilities include a Used Fuel Packaging Plant (UFPP); shaft headframes and hoists; underground ventilation systems; engineered seal fabrication plant; water treatment; ancillary facilities such as emergency backup power; and an excavated rock management area. The key surface facilities are shown in Figure 2.2.

For security purposes, part of the surface facilities will have restricted access. This restricted area includes the UFPP, Main Shaft complex, Service Shaft complex and Ventilation Shaft complex. Other surface areas would be outside the restricted area (also called the Protected Area), but within the overall fenceline of the surface facility.

From a radiological safety perspective, the main surface facility structure is the UFPP, as this is where the used fuel is handled. In the UFPP, the transport packages will be received carrying used fuel from interim storage locations to this site. These used fuel transportation packages (UFTPs) are opened, and the used fuel is removed and re-packaged it into long-lived containers (UFC) for placement in the repository. The UFPP is planned as a ground level building, in which repackaging of the used nuclear fuel will occur on the main level, and UFTP handling and UFC dispatch operations will occur in the basement level.

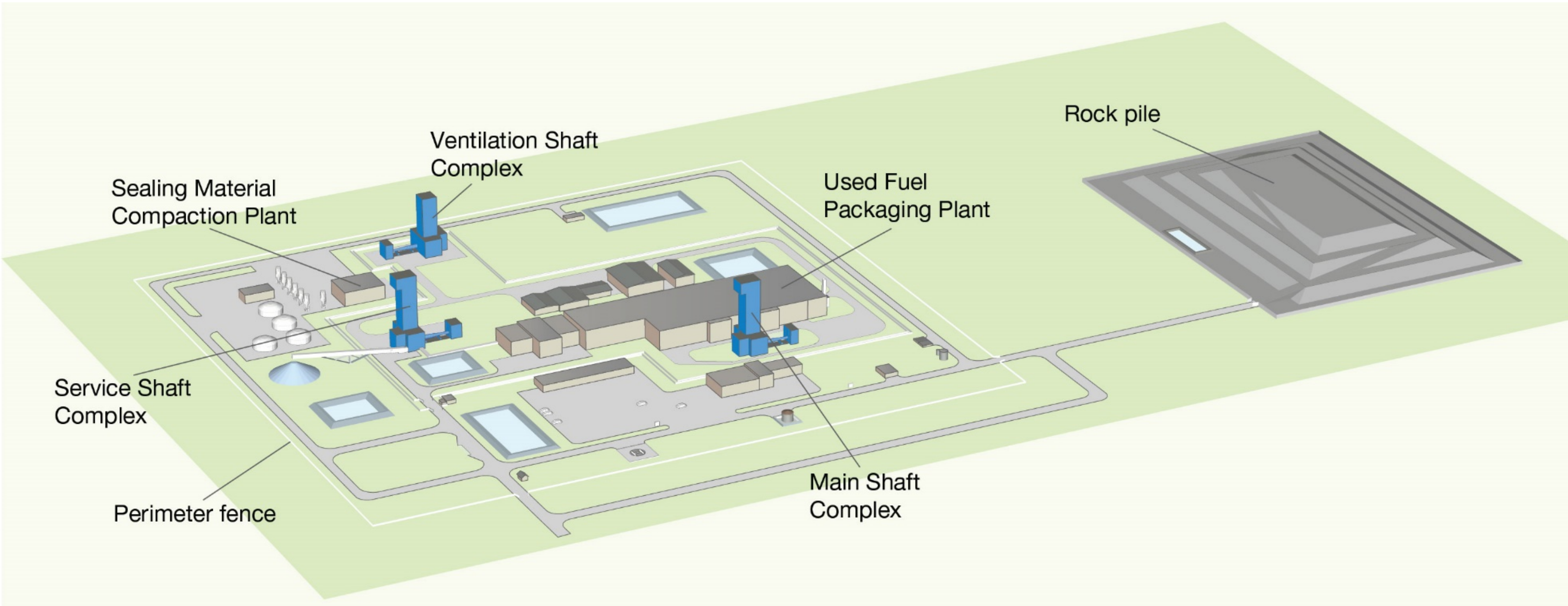

Figure 2.2: Key APM Surface Facilities

2.2 Waste Rock Pile

The Excavated Rock Management Area (ERMA) is located off-site and is required for both construction and long term support for the DGR. An area of approximately 20 ha will be required to develop the ERMA. The ERMA is shown in Figure 2.2. The ERMA Storm Water Management Pond is adjacent to the waste rock pile.

The estimated quantities of excavated materials are shown in Table 2.1 for both the sedimentary and crystalline host rock sites. The bulked rock quantity assumes a rock swell factor of 40%.

Table 2.1: Estimated Quantities of Excavated Materials

Location	Rock Quantity (in situ) (m^3)	Rock Quantity (Bulked) (m^3)
Crystalline Host Rock Site	1,640,000	2,290,000
Sedimentary Host Rock Site	1,660,000	2,330,000

For the purpose of this assessment, it is assumed that the waste rock pile is a rectangle shaped, flat-top pile. The final design will be site specific. For this assessment, it is assumed that the waste rock pile will be 15 m tall with a footprint of 500 m x 405 m for both host rock sites, with a capacity of 2.5×10^6 m^3.

2.3 Underground Facility Design

The underground facilities are comprised of the following two main areas: a) the underground services area; and b) the placement area.

The underground services area would provide a range of facilities to support DGR operations. Such facilities include:

- Underground Demonstration Facility
- Refuge stations, offices, and washrooms;
- Maintenance shop and warehouse;
- Battery charging station (for battery-powered forklifts for placing buffer boxes);
- Underground diesel fuelling station and equipment / material storage areas;
- Explosives and detonators magazines;
- Main electrical substation; and
- Truck dump equipped with grizzly and rockbreaker.

The basic arrangement of the placement area involves a series of parallel, dead-end placement rooms, organized into panels. The in-room placement of the buffer boxes containing the UFCs will involve a two-high stacking arrangement of the boxes. The rows of boxes will be separated by spacer blocks. The buffer boxes will be placed in a retreating arrangement within the placement room with any remaining voids backfilled with loose bentonite pellets. A schematic illustration of a filled placement room is given in Figure 2.3. Nominal dimensions of the facility from the conceptual design report (Norohna 2016) are described below.

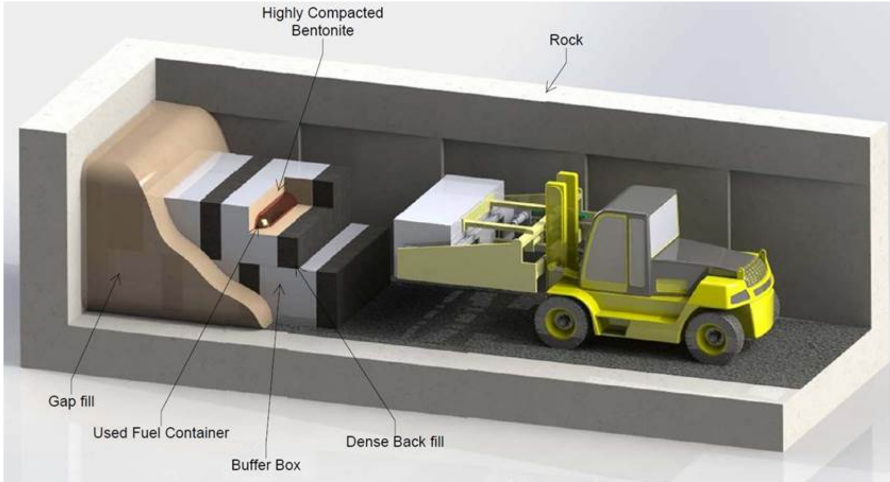

Figure 2.3: Illustration of Placement Room

In the Central Services Area, main access tunnels will have dimensions of 9 m wide by 4 m tall. Service access tunnels and ramps will have dimensions of 5 m wide by 5 m tall. Infrastructure excavations will have large headings which vary in size.

The conceptual design has approximately 270 placement rooms arranged in 8 panels, with each placement room being approximately 300 m long (with a width of 3.2 m and a height of 2.2 m). The access tunnels which extend from the central services area will have a width of 9 m and a height of 4 m, and the cross cuts between the access tunnels will have a width of 5 m and a height of 5 m.

The surface areas and volume of the repository central services area, placement rooms, and placement room access tunnels are presented in Table 2.2. These surface areas include the walls, floor and ceiling of the repository.

Table 2.2: Repository Surface Area and Volume

Location	Surface Area (m^2)	Volume (m^3)
Central Services Area	1.6E+05	2.1E+05
North Arm	1.0E+05	1.4E+05
West Arm	1.1E+05	1.5E+05
South Arm	6.0E+04	8.2E+04
Panel 1	1.0E+05	6.5E+04
Panel 2	1.0E+05	6.7E+04
Panel 3	8.3E+04	5.4E+04
Panel 4	8.0E+04	5.2E+04
Panel 5	1.2E+05	7.7E+04
Panel 6	1.3E+05	8.2E+04
Panel 7	1.3E+05	8.5E+04
Panel 8	1.5E+05	9.8E+04

2.4 Construction and Operations Summary

2.4.1 Construction

The construction approach for the repository is outlined in Noronha (2016).

All excavations associated with the repository will be carried out by drilling and controlled blasting techniques. Blasting operations include drilling holes in a converging pattern, placing an explosive and detonator in each hole, detonating the charge, and removing or excavating the excavated rock. Between the blasting cycles, fumes are vented, scaling is undertaken to remove loose rock, ground support is applied as required, and the next round of blasting is surveyed. Typical standard drill and blast practices result in a rate of advance in the range of 5 m to 15 m per day based on one crew working multiple headings. A typical drill and blast cycle is shown in Figure 2.4.

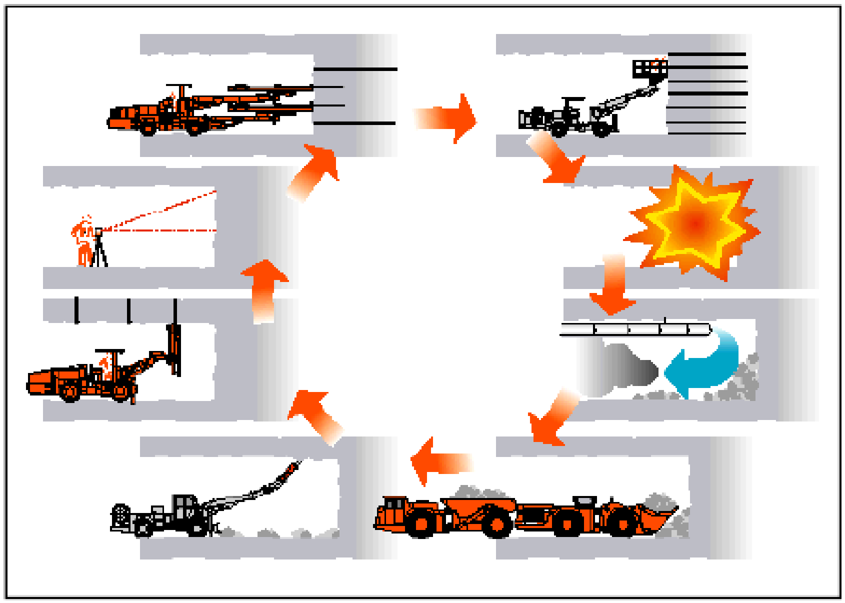

Figure 2.4: Typical Drill and Blast Excavation Cycle

Excavation will begin with the Service and Exhaust Ventilation shafts, followed by the main shaft. Lateral development will begin with the central services area, including the underground demonstration facility (UDF), and then continue with the excavation of the twin access tunnels for the placement room panels.

In the present analysis, the radon concentration is calculated after the flow-through ventilation has been established (i.e., after the service and exhaust shafts have been connected and equipped). Radon concentrations during shaft sinking are not expected to be significant due to the low uranium content of the rock, the limited amount of rock exposed, and the high ventilation rates associated with the shaft sinking work.

Lateral development will have a progressive build-up of equipment as space becomes available. As well, development will occur on multiple development headings in order to optimize the advance rates. For the majority of the lateral development schedule in the central services area, there will be a minimum of 5 development headings, with 2 to 3 headings advanced per day. The estimated advancement rates during lateral development are summarized in Table 2.3.

Table 2.3: Summary of Advancement Rates during DGR Lateral Development

Type	Ramp-Up		Maximum						Ramp-Down			No Development		Operations		
Time Period	2036	2037		2038		2039		2040		2041		2042		2043		2044
	H2	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2	H1	H2	H1
Advancement Rate (m/day)	8.4[A]	8.8[A]	12.8[A]	11.5[A] 2.2[B]	10.4[A] 2.2[B]	10.3[A]	10.3[A] 12.1[B]	10.3[A] 15.6[B]	7.9[A] 17.7[B]	6.9[A] 9.3[B]	2.6[A] 4.4[B]			7.0[B]	7.0[B]	7.0[B]
Number of Headings	4.0[A]	4.8[A]	7.5[A]	6.7[A] 0.4[B]	6.1[A] 0.4[B]	6.0[A]	6.0[A] 1.2[B]	6.0[A] 1.0[B]	4.6[A] 1.4[B]	4.0[A] 0.6[B]	1.5[A] 0.7[B]					

[A] Access or large type headings.
[B] Placement rooms or panels.

2.4.2 Operations

During the operations phase, there will be concurrent construction and placement activities. Placement of buffer boxes in placement rooms will be occurring in one panel, while additional placement rooms are being excavated in another panel. Development of all placement rooms would be completed before buffer box placement operations are commenced in a panel.

The development of the placement rooms is planned to approximately match the rate at which the rooms are filled. The filling rate has been assumed to be 2,500 UFCs/year, which equates to the development rate of 7.0 m/day. It is assumed that the repository will operate 250 days per year (or approximately 5 days per week). The estimated advancement rates for development the placement rooms during the operations phase are summarized in Table 2.3.

2.5 Preliminary Ventilation System Design

2.5.1 Ventilation during Construction

The total volume of air supplied to the repository will be periodically adjusted throughout the life cycle of the facility based on the nature of work being performed. During the initial off-shaft development activities, fresh air will flow down the Exhaust Ventilation and Service Shafts via ducting systems and return to surface through the access tunnels and shafts. Once the Exhaust Ventilation Shaft and Service Shaft have been connected, airflow will be provided by the Service Shaft, and exhausted up the Exhaust Ventilation Shaft. Auxiliary fans and steel ducting will be used to push the air into development headings during lateral development. Permanent configuration of the Main Shaft will be completed at the end of 2037, after which a portion of the airflow will be exhausted up the Main Shaft.

The airflow rate in the Exhaust Ventilation Shaft is variable depending on the activities occurring in the repository. The airflow rate through the Ventilation Shaft during construction will range from 169-421 m^3/s. Once connected, the volumetric flowrate of the ventilation exhaust is 15 m^3/s in the Main Shaft, and is not planned to be variable during the construction phase of the DGR.

2.5.2 UFPP Ventilation during Operations

In the UFPP, the ventilation system is divided into four separate exhaust systems for each of the four zoned areas.

Ventilation exhausts for the Zone 1 and 2 areas are not HEPA filtered. The primary exhaust will be released through vents on UFPP roof. However, air from the Zone 1 area can also be released through ground- or basement- level doors especially during UFTP arrival via truck or train.

Ventilation exhaust from the Zone 3 and 4 areas is released through a stack on top of the UFPP. Exhaust from these areas are continuously HEPA filtered. After any filtering or monitoring, air is released to the atmosphere. The height of each stack is assumed to be 3 m, on top of the height of the UFPP, which is nominally 6 m high. The assumed dimensions of the Zone 3 and Zone 4 UFPP stacks are shown in Table 2.4.

In all areas of the UFPP, the ventilation rate is assumed to be 4 air turnovers per hour. Volumetric flowrates in various areas of the UFPP can be calculated based on the dimensions of the UFPP conceptual design, and the turnover rate of 4 per hour.

Table 2.4: Assumed Nominal Dimensions of Ventilation System for UFPP

Location	UFPP Zone 4 Building Exhaust	UFPP Zone 3 Building Exhaust
Release Orientation	Vertical	Vertical
Release Height	9 m [A]	9 m [A]
Exit Velocity	11.4 m/s [B]	11.4 m/s [B]
Volumetric Flowrate	6.8 m^3/s [C]	47.5 m^3/s [C]

[A] Based on the UFPP height of 6 m plus stack height of 3 m.

[B] Based on design of the ventilation system for the Pickering B Irradiated Fuel Bay.

[C] Based on 4 air turnovers per hour in the UFPP Zone 4 volume of 6,080 m^3 or the UFPP Zone 3 volume of 42,775 m^3.

2.5.3 Repository Ventilation during Operations

Three primary airways are used to ventilate the repository. The Service Shaft constitutes a dedicated fresh air passage. It is used for movement of workers and supplies underground. The primary exhaust air passage is via the Ventilation Shaft, with a smaller amount of air exhaust via the Main Shaft. Waste packages are moved via the Main Shaft; the small air flow up this shaft ensures that any surface contamination on the packages is not blown down and through the repository. A series of surface fans and underground booster fans will be required to achieve the design air flow distribution in the underground repository. Auxiliary fans and ducting that are located in the underground tunnels and rooms will direct airflow into active placement rooms.

Ventilation exhaust from both the Main and Ventilation Shaft are assumed to be vertically oriented, with an assumed release height of 15 m. The airflow rate in the Exhaust Ventilation Shaft is variable depending on the activities occurring in the repository. The airflow rate through the Ventilation Shaft during operations will range from 154-195 m^3/s. In the event of fire, the airflow rate in the Exhaust Ventilation Shaft to mitigate fire roll-back in one placement arm vent circuit could be increased to 262 m^3/s. The volumetric flowrate of the ventilation exhaust is 15 m^3/s in the Main Shaft, and is not planned to be variable during the operation of the DGR. The assumed dimensions of the Ventilation Shaft and Main Shaft exhaust stacks are shown in Table 2.5.

Table 2.5: Assumed Nominal Dimensions of Ventilation Shaft and Main Shaft Exhaust

Location	**Ventilation Shaft Exhaust**	**Main Shaft Exhaust**
Release Orientation	Vertical	Vertical
Release Height	15 m	15 m
Exit Velocity	30 m/s [A]	30 m/s [A]
Volumetric Flowrate	154 - 262 m^3/s [B]	15 m^3/s [C]

[A] Based on design of an underground mine in the Great Lakes region.

[B] Based on a preliminary underground ventilation study, volumetric flow will be in the range of 154 to 195 m^3/s.The ventilation flowrate could be increaesd to 262 m^3/s to mitigate fire roll-back in one placement arm vent circuit. Flow will not be reduced in the event of ventilation exhaust being HEPA filtered.

[C] Based on a preliminary underground ventilation study.

During placement activities, the ventilation airflow is planned to keep the greatest number of workers in fresh air. Activities requiring the greatest number of placement workers (such as room preparations) would occur in the freshest air, with more remote controlled activities (such as UFC placement) and activities requiring a fewer number of workers (such as bentonite seal and concrete bulkhead construction) downwind of these activities.

The airflow rate through each arm will range from 18 - 55 m^3/s, with a minimum airflow velocity of 0.5 m/s for all access tunnels and occupied placement rooms. It is planned that ventilation air flow will be kept separate between the panels in which placement and development activities are occurring.

3. RADON EXPOSURE PATHWAYS

In order to assess the potential radon hazard in the DGR, both the construction phase and operations phase of the DGR are examined.

3.1 Natural Radon Concentration at Site

Site specific measurements of the background radon levels will be collected as part of the site-specific baseline monitoring program. This will provide a background level, to which further releases would add.

Radon concentration in outdoor air in cities across Canada has been previously measured (Grasty 1994), and the three-month summer average radon concentration ranged from 5 to 103 Bq/m^3. In Ontario, the average radon concentration was measured in 4 cities: Ottawa, Toronto, Thunder Bay and Sudbury. The three-month average outdoor radon concentration in Ontario was measured at 12 Bq/m^3.

3.2 Radon Concentration during Construction

During construction, natural radon is released from the underground host rock at the working face as a result of drilling, and by diffusion into the already excavated areas. This host rock radon would have normally decayed before reaching surface in the absence of a repository, but is released into the underground area and ventilated to surface where it adds to the natural level.

The rate of radon release is dependent on the emanation rate of radon from the rock and the rate of excavation of the DGR. For the following calculation, it is assumed that all radon inside the pores of the rock is released during drilling. As well, radon emanates into the excavation volume from the surrounding host rock and from the temporary waste rock pile inside the DGR.

The increased concentration of radon (relative to background) in the ventilation air leaving the DGR (C_i) can be estimated as a function of time according to Equation 3.1:

$$C_i(t) = \frac{\left(E \cdot SA_{walls} + E \cdot SA_{waste\ rock} + C_{pore\ space} \cdot V_R \cdot \phi\right)\left(1 - e^{\left(-(\lambda_{Rn}+\lambda_v)(t_i - t_{i-1})\right)}\right)}{V_{rep}(\lambda_{Rn}+\lambda_v)} + C_{i-1} e^{\left(-(\lambda_{Rn}+\lambda_v)(t_i - t_{i-1})\right)} \quad (3.1)$$

where (t_i-t_{i-1}) represents a time step over which the concentration change is calculated (s), E is the radon emanation rate from the rock (Bq/m^{2}s), SA is the surface area of the underground repository or the waste rock (m^2), $C_{pore\ space}$ is the concentration of radon in the host rock pore space (Bq/m^3), V_{rep} is the total excavated volume of the DGR at time t_i (m^3), V_R is the volume of rock excavated during time (t_i-t_{i-1}) (m^3/s), ϕ is the host rock porosity, λ_{Rn} is the Rn-222 decay rate (1/s), and λ_v is the ventilation rate (1/s). The derivation of this equation can be seen in Appendix B.

3.3 Radon Concentration near Above-Ground Waste Rock Pile

To assess the potential impact of radon on workers in the vicinity of the surface waste rock pile, the concentration of radon in an atmospheric compartment near the waste rock pile is considered. Two potential worker locations are analyzed: directly above the waste rock pile and down-wind of the waste rock pile. These locations contain the highest concentrations of radon.

For the case of a worker standing on top of the waste rock pile, radon enters the atmospheric compartment by radon emanation from the top of the waste rock pile, and leaves by decay and wind transport.

The increased concentration of radon (relative to background) in the atmospheric compartment above the pile (C_{top}) can be estimated according to Equation 3.2:

$$C_{top} = \frac{E\ SA_1}{V_{wind}SA_2 + \lambda_{Rn}V_C} \tag{3.2}$$

where SA_1 represents the surface area of the top of the waste rock pile (through which radon emanates) (m^2), V_{wind} represents the average wind velocity at the site (m/s), SA_2 represents the surface area of the compartment perpendicular to the direction of wind flow (m^2), and V_c represents the volume of the atmospheric compartment (m^3). The derivation of this equation can be found in Appendix C.

For the case of a worker standing near but down-wind of the waste rock pile, radon enters the atmospheric compartment by radon emanation from the waste rock pile and is carried downwind in the air flowing over the top of the waste rock pile. Radon leaves by decay and wind transport.

The increased concentration of radon (relative to background) in the atmospheric compartment downwind of the pile ($C_{downwind}$) can be estimated according to Equation 3.3:

$$C_{downwind} = \frac{E\ SA_3 + fV_{wind}SA_4C_{top}}{fV_{wind}SA_4 + \lambda_{Rn}V_C} \tag{3.3}$$

where SA_3 represents the surface area of the slope of the waste rock pile (through which radon emanates) (m^2), f is a factor which accounts for the wake region on the down-wind side of a pile and only a fraction of the upwind airflow proceeds into this compartment (-), SA_4 represents the surface area of the compartment perpendicular to the direction of wind flow (m^2), and C_{top} represents the concentration of radon in wind entering the compartment (as calculated for the atmospheric compartment above the waste rock pile) (Bq/m^3). The derivation of this equation can be found in Appendix D.

3.4 Radon Released through Waste Rock Pile Water

Water infiltrating through the above-ground waste rock pile following precipitation events may leach radium or radon from the rock. The composition of seepage water from a waste rock pile and its rate of discharge depend on a variety of factors, including the local climatic conditions, composition of the waste rock, and hydraulic properties of the pile. Typically, waste rock piles show significant variability of mineralogy, particle size, and porosity, with strong variations of hydrogeological and geochemical properties (Fala 2011). As such, the water distribution and flow systems within a waste rock pile are complex. Further, the chemical composition of water released from mine waste is strongly controlled by the residence time of the water within the medium (Trinchero et al. 2011).

Under normal temperature and pressure conditions, the solubility of radium and radon in water are low. As such, the concentration of radium or radon in water which has flowed through the waste rock pile, and the resulting radon release into surrounding air from this pathway, are expected to be very low. For example, analysis of leachate from waste rock from uranium mines in Colorado and Utah (Energy Fuels Resources (USA) Inc. 2014) indicates that the Ra-226 concentration ranged from <0.0074 Bq/L for waste rock containing 2.7-10.9 ppm uranium to

0.20 Bq/L for waste rock containing 139 ppm uranium. It should be noted that this work was focussed on recovery of uranium by leaching, so is very conservative in that the sample is ground to a very fine size and totally saturated with solution. This test is not representative of typical waste rock piles where the material is of coarser texture, unsaturated and compacted by haulage trucks. Given that the waste rock from the repository will contain less than 10 ppm uranium for both crystalline and sedimentary host rocks (which will be discussed further in Section 4.1 and Table 4.1), this data indicates that the estimated Ra-226 from the waste rock pile seepage water will be less than 0.0074 Bq/L. Overall, this source of radon release into the atmosphere surrounding the waste rock pile (i.e., via water leachate) is expected to be negligible, and will not be considered further.

Further, when calculating the radon released into the air surrounding the waste rock pile, it is conservative to assume that the waste rock pile is unsaturated. Saturation of the waste rock pile would reduce the radon emanation rate, as water would block the pores and slow the release of radon.

3.5 Radon Release from Used Fuel during UFPP Operations

In the UFPP, the transport packages will be received carrying used fuel from interim storage locations to this site. These used fuel transportation packages (UFTP) are opened, and the used fuel is removed and re-packaged it into long-lived containers (UFC) for placement in the repository.

Radon, which is generated from the decay of uranium in the fuel, can be released during handling operations in the UFPP. The two main sources of radon release in the UFPP are:

- Radon release from fuel bundles which are breached during transportation, and then are released into the UFPP upon opening of the UFTP; and
- Radon release from fuel bundles which are breached during handling in the UFPP.

Other potential sources of radon release from the used fuel include release from fuel bundles which were previously breached during reactor operation, wet storage or dry storage, surface deposits on the fuel bundle, and Zircaloy sheath surface corrosion.

For fuel bundles which were previously breached during irradiation or storage at the reactor sites, the radon release at the UFPP is expected to be negligible. First, fuel bundles which breached during reactor operation or wet storage will be identified and overpacked (or canned) prior to shipment to the UFPP. Second, fuel elements which failed at the reactor site would have released all available gases at that time. Therefore, the only radon source is from the slow decay of uranium in previously breached but uncanned bundles. This source of radon will be negligible, particularly relative to the conservative release from fuel bundle failure in the UFTP or UFPP, and is not considered further.

Intact fuel bundles normally have surface deposits of corrosion products carried by the primary heat transport system. The bundle surfaces also contain deposits of fission products, actinides and activation products that have escaped from the failed fuel elements to the primary heat transport system during reactor operation or the irradiated fuel bay. Radon released due to uranium deposits present on the surface of the used fuel bundles is expected to be a minor source of radon, given that radon is further down the uranium decay chain and the small amounts of uranium in these deposits.

The fuel element cladding itself also contains neutron activation products which, although they are fixed in the Zircaloy matrix, are potential sources of contamination, can be released by corrosion of the cladding. Radon may be produced by uranium in the Zircaloy. However, the amount will be trivial due to the small amount of uranium in the Zircaloy cladding, and the long half-life of uranium.

The release rate of radon from breach of a fuel bundle is calculated as:

$$Q = (IF_j / N_E) \times (f_H + f_T) \times f_E \times f_S \times N_H \qquad (3.5)$$

Where:

IF_j = Inventory of radionuclide j in a used fuel bundle (Bq/bundle)
N_E = Number of elements in a bundle (elements/bundle)
f_H = Fraction of fuel bundles failed arisen from handling at UFPP (-). It is assumed that one element of a failed fuel bundle fails.
f_T = Fraction of fuel bundles failed during transport in the UFTP (-). It is assumed that one element of a failed fuel bundle fails.
f_E = Fraction of the total element inventory which escapes the cladding when a fuel element ruptures (-)
f_S = Fraction of release from fuel element which is sufficiently small to remain in suspension in air (-)
N_H = Number of bundles handled at UFPP per year (bundles/year)

It is assumed that one fuel element fails in a bundle. The inputs to the source term for radon release from a failed fuel element are given in Table 3.1.

3.6 Radon Concentration during Repository Operations

The radon concentration in the DGR is dependent on the emanation rate of radon from the host rock and the used fuel, the ventilation rate, and the surface area and volume of the DGR. Radon enters the DGR by emanation from the host rock and the used fuel. It is removed by ventilation and decay.

The radon dose to workers in the DGR during the operations phase is estimated by calculating the radon concentration in the underground tunnels where workers are present. As well, the radon build-up in an empty and unventilated emplacement room is considered.

The radon concentration in the Ventilation Shaft and the radon release from the Ventilation Shaft is calculated in order to assess the public exposure to radon and the dose to a worker performing Ventilation Shaft inspections and maintenance.

Table 3.1: Inputs to Source Term for Radon Assessment

Parameter	Value	Basis
IF_j	7.14E+02 Bq/bundle	Rn-222 inventory in discharged (220/30) fuel is 22 Bq/kgU. An additional 10 years of Rn-222 build-up is assumed to account for the time between the bundle manufacture date and in-service date. During this time, Rn-222 would build-up from the decay of U-238. The combined Rn-222 concentration is 37 Bq/kgU.
f_H	0.005	The bundle defect failure rate is 0.1 per 1000 discharged bundles during reactor service, or 0.01%. The fuel bundle failure rate during handling at the UFPP is assumed to be 0.5%. This is an assumption, allowing for uncertainty in extent of fuel sheath degradation during interim storage period.
f_T	0.005	A fuel bundle failure rate of 0.5% during transportation is assumed. This is an assumption, allowing for uncertainty in extent of fuel sheath degradation prior to shipping to the DGR. Various studies have shown that fuel failure is not expected to be significant during transportation under normal operating conditions. This is also supported by experience transporting used CANDU fuel.
.f_E	0.09	The fractional quantity of release for gases is the free inventory fraction plus an estimated 10 percent of the grain boundary inventory. For Kr-85, the fractional release is 9%, based on a free inventory fraction of 8.63% and a grain boundary inventory fraction of 4.1% (Batters et al. 2012). The same fractional inventories are assumed for radon as it is also chemically an inert gas.
f_S	1	Gas remains in atmosphere and does not settle.
N_H	120,000 bundles/year	Reference throughput of fuel for UFPP.
N_E	37 elements/fuel bundle	Reference fuel is Bruce 37 element fuel bundle.
Q	2.1E+03 Bq/year	Calculated per Equation 3.5 for Rn-222 for 220/30 fuel

3.6.1 Radon Concentration as a Function of Repository Location

The radon level in the DGR varies depending on location. Air entering through the service shaft has a low concentration of radon (due to naturally occurring radon present at surface). As air travels from the service shaft, through the repository and out the ventilation (or main) shaft, radon builds up due to the radon released from the underground rock.

The radon concentration as a function of location can be estimated by treating the DGR as one long tunnel. The increased radon concentration (relative to background) can be calculated from Equation 3.6.

$$C_i(x) = \frac{E\cdot(2w+2h)\left(1-e^{\left(-\frac{\lambda_{Rn}wh}{\dot{V}}(x_i-x_{i-1})\right)}\right)}{\lambda_{Rn}wh} + C_{i-1}e^{\left(-\frac{\lambda_{Rn}wh}{\dot{V}}(x_i-x_{i-1})\right)} \quad (3.6)$$

where (x_i-x_{i-1}) represents the iteration interval (a distance) over which the radon concentration change is calculated (m), $\dot{V}$ is the volumetric flow rate through the DGR (m^3/s), w is the width of the tunnel (representing the DGR) (m), and h is the height of the tunnel (m). Details of this derivation are shown in Appendix E.

3.6.2 Radon Concentration as a Function of Time

The radon concentration in the repository will vary as a function of time. During the operations phase, there will be concurrent construction and placement activities, as described in Section 2.4.2. As such, the open volume in the repository will change over time, increasing due to excavation activities and decreasing due to placement activities.

The radon concentration in the Ventilation or Main Shaft as a function of time can be estimated from Equation 3.1. From this equation, the rate of radon release is dependent on the emanation rate of radon from the rock and the rate of excavation of the DGR. As well, radon emanates into the excavation volume from the surrounding host rock and from the temporary waste rock pile inside the DGR. The used nuclear fuel in the underground repository is inside welded containers, and as such there will be no radon emissions from the used fuel (i.e., R_w=0).

Air exiting the repository through the Main Shaft and the Ventilation Shaft will travel through different pathways and have different ventilation rates, and as such will contain different concentrations of radon. The radon concentration in these air pathways can be calculated separately using Equation 3.1.

As well, the increased concentration of radon (relative to background) in a placement room as a function of time (C_i) can be estimated according to:

$$C_i(t) = \left(\frac{E \cdot SA_{walls}}{V_{rep}} + R_w\right) \frac{\left(1 - e^{\left(-(\lambda_{Rn}+\lambda_v)(t_i - t_{i-1})\right)}\right)}{(\lambda_{Rn}+\lambda_v)} + C_{i-1} e^{\left(-(\lambda_{Rn}+\lambda_v)(t_i - t_{i-1})\right)} \tag{3.7}$$

where (t_i-t_{i-1}) represents a time step over which the concentration change is calculated (s), SA_{walls} is the surface area inside the placement room (m^2), V_{rep} is the excavated volume of the placement room (m^3) and R_w is the radon emissions from used fuel (Bq/m^3s). The details of derivation of this equation can be seen in Appendix F. Note that this does not take any credit for the effectiveness of flooring or wall shotcrete in reducing the diffusion rate of radon into the DGR. For calculation of the radon concentration in an empty placement room, the ventilation rate is set to 0 (λ_V=0). Furthermore, used fuel is handled and emplaced inside sealed containers; so there are no radon emissions from used fuel (i.e., R_w=0).

3.6.3 Radon in Repository Water

For the underground repository in crystalline or sedimentary rock, water percolating through the host rock will pick up radon from the radium or uranium in the host rock. On entry into the mine, the dissolved radon will be released due to agitation and lower pressure in the mine compared to the host rock pore spaces. The flow of water from the host rock into the mine could potentially bring in more radon than that from gaseous diffusion from the bulk rock in a dry mine (Sahu et al. 2016). However, studies have shown that the contribution of radon-rich groundwater to radon content in air in uranium mines is very low, less than 0.5% (Sahu et al. 2016). This is expected to be the case in the repository, as the rock will be selected because it has low porosity and low flow of groundwater.

It is therefore considered unlikely that water percolating into the repository will be a significant source of radon in the atmosphere, and will not be considered further. However, it is recommended radium or radon concentration in groundwater be measured for the selected site for the repository to confirm this assumption.

3.7 Receptor Characteristics

Worker and public exposure to radon are considered during the construction and operations of the DGR.

As described in Sections 3.2 and 3.3, worker exposure to radon during the construction phase is considered for the underground facilities and near the waste rock pile. As described in Sections 3.5 and 3.6, the radon dose to workers during the operations phase is estimated for workers in the UFPP, in the underground tunnels, and in the Ventilation Shaft (where workers may be present for shaft inspections and maintenance). For worker exposure, an occupational exposure of 2000 hours per year is assumed.

For public exposure, it is assumed that the receptor is in the direct plume path at the location of the maximum ADF. The maximum ADF represents a location downstream from the release point where the airborne concentration of radionuclides would be the highest. This location represents the maximally exposed receptor.

3.8 Dispersion Modelling for Radon Release

An ADF is used to provide an estimate of the amount of dispersion or dilution experienced by a contaminant released into the atmosphere, between the point of release and the public receptor location. ADFs are derived based on the Gaussian dispersion model described in CSA N288.1-14 (CSA 2014).

Long-term average ADF values resulting from a continuous release are calculated from the sector-averaged version of the Gaussian plume model (CSA 2014 and references therein), which assumes a laterally uniform concentration in each wind direction sector because of wind meander over prolonged periods of time.

Default ADF values for various effective release heights are shown in Figure A.1 of CSA N288.1-14 (CSA 2014) and reproduced in Figure 3.1. These ADF values assumed that:

- wind speed and the frequency of occurrence of stability class are independent of wind direction;
- wind speed is correlated with stability class;
- the wind rose is uniform, so that the wind blows into each sector with a probability of 6.25%;
- the release heights are effective release heights that include the effects of plume rise, downwash, and entrainment;
- the release is not subject to plume broadening due to building wake effects and undergoes no radioactive decay or build-up;
- the surface roughness length is 0.4 m corresponding to rural-area terrain; and
- the frequency of occurrence of the stability classes and the mean wind speed in each class are shown in Table 3.2 (Table A.1 from CSA 2014).

Table 3.2: Default Stability Class Frequencies and Mean Wind Speeds

Stability Class	Frequency of occurrence (%)	Mean wind speed (m/s)
A	1	1
B	6	2
C	10	5
D	56	5
E	10	3
F	17	2

Reference ADFs are summarized in Table 3.3. ADF values for the preliminary radon assessment are selected by taking the peak ADF value for a given release height based on Figure 3.1.

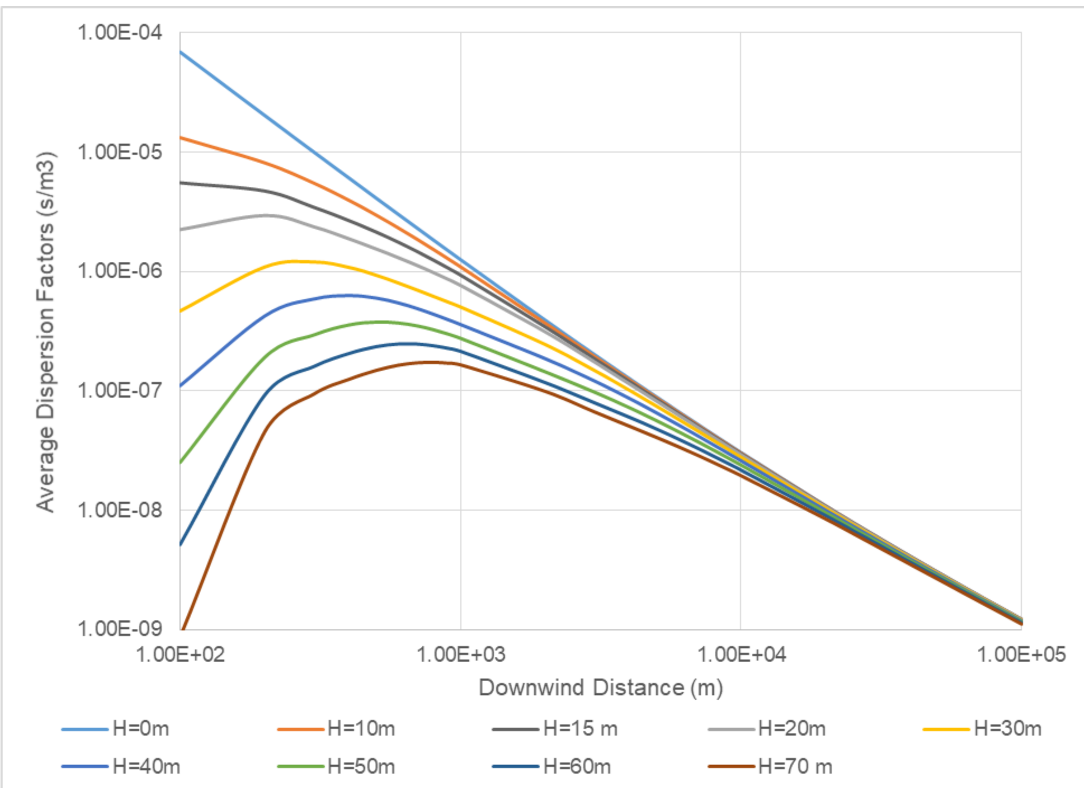

Figure 3.1: Default Atmospheric Dispersion Factors from CSA N288.1-14 (CSA 2014)

Table 3.3: ADFs for the Public

Location	Release Type	Effective Release Height (m)	ADF (s/m^3)	Distance from Release Location (m) [A,B]
UFPP	Zone 4 (filtered vertical stack release)	9	1.6E-05 [A]	100 [A,B]
			1.1E-06	1000
	Zone 3 (filtered vertical stack release)	9	1.6E-05 [A]	100 [A,B]
			1.1E-06	1000
Underground	Ventilation Shaft (filtered vertical stack release)	15	5.5E-06 [A]	100 [A,B]
			9.4E-07	1000
	Main Shaft (filtered vertical stack release)	15	5.5E-06 [A]	100 [A,B]
			9.4E-07	1000
Waste Rock Pile	Emissions from waste rock pile	15	5.5E-06 [A]	100 [A,B]
			9.4E-07	1000

[A] Peak ADF value from Figure 3.1.
[B] 100 m is the nearest distance evaluated.

The uncertainties of using a generic site ADF value are addressed by utilizing conservative default values for this analysis. As per CSA (2014), the frequencies assumed for Classes E and F in Table 3.2 are generally representative of conditions in Canada, but Class D is overestimated and the unstable classes (A, B, and C) are underestimated. A stable atmosphere will decrease dispersion, and increase the contaminant concentration. Underestimating the unstable classes is conservative, because an unstable atmosphere will increase dispersion, resulting in lower contaminant concentrations. In the future, site-specific radon assessment will be conducted. Consistent with CSA guidance, local meteorological data will be used to calculate site specific ADF values for those analysis, in place of the default values used here.

In order to apply the default values for long-term average ADFs from CSA (2014), the effective release height must first be calculated. The effective height H used in the Gaussian dispersion model is the physical stack height of the release point corrected for downwash, entrainment, buoyancy, and momentum rise.

Correction for downwash occurs when some of the emitted material from a stack is drawn downward into the low pressure region on the lee side of the stack. This effect is noticeable when the efflux velocity (w_o) is comparable to or smaller than the mean wind speed at the stack height. For the default values of ADFs supplied by CSA (2014), the mean wind speed for all stability classes (based on Table 3.2) is less than the efflux velocity of 11.4 m/s for the UFPP (Table 2.4) or 30 m/s for the main and Ventilation Shaft (Table 2.5). As such, downwash does not need to be considered.

Correction for entrainment occurs when the discharged effluent is entrained or caught in the aerodynamic cavity of the lee side of a nearby building. For the current assessment, it is assumed that there are no building wake effects. As such, entrainment does not need to be considered. This assumption should be reviewed when a final design is available for the surface facilities.

Correction for buoyancy and momentum increases the effective stack height due to the heat content of the plume or the vertical momentum of the release. For the current assessment, an increase in the effective release height due to momentum or buoyance is conservatively ignored.

Overall, the effective release height is assumed to be equal to the physical height of the stack (9 m for UFPP and 15 m for the Ventilation and Main Shafts as described in Table 2.4 and Table 2.5).

ADFs for the radon release from the waste rock pile are also estimated using the default ADF values from CSA N288.1-14 (CSA 2014). The effective release height is taken to be the height of the waste rock pile (15 m, as discussed in Section 2.2).

3.9 Preliminary Dose Calculations

As per the Canadian Guidelines for Management of NORM (Health Canada 2011), a radon concentration of approximately 200 Bq/m^3 is equivalent to a radon progeny concentration of 0.25 WLM and gives a dose of 1.4 mSv/a, based on occupational exposure (2000 hours per year). The dose to a worker in the UFPP, in the vicinity of the waste rock pile or in the underground repository, is estimated by scaling with the annual radiation dose from Health Canada (2011) based on the calculated concentration of radon in a given location.

For dispersion outside UFPP or from the underground exhausts, the average emission rate of radionuclide *i* (source term ventilated out or released at certain rate) is multiplied by the ADF to estimate the air concentrations at the location of public receptors due to emissions from the UFPP and DGR:

$$C_P^i = ER^i \times ADF \tag{3.8}$$

where:

C_P^i = Air concentration of respirable radionuclide *i* near public receptor (Bq/m^3)

ER^i = Average emission rate of radionuclide *i* (Bq/s)

ADF = Atmospheric dispersion factor (s/m^3)

The average radon concentration near the public receptor will be collected as part of the site specific baseline monitoring program. For the current calculations, radon concentrations for a public receptor can be compared to the average radon concentration in Ontario of 12 Bq/m^3 (as described in Section 3.1).

To calculate the dose to a public receptor, a dose coefficient of 6.7 x 10^{-6} (mSv/h)/(Bq/m^3) is recommended for radon gas and its progeny by the International Commission on Radiological Protection (ICRP 2018). This dose coefficient was developed for workers in buildings and underground mines, but it is intended that this same dose coefficient applies to exposure of the public in homes.

4. ESTIMATION OF RADON EMANATION RATE FROM THE HOST ROCK

Radon emanation from the surrounding host rock into the DGR is dependent on the properties of the host rock, including the uranium/radium content of the host rock, and the properties of radon. The methodology to estimate the radon emanation rate is found in mining texts/handbooks, which focus on the airborne hazards that are encountered in underground openings (i.e., mines). The references used for the following calculations are Mine Environmental Engineering, Volume One (Chapter 2, Sengupta 1990), and Subsurface Ventilation and Environmental Engineering (Chapter 13, McPherson 1993).

The following sections describe the estimation of the radium and radon content of the host rock, the radon emanation coefficient, the radon emanation power and the radon emanation rate.

4.1 Rock Properties

The radon emanation rate is based on the properties of the host rock, including the rock porosity, the effective diffusion coefficient of gases in the rock, and the uranium content.

The properties of the host rock, which are used to estimate the radon emanation rate, are summarized in Table 4.1. The reference crystalline host rock properties are based on Canadian Shield granite (Gobien et al. 2016). The reference sedimentary host rock properties are based on low-permeability Cobourg limestone in the Michigan Basin sedimentary rock (Gobien et al. 2018).

Table 4.1: Rock Properties

Property	Crystalline Host Rock	Sedimentary Host Rock
Uranium Content (ppm)	1.6	1.2
Porosity (-)	0.003	0.015
Tortuosity factor (-)	0.06	0.03
Density (kg/m^3)	2700	2660

The radium concentration is assumed to be in secular equilibrium with uranium. Based on this assumption and taking the uranium concentration to be 1.6 ppm for crystalline rock and 1.2 ppm for sedimentary rock, the radium concentration is calculated as 5.3 x 10^4 Bq/m^3 for crystalline rock and 3.9 x 10^4 Bq/m^3 for sedimentary rock (Appendix A).

4.2 Radon Emanation Coefficient

When radium decays to radon, the energy generated propels the radon atom a certain distance, called the alpha recoil distance. This distance is dependent on the rock properties, including density and composition of the material. If the decay of a radium atom occurs within the recoil distance of the grain surface, the radon atom will have enough energy to escape into the intergranular space, while the remaining radon atoms remain bound inside the grains. The fraction of atoms released into the pore space from a radium-bearing grain is called the radon emanation coefficient and is expressed as a percentage of the total. In natural conditions, it is virtually always less than 100% (Przylibski 2000). The radon emanation coefficients of typical rocks and soil range from 5 to 70% (Schumann and Gundersen 1996). In practise, the emanation coefficient has to be measured for each material being studied (IAEA 2013).

Based on the literature, the emanation coefficient in granite rock varies widely. Eighteen samples of granite from various world localities yielded emanation coefficients ranging from 3.0 to 40% (Barretto 1975), with an average value of 14%. Measurements of radon emanation coefficients from different varieties of large granite tiles quarried from various parts of India ranged from 3.3% to 9.7% (Sundar et al. 2003).

In general, the emanation coefficient is influenced by the porosity of the host rock. For the selected site, a low emanation coefficient is anticipated, because the rock selected will have a low porosity. For the crystalline host rock, the radon emanation coefficient of 14% is adopted based on the average emanation coefficient of the granite samples reported by Barretto (1975) (i.e., 14% of the radon generated would be released into the pore space, with the remainder staying in the grains of the host rock).

Five samples of limestone bedrock from various world localities yielded emanation coefficients ranging from 0.6 to 2.2% (Barretto 1975). Due to the low porosity of the sedimentary rock formation, an emanation coefficient of 1.6% is assumed, based on the average emanation coefficient of the limestone samples.

The properties of the waste rock pile are significantly different from those of the underground rock in the DGR. The fragmented rock constitutes a source of higher radon exhalation due to the increased exposed surface areas. As well, various authors in literature have identified that the radon emanation increases with decreasing particle size (Barretto 1975). An emanation coefficient of 50% is conservatively assumed for the waste rock pile.

4.3 Emanation Power

The emanation power (Bq/m^{3}s) is defined as the total amount of radon emanating from the mineral grains per unit volume of rock, and by definition it can be calculated as follows:

$$\beta = \alpha A_{Ra226} \lambda_{Rn} \qquad (4.1)$$

where α is the emanation coefficient (-), as discussed in Section 4.2, A_{Ra226} is the activity of radium per unit rock volume which decays to produce radon (Bq/m^3), and λ_{Rn} is the radon decay rate (1/s).

From Equation 4.1, the radon emanation power is calculated as shown in Table 4.2.

Table 4.2: Radon Emanation Power

Property	Crystalline Host Rock	Sedimentary Host Rock
Emanation Coefficient (-)	1.4E-01	1.6E-02
Radium-226 Activity (Bq/m^3)	5.3E+04	3.9E+04
Decay Rate of Radon (1/s)	2.1E-06	2.1E-06
Radon Emanation Power (Bq/m^{3}s)	1.6E-02	1.3E-03

4.4 Emanation Rate

The rate of release of radon at the rock surface is called the emanation rate, and is calculated as (McPherson 1993):

$$E = \beta\sqrt{\frac{D_e}{\lambda_{Rn}\phi}} \quad (4.2)$$

where D_e is the effective diffusion coefficient for radon rock through the pore space (m^2/s), and ϕ is the rock porosity (fraction) (-).

The effective diffusion coefficient for radon in the host rock assumes that the rock surfaces in the DGR are completely dewatered (i.e., saturation will be 0%). Therefore, the effective diffusion coefficient is calculated by multiplying the diffusion of radon in open air by the tortuosity factor and porosity of the host rock, as shown in Table 4.3.

Table 4.3: Effective Diffusion Coefficient

Property	Crystalline Host Rock	Sedimentary Host Rock
Rock Porosity (-)	0.003 [A]	0.015 [A]
Tortuosity factor (-)	0.06 [A]	0.03 [A]
Diffusion of Radon in Open Air (m^2/s)	1.2E-05 [B]	1.2E-05 [B]
Effective Diffusion Coefficient (m^2/s)	2.2E-09	5.4E-09

[A] Table 4.1.

[B] Sengupta 1990.

From Equation 4.2, the radon emanation rate can be calculated, as shown in Table 4.4.

Table 4.4: Radon Emanation Rate

Property	Crystalline Host Rock	Sedimentary Host Rock
Emanation Power (Bq/m^3s)	1.6E-02	1.3E-03
Effective Diffusion Coefficient (m^2/s)	2.2E-09	5.4E-09
Decay Rate of Radon (1/s)	2.1E-06	2.1E-06
Rock Porosity (-)	3.0E-03	1.5E-02
Emanation Rate (Bq/m^2s)	9.2E-03	5.5E-04

A radon emanation rate of 9.2×10^{-3} Bq/m^2s for crystalline host rock and 5.5×10^{-4} Bq/m^2s for sedimentary rock, as calculated in Table 4.4, are well below the average measured radon emanation rate of 2.6×10^{-1} Bq/m^2s from the non-porous uranium ore found in Elliot Lake, Ontario, Canada (Chapter 2, Sengupta 1990). This is due to the greater amount of uranium in the Elliot Lake ore than that for the DGR host rock (Elliot Lake is approximately 1.5% grade uranium ore, or 4 orders of magnitude more enriched than the crystalline or sedimentary host rock). Ore grade is expected to relate to radon gas emanation, as radium is in secular equilibrium with uranium.

5. PRELIMINARY RADON ASSESSMENT

In order to assess the radon hazard, both the construction phase and operations phase are examined. The increase in radon concentration (relative to background) is calculated for the UFPP, the underground repository and near the waste rock pile, and compared to the DWL of 200 Bq/m^3 in order to determine whether further action is necessary (as discussed in Section 1.3).

5.1 Maximum Concentration of Radon in the Host Rock Pores Space

The maximum concentration of radon occurs in the pore spaces, between the grains of uranium containing rock. It can be determined by dividing the emanation power by the decay rate of radon and the porosity of the host rock (Sengupta 1990):

$$C_{max} = \frac{\beta}{\lambda_{Rn}\phi} \qquad (5.1)$$

where:

C_{max}	=	Maximum concentration of radon in the host rock pore volume (Bq/m^3)
β	=	Radon emanation power (Bq/m^3s)
λ_{Rn}	=	Decay rate for radon (1/s)
ϕ	=	Rock porosity (fraction) (-)

The calculated radon concentration in the crystalline and sedimentary host rock pore spaces (the maximum radon concentration) is 2.5 x 10^6 Bq/m^3 and 4.2 x 10^4 Bq/m^3, respectively. It is emphasized that this concentration is strictly within the small pore spaces in the rock, and is not reached in the repository, as there will be ventilation in the DGR.

5.2 Preliminary Radon Assessment during Construction

The average concentration of radon in the DGR during the construction phase is calculated based on Equation 3.2 (as described in Section 3.2).

The mass of excavated rock per day is calculated based on the advancement rates provided in Table 2.3 as a function of time. The daily excavation increases over the course of the development, because more rock faces become available for excavation. They then ramp down as the construction phase nears completion. The surface area and volume of the repository increase as lateral development progresses. The repository surface area and volume are calculated based on the excavated tunnel length, width and height. The tunnel length is calculated based on the excavation rate and the time since construction began. An average access tunnel width and height of 8.4 m and 4.0 m, respectively, are calculated based on the planned dimensions of the main access tunnels, service access tunnels, ramps, cross cuts and infrastructure excavations. The width and height of the placement rooms are all 3.2 m and 2.2 m, respectively.

It is assumed that the underground temporary waste rock pile has a constant mass of 400 Mg.

The concentration of radon in the host rock pores spaces is calculated to be 2.5 x 10^6 Bq/m^3 in crystalline host rock and 4.2 x 10^4 Bq/m^3 in sedimentary host rock, as described in Section 5.1. This is the source of radon release during excavation.

As described in Section 2.5.1, the ventilation rate will vary over the construction phase, driven by the diesel powered equipment assumed used for development. It is assumed that the ventilation rate is 69 m^3/s after the connection between the main and service shaft (at the end of 2037). Following the connection of the main and service shafts, the ventilation flow will be in the range of 169 to 421 m^3/s. For the purpose of this assessment, it is assumed that the ventilation rate is 169 m^3/s during the construction phase, as this provide the most conservative results for the calculated radon concentration.

Air exiting the repository through the Main Shaft and the Ventilation Shaft will travel through different pathways and have different ventilation rates. As such, these pathways will contain different concentrations of radon. The concentration of radon observed during the construction phase reaches 33.2 Bq/m^3 in crystalline host rock and 2.0 Bq/m^3 in sedimentary host rock, as shown in Figure 5.1 and Figure 5.2, respectively. This concentration represents the concentration of radon in the Ventilation Shaft. The concentration of radon will likely be higher at the rock face; however, following a blast, the tunnel will be ventilated to clear blasting fumes (and radon) before workers will be permitted to re-enter the area.

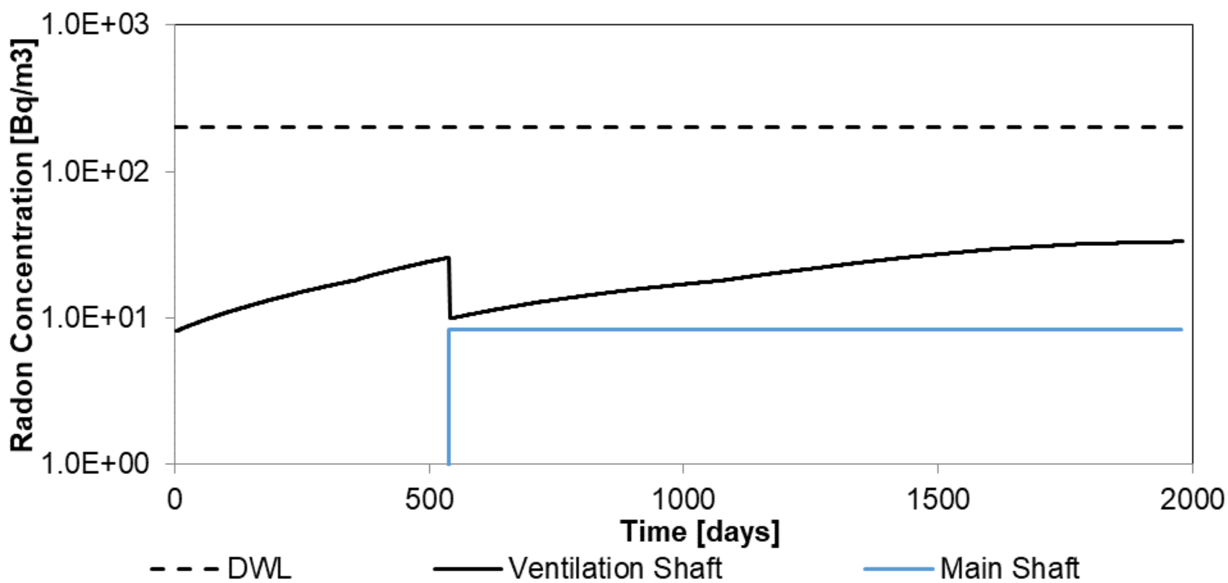

Figure 5.1: Radon Concentration in the Ventilation Shaft and Main Shaft during Construction (Crystalline Host Rock)

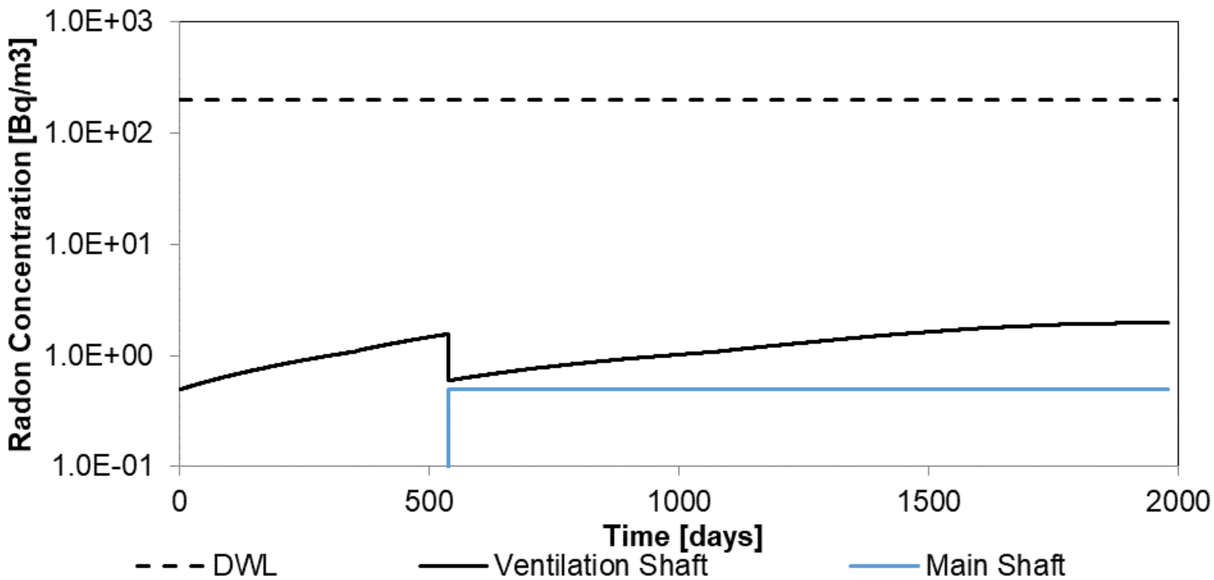

Figure 5.2: Radon Concentration in the Ventilation Shaft and Main Shaft during Construction (Sedimentary Host Rock)

To calculate the dose to a worker from radon, a conversion from radon concentration to WLM and dose to workers (in mSv) is provided by the Canadian Guidelines for Management of NORM (Health Canada 2011). A radon concentration of 200 Bq/m^3 is equivalent to a radon progeny concentration of 0.25 WLM and gives a dose of 1.4 mSv/a, based on an occupational exposure of 2000 hours per year (Health Canada 2011). Therefore, during construction in crystalline host rock, the calculated radon progeny concentration is approximately 0.04 WLM and the calculated inhalation dose to workers in the DGR due to radon and its progeny is approximately 0.23 mSv/a. In sedimentary rock, the calculated radon progeny concentration is approximately 0.0025 WLM and the calculated inhalation dose to workers in the DGR due to radon and its progeny is approximately 0.014 mSv/a.

To calculate the impact to the public, the source term emission rate into air is estimated using the radon concentration and ventilation rate in the Ventilation or Main Shaft. The concentration of radon in the vicinity of the public is calculated with Equation 3.8 at the location where the ADF is a maximum.

To calculate the dose to a public receptor, a dose coefficient of 6.7×10^{-6} (mSv/h)/(Bq/m^3) is recommended for radon gas and its progeny by the International Commission on Radiological Protection (ICRP 2018). The maximum radon concentration in the vicinity of the public receptor and the dose to the public receptor during construction for both the crystalline and sedimentary rock cases are summarized in Table 5.1.

The maximum radon concentration, which occurs at a distance of 100 m from the release location, is calculated as 0.032 Bq/m^3 for the crystalline host rock and 0.0019 Bq/m^3 for the sedimentary host rock, based on the sum of the releases form the Ventilation and Main Shafts. In comparison, these concentrations are much less than the average radon concentration in Ontario of 12 Bq/m^3 (as described in Section 3.1).

For comparison, the radon concentration at a distance of 1,000 m from the release location is presented in Table 5.2. The radon concentration at this location is a factor of 6 lower than the maximum value at 100 m from the release point.

Table 5.1: Radon Dose at 100 m during Construction

Parameter	Crystalline Host Rock		Sedimentary Host Rock	
	Ventilation Shaft	Main Shaft	Ventilation Shaft	Main Shaft
Radon Concentration in Shaft at Release Point (Bq/m^3)	3.3E+01	8.3E+00	2.0E+00	4.9E-01
Ventilation Rate (m^3/s)	169	15	169	15
ADF at 100 m (s/m^3) [A]	5.5E-06	5.5E-06	5.5E-06	5.5E-06
Radon Concentration at 100 m (Bq/m^3) [B]	3.2E-02		1.9E-03	
Public Dose at 100 m (mSv/a)	1.9E-03		1.1E-04	

[A] Maximum ADF value from Figure 3.1 occurs at 100 m from release point.

[B] Increase in radon concentration compared to natural background.

Table 5.2: Radon Dose at 1,000 m during Construction

Parameter	Crystalline Host Rock		Sedimentary Host Rock	
	Ventilation Shaft	Main Shaft	Ventilation Shaft	Main Shaft
Radon Concentration in Shaft at Release Point (Bq/m^3)	3.3E+01	8.3E+00	2.0E+00	4.9E-01
Ventilation Rate (m^3/s)	169	15	169	15
ADF at 1,000 m (s/m^3)	9.4E-07	9.4E-07	9.4E-07	9.4E-07
Radon Concentration at 1,000 m (Bq/m^3) [A]	5.4E-03		3.2E-04	
Public Dose at 1,000 m (mSv/a)	3.2E-04		1.9E-05	

[A] Increase in radon concentration compared to natural background.

5.3 Preliminary Radon Assessment for the Above-Ground Waste Rock Pile

In this section, the radon emissions from the waste rock pile are estimated.

Generally, the rock pile would contain some moisture; this would likely vary daily depending on the recent weather. For the purpose of this assessment, it is conservatively assumed that the waste rock pile is unsaturated. As such, the diffusion coefficient for radon in the waste rock pile is based on an open air value. The diffusion coefficient of radon in the waste rock pile can be approximately calculated by the following relationship (Chapter 2, Sengupta 1990):

$$D_e = 0.66\phi_{WRP}D_a^0 \tag{5.2}$$

where:

D_a^0 = Open air diffusion coefficient (m^2/s)

ϕ_{WRP} = Porosity (fraction) of the waste rock pile (-)

The diffusion coefficient of radon in open air is 1.2 x 10^{-5} m^2/s (Chapter 2, Sengupta 1990). The emanation rate can be estimated for the waste rock pile using Equations 4.1 and 4.2. An emanation coefficient of 50% is conservatively assumed. The details of this calculation are shown in Table 5.3.

Table 5.3: Radon Emanation Power and Emanation Rate from the Waste Rock Pile

Parameter	Crystalline Host Rock	Sedimentary Host Rock
Emanation Coefficient (-)	0.5	0.5
Activity of Radium (in bulked rock) (Bq/m^3) [A]	3.8E+04	2.8E+04
Decay Rate of Radon (1/s)	2.1E-06	2.1E-06
Emanation Power (Bq/m^3s)	4.0E-02	3.0E-02
Diffusion of Radon in Air (m^2/s)	1.2E-05	1.2E-05
Porosity of Waste Rock Pile (-)	4.0E-01	4.0E-01
Emanation Rate (Bq/m^2s)	7.8E-02	5.8E-02

[A] Activity of radium in bulked rock is estimated by multiplying the activity of radium in compacted rock by the volume of compacted rock and dividing by the volume of the rock pile.

To assess the potential impact of radon on workers in the vicinity of the waste rock pile, the concentration of radon in an atmospheric compartment directly above the waste rock pile and down-wind of the waste rock pile are calculated, as described in Section 3.3.

The concentration of radon in the atmospheric compartment above the pile (C_{top}) can be estimated according to Equation 3.2.

The size of the rock pile has been discussed in Section 2.2. The atmospheric compartment considered for this analysis measures 2 m x 425 m x 330 m (the area at the top of the waste rock pile). A drawing of this compartment can be seen in Appendix C.

A low wind speed of 1 m/s is used in this assessment for both generic crystalline and sedimentary host rock sites.

The average concentration of radon in the atmospheric compartment on top of the waste rock pile is 16.5 Bq/m^3 for a crystalline host rock site, and 12.2 Bq/m^3 for a sedimentary host rock site. A worker inhalation dose of 0.12 mSv/a and 0.085 mSv/a due to radon is estimated for a crystalline host rock site and a sedimentary host rock site, respectively, conservatively assuming that 2000 hours per year are spent standing on top of the waste rock pile under these low wind conditions.

The concentration of radon in the atmospheric compartment downwind of the pile ($C_{downwind}$) can be estimated according to Equation 3.3.

The atmospheric compartment for this analysis measured 2 m thick (perpendicular distance from the slope of the waste rock pile to the parallel boundary of the compartment), and extends 330 m (the estimated length of the waste rock pile to the top of the slope (15 m off the ground, with a slope of 40 m). This compartment is shown in Appendix D.

A wake region forms on the down-wind side of the waste rock pile. Billman and Arya (1985) studied wind flow over an oval flat topped pile (11 m tall, 78 m long and 63 m wide), and reported that wind velocity over the pile decreased to as low as 20% of nominal wind velocity, and was minimum on the leeward side of the pile. For this assessment, it is assumed that the wind velocity on the leeward side of the waste rock pile is 20% of the annual average wind velocity at the site (i.e., f is equal to 0.2).

The average concentration in the atmospheric compartment down-wind of the waste rock pile is 24.4 Bq/m^3 for a crystalline host rock site and 18.0 Bq/m^3 for a sedimentary host rock location. A worker inhalation dose of 0.17 mSv/a and 0.13 mSv/a due to radon are estimated for a crystalline host rock site and a sedimentary host rock site, respectively, conservatively assuming that the worker spends 2000 hours/year near the waste rock pile.

The impact of radon release from the waste rock pile on the public is also estimated. The radon concentration in the vicinity of the public receptor is calculated by multiplying the average emission rate by the ADF, as described in Equation 3.8. The maximum radon concentration in the vicinity of the public receptor is summarized in Table 5.4, assuming that the public is at 100 m from the waste rock pile. For comparison, the radon concentration at a distance of 1,000 m from the release location is also presented in Table 5.4. The radon concentration at this location is a factor of 6 lower than the maximum value at 100 m from the release point.

Table 5.4: Radon Dose Due to Release from the Waste Rock Pile

Parameter	Crystalline Host Rock	Sedimentary Host Rock
Emanation Rate (Bq/m^{2}s)	7.8E-02	5.8E-02
Approximate Surface Area of the Waste Rock Pile (m^2)	2.0E+05	2.0E+05
Average Rate of Emission (Bq/s)	1.6E+04	1.2E+04
ADF at 100 m (s/m^3) [A]	5.5E-06	5.5E-06
Radon Concentration at 100 m (Bq/m^3) [B]	8.6E-02	6.4E-02
Public Dose at 100 m (mSv/a)	**5.1E-03**	**3.7E-03**
ADF at 1,000 m (s/m^3)	9.4E-07	9.4E-07
Radon Concentration at 1,000 m (Bq/m^3) [B]	1.5E-02	1.1E-02
Public Dose at 1,000 m (mSv/a)	**8.6E-04**	**6.4E-04**

[A] Maximum ADF value from Figure 3.1 occurs at 100 m from release point.

[B] Increase in radon concentration compared to natural background.

The dose to a public receptor is also shown in Table 5.4. To calculate the dose to a public receptor, a dose coefficient of 6.7 x 10^{-6} (mSv/h)/(Bq/m^3) is recommended for radon gas and its progeny by the International Commission on Radiological Protection (ICRP 2018).

5.4 Radon Release from Used Fuel during UFPP Operations

In this section, the radon emission rate from the UFPP as a result of repacking of used fuel (as calculated in Section 3.5) is used to estimate the radon concentration and dose to a public receptor.

The radon concentration in the vicinity of the public receptor can be calculated by multiplying the average emission rate (i.e., the source term ventilated out of the UFPP) by the ADF, as described in Equation 3.8. The radon emission rate from the UFPP is shown in Table 3.1. The reference ADFs are summarized in Table 3.3.

To calculate the dose to a public receptor, a dose coefficient of 6.7 x 10^{-6} (mSv/h)/(Bq/m^3) is recommended for radon gas and its progeny by the International Commission on Radiological Protection (ICRP 2018).

The radon concentration and dose to a public receptor at 100 m (the location of the maximum radon concentration) and 1,000 m are summarized in Table 5.5.

Table 5.5: Radon Dose Due to Release from UFPP Operations

Parameter	Value
Radon release rate from the UFPP (Bq/s)	6.6E-05
ADF at 100 m (s/m^3) [A]	1.6E-05
Radon Concentration at 100 m (Bq/m^3) [B]	1.1E-09
Public Dose at 100 m (mSv/a)	**6.2E-11**
ADF at 1,000 m (s/m^3)	1.1E-06
Radon Concentration at 1,000 m (Bq/m^3) [B]	7.3E-11
Public Dose at 1,000 m (mSv/a)	**4.3E-12**
[A] Maximum ADF value from Figure 3.1 occurs at 100 m from release point. [B] Increase in radon concentration compared to natural background.	

5.5 Preliminary Radon Assessment during Underground Operations

5.5.1 Radon Concentration as a Function of Repository Location

The radon level in the DGR varies depending on location. Air will enter the repository through the service shaft. Radon builds up as air travels from the service shaft, through the repository, and out through the Ventilation or Main Shaft. The used fuel in the underground repository is inside welded containers, and as such there will be no radon emissions from the used fuel. Therefore, the air leaving through the Ventilation and Main Shafts will contain a higher concentration of radon, compared to that entering the service shaft. The radon concentration as a function of location can be estimated as described in Section 3.6.1.

One air pathway, from the entry of air into the DGR by the service shaft to the end of a placement room in the North Arm, can be represented as a tunnel. From the service shaft, fresh air travels through the fresh air distribution level to a Fresh Air Raise (FAR), which delivers the air to the repository level. The fresh air then travels through the west access tunnel to the north arm. In the north arm, the air travels through the west access tunnel to a cross cut after the Panel 4 placement rooms, and returns via the east access tunnel to the last placement room in Panel 4 (as shown in Figure 5.3). Cross cuts connect the west and east access tunnels at nominal 125 m intervals. The cross cuts are included in the analysis as additional length of the access tunnel. Air flows into ventilated placement rooms prior to the active placement room. Similar to the cross cuts, these placement rooms are included in the assessment as additional length of the access tunnel. Finally, the air flows into the placement room, and is removed by a duct.

The ventilation rate in the north arm will be in the range of 18 m^3/s to 55 m^3/s (Section 2.5.3). For the purpose of this assessment, it is assumed that the ventilation rate is 18 m^3/s, as this will provide the most conservative results for the calculated radon concentration. The minimum airflow velocity of 0.5 m/s for all access tunnels and occupied placement rooms is adopted for this calculation for the placement room (Section 2.5.3). Overall, the highest radon concentration occurs at the end of a placement room, as the ventilation flow rate will be a minimum at this location. The radon concentration in the Ventilation Shaft is discussed in Section 5.5.2.

The properties for each section are listed in Table 5.6. The radon emanation rate is summarized in Section 4.4.

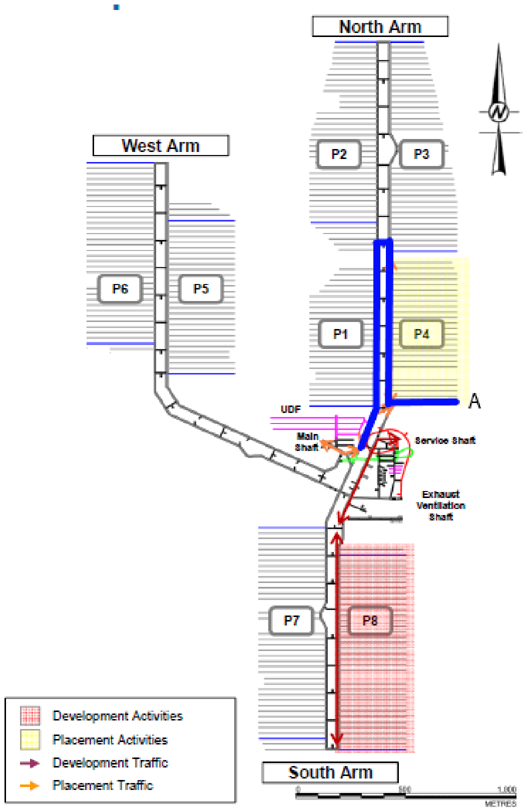

Figure 5.3: DGR Layout with Ventilation Path of Radon Concentration Analysis

Table 5.6: DGR Properties by Location

Location	Length (m)	Width (m)	Height (m)	Volume (m^3)	Ventilation Rate (m^3/s)
Fresh Air Level - Transfer Tunnel	2.9E+02	9	5	1.3E+04	18
Fresh Air Level - North Arm Access	1.0E+01	5	5	2.5E+02	18
Fresh Air Raise – North Arm	2.0E+01	4 [A]	-	2.5E+02	18
West Access Tunnel	1.0E+03	9	4	3.6E+04	18
East Access Tunnel	7.5E+02	9	4	2.7E+04	18
Cross Cuts	3.2E+02	5	5	7.9E+03	18
Ventilated Placement Rooms	3.6E+03	3.2	2.2	2.5E+04	18
Placement Room	3.0E+02	3.2	2.2	2.1E+03	3.5

[A] Diameter.

In crystalline host rock, the maximum radon concentration reached in the DGR for the pathway shown in Figure 5.3 (point A) is 59 Bq/m^3, occurring at the end of an active and ventilated placement room. A worker dose of 0.41 mSv/a due to inhalation of radon and its progeny is estimated (based on 2000 hrs at this location). In sedimentary host rock, the maximum radon concentration reached in the DGR for the pathway shown in Figure 5.3 (point A) is calculated to be 3.5 Bq/m^3, with a corresponding worker dose of 0.024 mSv/a.

5.5.2 Radon Concentration as a Function of Time

The concentration of radon in the Ventilation Shaft and Main Shaft during the underground operations phase is calculated as described in Section 3.6.2.

The calculation considered the entire DGR surface area and volume (Table 2.2). The majority of the DGR is ventilated through the Ventilation Shaft, with a smaller airflow being exhausted through the Main Shaft.

During the operations phase, UFCs will be placed into one panel of placement rooms, while another panel is being developed. This calculation is based on the first phase of operations in the DGR, during which used fuel is placed into the placement rooms in Panel 1 (north arm), while development is occurring in Panel 5 (west arm), as shown in Figure 5.4. Development and placement activities occur 5 days per week, with development proceeding at a rate of 7 m/day (Table 2.3). The rate of placement activities is scaled based on the development rate, so that the activities occurring in each panel are completed at the same time, i.e., fill rate in Panel 1 = 7 m/day x length of Panel 1 placement rooms (9,220 m) / length of Panel 5 placement rooms (10,880 m) = 5.9 m/day. The placement room dimensions are 3.2 m wide by 2.2 m tall. It is assumed that filled placement rooms do not release radon, as there is no ventilation to a filled placement room.

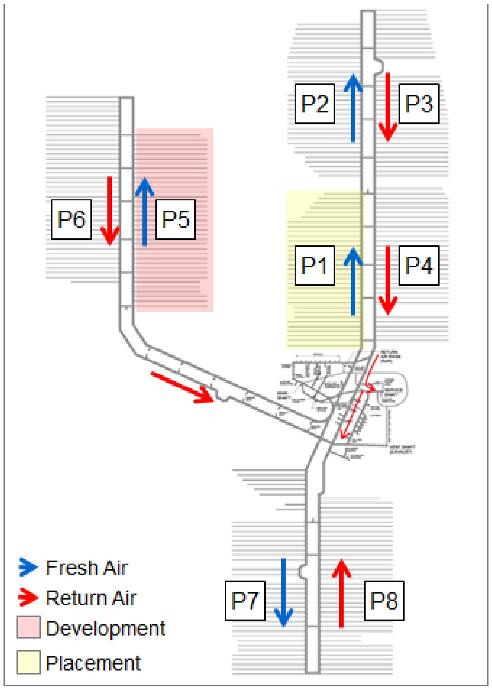

Figure 5.4: Operations Phase Ventilation Flow

During the operations phase, the ventilation flow exhausted through the Ventilation Shaft will be in the range of 154 m^3/s to 262 m^3/s (Section 2.5.3). For the purpose of this assessment, it is assumed that the ventilation rate is 154 m^3/s during the operations phase, as this provides the most conservative results for the calculated radon concentration.

A small amount of air will be exhausted via the Main Shaft. Waste packages are moved via the Main Shaft; the small air flow up this shaft ensures that any surface contamination on the packages is not blown down and through the repository. Ventilation doors will be closed to form an airlock between the Main Shaft and each of the arm access tunnels. The ventilation flow through the Main Shaft is 15 m^3/s (Section 2.5.3).

Used fuel bundles will be loaded into UFCs in the UFPP. The containers will be welded shut and transported underground inside of a shielded transportation cask. As such, there will be no radon emissions from the used fuel in the DGR.

The estimated average radon concentration in the Ventilation and Main Shafts is shown in Figure 5.5 for crystalline host rock, and Figure 5.6 for sedimentary host rock. The figures show that the average radon levels are less than the DWL of 200 Bq/m^3.

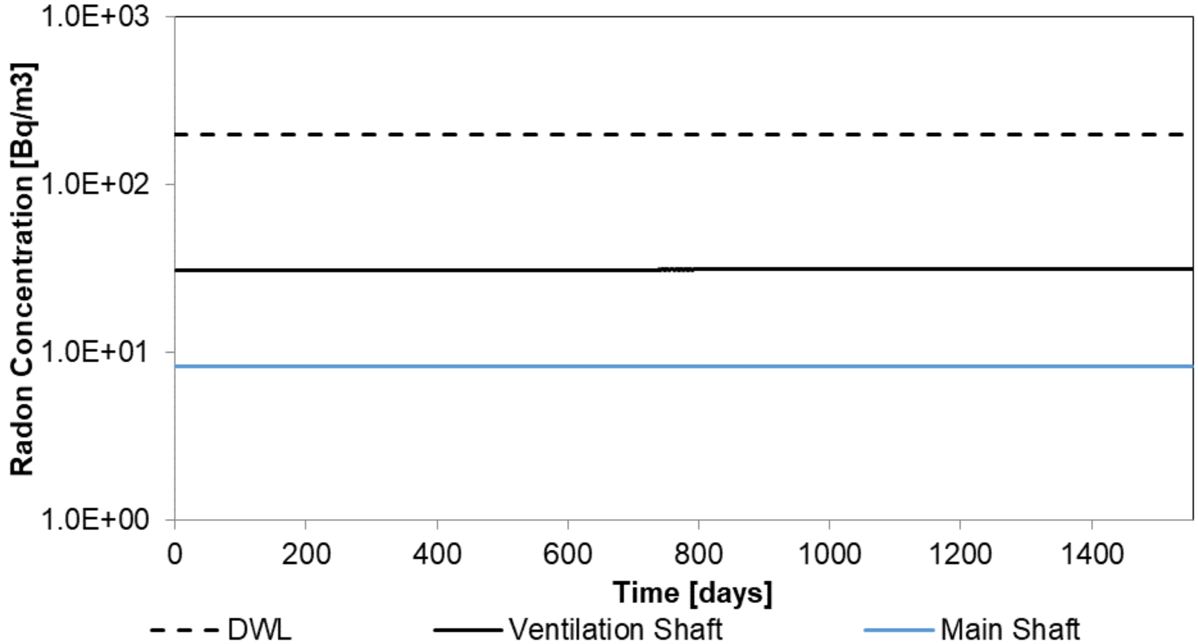

Figure 5.5: Radon Concentration in the Ventilation Shaft and Main Shaft during Underground Operations (Crystalline Rock)

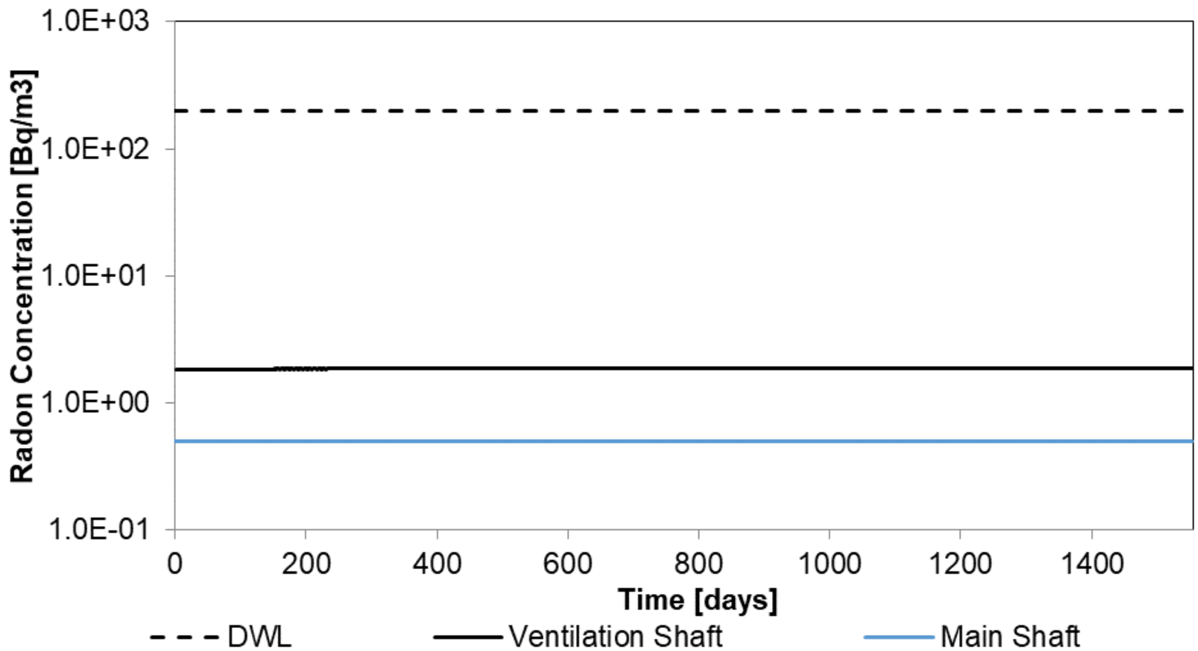

Figure 5.6: Radon Concentration in the Ventilation Shaft and Main Shaft during Underground Operations (Sedimentary Rock)

For a repository in crystalline rock, the maximum concentration observed in the DGR exhaust during the underground operations is calculated to be 31 Bq/m^3 in the Ventilation Shaft, a factor of 7 less than the DWL of 200 Bq/m^3. The radon progeny concentration is approximately 0.04 WLM and the inhalation dose to workers in the DGR due to radon and its progeny is approximately 0.22 mSv/a based on occupational exposure of 2000 hours per year.

For a repository in sedimentary rock, the maximum concentration observed in the DGR exhaust during the underground operations is calculated to be 1.9 Bq/m^3 in the Ventilation Shaft. The calculated radon progeny concentration is approximately 0.0024 WLM and the calculated inhalation dose to workers in the DGR due to radon and its progeny is approximately 0.013 mSv/a based on occupational exposure of 2000 hours per year.

The maximum radon concentration to a public receptor is at the location of the maximum ADF value, or 100 m from Ventilation or Main Shaft. The corresponding maximum radon concentration and public dose during underground operations for both the crystalline and sedimentary rock cases are summarized in Table 5.7. For comparison, the radon concentration at a distance of 1,000 m from the release location is presented in Table 5.8. The radon concentration at this location is a factor of 6 lower than the maximum value at 100 m from the release point.

Table 5.7: Radon Dose at 100 m during Underground Operations

Parameter	Crystalline Host Rock		Sedimentary Host Rock	
	Ventilation Shaft	Main Shaft	Ventilation Shaft	Main Shaft
Radon Concentration in Shaft at Release Point (Bq/m^3)	3.2E+01	8.3E+00	1.9E+00	4.9E-01
Ventilation Rate (m^3/s)	154	15	154	15
ADF at 100 m (s/m^3) [A]	5.5E-06	5.5E-06	5.5E-06	5.5E-06
Radon Concentration at 100 m (Bq/m^3) [B]	2.7E-02		1.6E-03	
Public Dose at 100 m (mSv/a)	1.6E-03		9.6E-05	

[A] Maximum ADF value from Figure 3.1 occurs at 100 m from release point.

[B] Increase in radon concentration compared to natural background.

Table 5.8: Radon Dose at 1,000 m during Underground Operations

Parameter	Crystalline Host Rock		Sedimentary Host Rock	
	Ventilation Shaft	**Main Shaft**	**Ventilation Shaft**	**Main Shaft**
Radon Concentration in Shaft at Release Point (Bq/m^3)	3.2E+01	8.3E+00	1.9E+00	4.9E-01
Ventilation Rate (m^3/s)	154	15	154	15
ADF at 1,000 m (s/m^3)	9.4E-07	9.4E-07	9.4E-07	9.4E-07
Radon Concentration at 1,000 m (Bq/m^3) [A]	4.7E-03		2.8E-04	
Public Dose at 1,000 m (mSv/a)	2.7E-04		1.6E-05	

[A] Increase in radon concentration compared to natural background.

6. CONCLUSIONS

An assessment of the potential radon hazard during construction and operation of the DGR was performed for a generic crystalline or sedimentary rock site.

Radon is a gaseous radioactive atom produced by the radioactive decay of uranium, thorium and actinides. It is naturally produced from the uranium and thorium present in the host rock of any repository site. Radon is also generated from the decay of the used nuclear fuel.

In this assessment, worker and public exposure to radon were considered for the surface and underground facilities and near the waste rock pile for both the construction and operations phases. In the underground repository, radon is released at the working face as a result of drilling, by emanation from the walls of the repository in areas that have been previously excavated, and emanation from the underground temporary waste rock pile. At the surface, radon is released from the ventilation stacks and from the main waste rock management pile. Radon is removed by air flow and by decay.

The maximum increase in radon concentration in the underground repository and adjacent to the waste rock pile during the construction and operation phases of the DGR, and the resulting worker dose are summarized in Table 6.1. Overall, there is no significant radon hazard either during construction or operation of the DGR. Due to the low concentration of uranium (and consequently radium and radon) in the host rock, the low porosity of the rock, and the facility ventilation, the concentration of radon in the repository remains low during all phases of development. The highest concentration in an underground area where workers may be present is at the end of a placement room, where the ventilation rate is reduced compared to the access tunnel.

Considering the Derived Working Limit of 200 Bq/m^3 from the Canadian Guidelines for Management of Naturally Occurring Radioactive Materials, there is no need for routine radon monitoring or development of any action level. However, radon concentrations should be checked during construction, and then periodically during operation as part of routine air quality and radiological surveys to confirm expected low radon levels.

Radon released from the underground repository, the UFPP and the waste rock pile was considered for public dose calculations.

Atmospheric dispersion factors were used to provide an estimate of the amount of dispersion or dilution experienced by radon released into the atmosphere, between the point of release and the public receptor location. Since radon gas would be a routine emission, long-term average ADF values resulting from a continuous release were calculated using from the non-site-specific sector-averaged version of the Gaussian plume model (CSA 2014 and references therein), which assumes a laterally uniform concentration in each wind direction sector because of wind meander over prolonged periods of time.

The maximum increase in radon concentration due to the construction and operation of the DGR and related surface facilities, and the resulting public dose are summarized in Table 6.2. These values are significantly less than the average outdoor air radon concentration in Ontario of 12 Bq/m^3. For comparison, the radon concentration and dose to public at 1,000 m from the release location is also presented in Table 6.3. The radon concentration at this location is a factor of 6 lower than the maximum value at 100 m from the release point.

This assessment should be updated with site-specific data, once it becomes available.

Table 6.1: Summary of Radon Concentration and Dose for Workers

<table>
<tr><th colspan="2" rowspan="2">Location</th><th colspan="2">Crystalline Host Rock</th><th colspan="2">Sedimentary Host Rock</th></tr>
<tr><th>Maximum Radon Concentration (Bq/m^3)</th><th>Maximum Dose Rate [A] (mSv/a)</th><th>Maximum Radon Concentration (Bq/m^3)</th><th>Maximum Dose Rate [A] (mSv/a)</th></tr>
<tr><td rowspan="2">Construction Phase</td><td>Ventilation Shaft</td><td>33.2</td><td>0.23</td><td>2.0</td><td>0.014</td></tr>
<tr><td>Main Shaft</td><td>8.3</td><td>0.058</td><td>0.49</td><td>0.0035</td></tr>
<tr><td rowspan="2">Waste Rock Pile</td><td>Worker (standing on pile)</td><td>16.5</td><td>0.12</td><td>12.2</td><td>0.085</td></tr>
<tr><td>Worker (leeward side of pile)</td><td>24.4</td><td>0.17</td><td>18.0</td><td>0.13</td></tr>
<tr><td rowspan="4">Operations Phase</td><td>Underground Tunnel</td><td>58.6</td><td>0.41</td><td>3.5</td><td>0.024</td></tr>
<tr><td>Empty, ventilated room</td><td>8.4</td><td>0.059</td><td>0.5</td><td>0.0035</td></tr>
<tr><td>Ventilation Shaft</td><td>31.5</td><td>0.22</td><td>1.9</td><td>0.013</td></tr>
<tr><td>Main Shaft</td><td>8.3</td><td>0.058</td><td>0.49</td><td>0.0035</td></tr>
<tr><td colspan="2">Derived Working Limit</td><td>200</td><td>1.4</td><td>200</td><td>1.4</td></tr>
<tr><td colspan="6">[A] Based on 2000 hrs at this location.</td></tr>
</table>

Table 6.2: Summary of Maximum Radon Concentration and Dose for Members of the Public

Location	Crystalline Host Rock		Sedimentary Host Rock	
	Maximum Radon Concentration (Bq/m^3) [A]	Maximum Dose Rate (mSv/a)	Maximum Radon Concentration (Bq/m^3) [A]	Maximum Dose Rate (mSv/a)
Shafts - Construction Phase	0.032	0.0019	0.0019	0.00011
Waste Rock Pile	0.086	0.0051	0.064	0.0037
Shafts - Operations Phase	0.027	0.0016	0.0016	0.000096
Used Fuel Packaging Plant	1.E-09	< 0.000001	1.E-09	< 0.000001
Average radon concentration in Ontario	12	-	12	-
[A] Maximum ADF value from Figure 3.1 occurs at 100 m from release point.				

Table 6.3: Summary of Radon Concentration and Dose for Members of the Public at 1,000 m from Release Point

Location	Crystalline Host Rock		Sedimentary Host Rock	
	Radon Concentration (Bq/m^3)	Dose Rate (mSv/a)	Radon Concentration (Bq/m^3)	Dose Rate (mSv/a)
Shafts - Construction Phase	0.0054	0.00032	0.00032	0.000019
Waste Rock Pile	0.015	0.00086	0.011	0.00064
Shafts - Operations Phase	0.0047	0.00027	0.00028	0.000016
Used Fuel Packaging Plant	7E-11	< 0.000001	7E-11	< 0.000001
Average radon concentration in Ontario	12	-	12	-

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8. LIST OF ACRONYMS

ADF	Atmospheric Dispersion Factor
APM	Adaptive Phased Management
Bi-210	Bismuth-210
Bi-214	Bismuth-214
CCTV	Closed Circuit Television
CNSC	Canadian Nuclear Safety Commission
CSA	Canadian Standards Association
DGR	Deep Geological Repository
DWL	Derived Working Limit
EBS	Engineered Barrier System
ERMA	Excavated Rock Management Area
FAR	Fresh Air Raise
HEPA	High Efficiency Particulate Air
HVAC	Heating, Ventilation and Air Conditioning
NEW	Nuclear Energy Worker
NORM	Naturally Occurring Radioactive Materials
NWMO	Nuclear Waste Management Organization
OTC	Overhead Transfer Crane
Pb-210	Lead-210
Pb-214	Lead-214
Po-210	Polonium-210
Po-214	Polonium-214
Po-218	Polonium-218
Ra-226	Radium-226
Rn-222	Radon-222
U-238	Uranium-238
UDF	Underground Demonstration Facility
UFC	Used Fuel Container

UFPP	Used Fuel Packaging Plant
UFTP	Used Fuel Transportation Package
WL	Working Level
WLM	Working Level Month

APPENDIX A: CONCENTRATION OF RADIUM IN HOST ROCK

The radium concentration in the host rock is expected to be in secular equilibrium with uranium since the rock has been in place for millions of years. Therefore, the radium concentration can be calculated as shown below, same as the U-238 concentration.

Parameter	Crystalline Host Rock	Reference
Uranium in host rock (ppm)	1.6	Table 4.1
Density of host rock (kg/m^3)	2700	Table 4.1
Amount of uranium (mol/m^3)	1.8E-02	-
Fraction U-238/Uranium (%)	99.3	Natural abundance
Amount of U-238 (mol/m^3)	1.8E-02	-
Specific Activity U-238 (Bq/g)	1.2E+04	-
Activity of U-238 (Bq/m^3)	5.3E+04	-
Half-life U-238 (a)	4.5E+09	ENDF.B-VII.1
Half-life Ra-226 (a)	1.6E+03	ENDF.B-VII.1
Amount of Ra-226 (mol/m^3)	6.5E-09	-
Specific Activity Ra-226 (Bq/g)	3.7E+10	-
Activity of Ra-226 (Bq/m^3)	5.3E+04	-

Parameter	Sedimentary Host Rock	Reference
Uranium in host rock (ppm)	1.2	Table 4.1
Density of host rock (kg/m^3)	2660	Table 4.1
Amount of uranium (mol/m^3)	1.3E-02	
Fraction U-238/Uranium (%)	99.3	Natural abundance
Amount of U-238 (mol/m^3)	1.3E-02	-
Specific Activity U-238 (Bq/g)	1.2E+04	-
Activity of U-238 (Bq/m^3)	3.9E+04	-
Half-life U-238 (a)	4.5E+09	ENDF.B-VII.1
Half-life Ra-226 (a)	1.6E+03	ENDF.B-VII.1
Amount of Ra-226 (mol/m^3)	4.8E-09	-
Specific Activity Ra-226 (Bq/g)	3.7E+10	-
Activity of Ra-226 (Bq/m^3)	3.9E+04	-

APPENDIX B: DERIVATION OF EQUATION USED TO ESTIMATE THE RADON CONCENTRATION IN THE DGR DURING THE CONSTRUCTION PHASE (EQUATION 3.1)

The rate of change of radon concentration in the DGR is based on a mass balance of the amount of radon present at time t.

The change in concentration of radon (C) in the DGR is equal to the amount entering (IN) less the amount leaving (OUT).

$$\frac{\partial C}{\partial t} = IN - OUT \tag{B.1}$$

Radon enters the DGR during the construction phase by three pathways:

- Emanation through the walls of the repository,
- Emanation from the underground waste rock pile (assumed to be cleared out once a day), and
- Release from the pore spaces when the rocks are removed during excavation.

Radon leaves the DGR during construction by two pathways:

- Ventilation, and
- Decay.

$$\frac{\partial C}{\partial t} = \frac{E \cdot SA_{walls}}{V_{rep}} + \frac{E \cdot SA_{waste\ rock}}{V_{rep}} + \frac{C_{pore\ space} \cdot V_R \cdot \phi}{V_{rep}} - \lambda_{Rn} C - \lambda_v C \tag{B.2}$$

Where E is the emanation rate (Bq/m^{2}s), SA is the time-varying surface area of the repository or the waste rock (m^2), V_{rep} is the time-varying total excavated volume of the DGR (m^3), $C_{pore\ space}$ is the concentration of radon in the host rock pore space (as calculated by Equation 4.1) (Bq/m^3), V_R is the volume of rock excavated during time t (m^3/s), ϕ is the rock porosity (fraction) (-), λ_{Rn} is the decay rate of Radon-222 (1/s), and λ_v is the ventilation rate (1/s).

Let $$m = \frac{E \cdot SA_{walls}}{V_{rep}} + \frac{E \cdot SA_{waste\ rock}}{V_{rep}} + \frac{C_{pore\ space} \cdot V_R \cdot \phi}{V_{rep}} \text{ and } n = \lambda_{Rn} + \lambda_v \tag{B.3}$$

$$\frac{\partial C}{\partial t} = m - nC \tag{B.4}$$

$$\frac{\partial C}{m - nC} = \partial t \tag{B.5}$$

We integrate over a time step defined as: $t_i - t_{i-1}$. At time t_i the radon concentration averaged over the DGR is C_i and at time t_{i-1} the radon concentration is C_{i-1}.

$$\int_{C_{i-1}}^{C_i} \frac{dC}{m - nC} = \int_{t_{i-1}}^{t_i} dt \tag{B.6}$$

$$C_i = \frac{m\left(1 - e^{\left(-n(t_i - t_{i-1})\right)}\right)}{n} + C_{i-1} e^{\left(-n(t_i - t_{i-1})\right)} \tag{B.7}$$

$$\boxed{C = \frac{\left(E \cdot SA_{walls} + E \cdot SA_{waste\ rock} + C_{pore\ space} \cdot V_R \cdot \phi\right)\left(1 - e^{\left(-(\lambda_{Rn} + \lambda_v)(t_i - t_{i-1})\right)}\right)}{V_{rep}(\lambda_{Rn} + \lambda_v)} + C_{i-1} e^{\left(-(\lambda_{Rn} + \lambda_v)(t_i - t_{i-1})\right)}} \qquad \text{(B.8)}$$

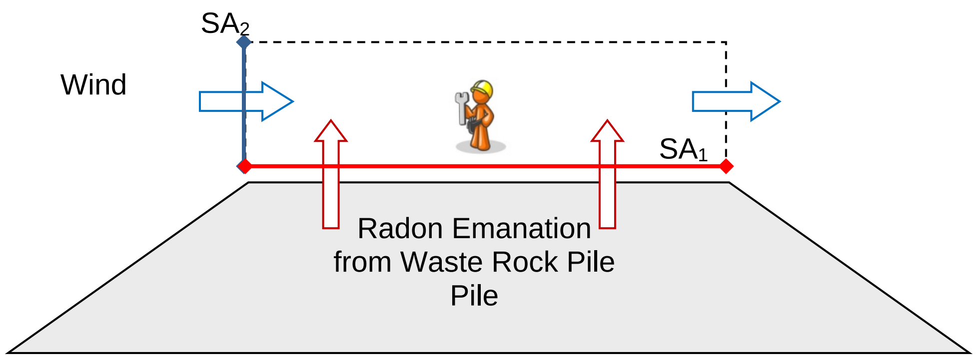
APPENDIX C: DERIVATION OF EQUATION USED TO ESTIMATE THE RADON CONCENTRATION IN AN ATMOSPHERIC COMPARTMENT ON TOP OF THE WASTE ROCK PILE (EQUATION 3.2)

The rate of change of radon concentration in an atmospheric compartment above the waste rock pile is based on a mass balance of the amount of radon present at time t.

The change in concentration of radon (C_{top}) in the atmospheric compartment is equal to the amount entering (IN) less the amount leaving (OUT).

$$\frac{\partial C_{top}}{\partial t} = IN - OUT \quad \text{(C.1)}$$

Radon enters the atmospheric compartment in which the worker is standing by emanation from the waste rock pile. Radon leaves the compartment by decay and wind flow.



$$\frac{\partial C}{\partial t} = E\ SA_1 - V_{wind} SA_2 C_{top} - \lambda_{Rn} V_C C_{top} \quad \text{(C.2)}$$

Where E represents the emanation rate of radon from the waste rock pile (Bq/m^{2}s), SA_1 represents the surface area of the top of the waste rock pile (through which radon emanates) (m^2), V_{wind} represents the annual average wind velocity at a site (m/s), SA_2 represents the surface area of the compartment perpendicular to the direction of wind flow (m^2), V_c represents the volume of the atmospheric compartment (m^3), and C_{top} represents the concentration of radon in the atmospheric compartment (Bq/m^3).

Let $m = E\ SA_1$ and $n = V_{wind} SA_2 + \lambda_{Rn} V_C$

$$\frac{\partial C}{\partial t} = m - nC_{top} \quad \text{(C.3)}$$

When steady-state is reached in the atmospheric compartment (i.e., as $t \to \infty$):

$$\frac{\partial C}{\partial t} = m - nC_{top} = 0 \quad \text{(C.4)}$$

$$C_{top} = \frac{m}{n} \quad \text{(C.5)}$$

$$C_{top} = \frac{E\ SA_1}{V_{wind} SA_2 + \lambda_{Rn} V_C} \quad \text{(C.6)}$$

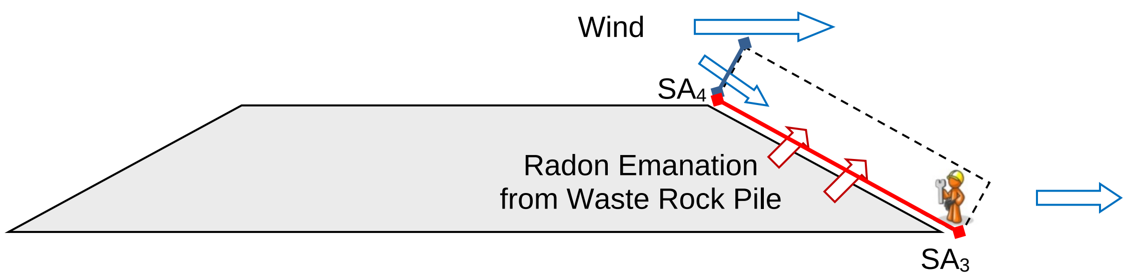
APPENDIX D: DERIVATION OF EQUATION USED TO ESTIMATE THE RADON CONCENTRATION IN AN ATMOSPHERIC COMPARTMENT DOWN-WIND OF THE WASTE ROCK PILE (EQUATION 3.3)

The rate of change of radon concentration in an atmospheric compartment down-wind of the waste rock pile is based on a mass balance of the amount of radon present at time t.

The change in concentration of radon ($C_{downwind}$) in the atmospheric compartment is equal to the amount entering (IN) less the amount leaving (OUT).

$$\frac{\partial C_{downwind}}{\partial t} = IN - OUT \tag{D.1}$$

Radon enters the atmospheric compartment in which the worker is standing by emanation from the waste rock pile and by wind flow, picked up from radon emanating off the top of the waste rock pile. Radon leaves the compartment by decay and wind flow.



$$\frac{\partial C_{downwind}}{\partial t} = E\,SA_3 + fV_{wind}SA_4C_{top} - fV_{wind}SA_4C_{downwind} - \lambda_{Rn}V_C C_{downwind} \tag{D.2}$$

Where E represents the emanation of radon from the waste rock pile (Bq/m^{2}s), SA_3 represents the surface area of the top of the waste rock pile (through which radon emanates) (m^2), V_{wind} represents the annual average wind velocity at a site (m/s), f is a factor of 0.2, representing the fact that there is a wake region on the down-wind side of a pile and only a fraction of the nominal wind velocity will proceed into this compartment (-), SA_4 represents the surface area of the compartment perpendicular to the direction of wind flow (m^2), C_{top} represents the concentration of radon in wind entering the compartment, as calculated for the atmospheric compartment above the waste rock pile (Bq/m^3), V_c represents the volume of the atmospheric compartment (m^3), and $C_{downwind}$ represents the concentration of radon in the atmospheric compartment (Bq/m^3). Note that it is assumed that the volumetric flow rate of air remains constant and no pressure changes in the compartment are considered.

Let $m = E\,SA_3 + fV_{wind}SA_4C_{top}$ and $n = fV_{wind}SA_4 + \lambda_{Rn}V_C$

$$\frac{\partial C_{downwind}}{\partial t} = m - nC_{downwind} \tag{D.3}$$

When steady-state is reached in the atmospheric compartment (i.e. as t→∞):

$$\frac{\partial C_{downwind}}{\partial t} = m - nC_{downwind} = 0 \tag{D.4}$$

$$C_{downwind} = \frac{m}{n} \quad \text{(D.5)}$$

$$C_{downwind} = \frac{E\ SA_3 + fV_{wind}SA_4C_{top}}{fV_{wind}SA_4 + \lambda_{Rn}V_C} \quad \text{(D.6)}$$

APPENDIX E: DERIVATION OF EQUATION USED TO ESTIMATE THE RADON CONCENTRATION IN THE DGR DURING OPERATIONS PHASE AS A FUNCTION OF TUNNEL LENGTH (EQUATION 3.6)

The rate of change of radon concentration in the DGR is based on a mass balance of the amount of radon present at in a location at distance x from the entrance to the DGR.

The change in concentration of radon in the DGR (C) is equal to the amount entering, IN (by emanation through the rock walls) less the amount leaving, OUT (by decay).

$$\frac{\partial C}{\partial x} = IN - OUT \tag{E.1}$$

$$\frac{\partial C}{\partial t} = \frac{E \cdot (2w+2h)}{\dot{V}} - \frac{\lambda_{Rn} wh}{\dot{V}} C \tag{E.2}$$

Where E is the emanation rate (Bq/m^{2}s), w is the width of the tunnel (m), h is the height of the tunnel (m), $\dot{V}$ is the volumetric flow rate through the DGR (m^3/s), and λ_{Rn} is the decay rate of radon-222 (1/s).

Let $m = \frac{E \cdot (2w+2h)}{\dot{V}}$ and $n = \frac{\lambda_{Rn} wh}{\dot{V}}$

$$\frac{\partial C}{\partial x} = m - nC \tag{E.3}$$

$$\frac{\partial C}{m - nC} = \partial x \tag{E.4}$$

We integrate over a time step defined as: x_i- x_{i-1}.

At time x_i the radon concentration averaged over the DGR is C_i and at time x_{i-1} the radon concentration is C_{i-1}.

$$C_i = \frac{m\left(1 - e^{\left(-n(x_i - x_{i-1})\right)}\right)}{n} + C_{i-1} e^{\left(-n(x_i - x_{i-1})\right)} \tag{E.5}$$

$$C_i = \frac{E \cdot (2w+2h)\left(1 - e^{\left(-\frac{\lambda_{Rn} wh}{\dot{V}}(x_i - x_{i-1})\right)}\right)}{\lambda_{Rn} wh} + C_{i-1} e^{\left(-\frac{\lambda_{Rn} wh}{\dot{V}}(x_i - x_{i-1})\right)} \tag{E.6}$$

APPENDIX F: DERIVATION OF EQUATION USED TO ESTIMATE THE RADON CONCENTRATION IN AN EMPLACEMENT ROOM OR THE DGR DURING OPERATIONS PHASE (EQUATION 3.7)

The rate of change of radon concentration in the DGR is based on a mass balance of the amount of radon present at time t.

The change in concentration of radon in the DGR (C) is equal to the amount entering, IN (by emanation through the rock walls) less the amount leaving, OUT (by decay and ventilation).

$$\frac{\partial C}{\partial t} = IN - OUT \tag{F.1}$$

$$\frac{\partial C}{\partial t} = \frac{E \cdot SA_{wall}}{V_{rep}} + R_w - \lambda_{Rn} C - \lambda_v C \tag{F.2}$$

Where E is the emanation rate (Bq/m^{2}s), SA_{wall} is the time-varying surface area inside an emplacement room or the entire DGR (m^2), V_{rep} is the time-varying excavated volume of an emplacement room or the entire DGR (m^3), R_w is the radon emissions from the used fuel (Bq/m^{3}s), λ_{Rn} is the decay rate of radon-222 (1/s), and λ_v is the ventilation rate (1/s).

Let $m = \frac{E \cdot SA}{V_{rep}} + R_w$ and $n = \lambda_{Rn} + \lambda_v$

$$\frac{\partial C}{\partial t} = m - nC \tag{F.3}$$

$$\frac{\partial C}{m - nC} = \partial t \tag{F.4}$$

We integrate over a time step defined as: t_i- t_{i-1}.

At time t_i the radon concentration averaged over the DGR is C_i and at time t_{i-1} the radon concentration is C_{i-1}.

$$C_i = \frac{m\left(1 - e^{\left(-n(t_i - t_{i-1})\right)}\right)}{n} + C_{i-1} e^{\left(-n(t_i - t_{i-1})\right)} \tag{F.5}$$

$$C_i = \left(\frac{E \cdot SA}{V_{rep}} + R_w\right) \frac{\left(1 - e^{\left(-(\lambda_{Rn} + \lambda_v)(t_i - t_{i-1})\right)}\right)}{(\lambda_{Rn} + \lambda_v)} + C_{i-1} e^{\left(-(\lambda_{Rn} + \lambda_v)(t_i - t_{i-1})\right)} \tag{F.6}$$