OPG's DEEP GEOLOGIC

REPOSITORY

FOR LOW & INTERMEDIATE LEVEL WASTE

Radon Assessment

March 2011

Prepared by: Nuclear Waste Management Organization

NWMO DGR-TR-2011-34

nwmo
NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

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EXECUTIVE SUMMARY

Ontario Power Generation (OPG) is proposing to build a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) near the existing Western Waste Management Facility at the Bruce nuclear site in the Municipality of Kincardine, Ontario. The Nuclear Waste Management Organization (NWMO), on behalf of OPG, is preparing the Environmental Impact Statement (EIS) and Preliminary Safety Report (PSR) for the proposed repository.

An assessment of the radon hazard during construction and operation of the DGR is performed to determine whether there is a need for radon monitoring or development of any action levels in order to be in compliance with the applicable regulatory requirements.

The most abundant form of radon gas in nature is Rn-222, with a half-life of 3.82 days. It is formed by the radioactive decay of U-238 (and consequently Ra-226), which is a natural component of soil and rock. In the case of the DGR, another potential source of Rn-222 is Ra-226 from the radioactive waste itself.

The results of the assessment indicate there is no significant radon hazard to the workers or general public during construction and operation of the DGR. The concentration of radon in the repository remains low during all phases of development. The highest concentration in an area where workers may be present is on or near the waste rock pile, or in the ventilation exhaust tunnel. The concentration of radon in all locations is less than the Derived Working Limit of 150 Bq/m^3, based on the Canadian Guidelines for Management of Naturally Occurring Radioactive Materials (unrestricted classification). In addition, the worker dose rate is less than 1 mSv/year.

Considering the Derived Working Limit of 150 Bq/m^3, there is no need for routine radon monitoring or development of an action level. Radon concentration should be checked during construction, and then periodically during operation as part of routine air quality and radiological surveys to assess its importance.

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1. INTRODUCTION

Ontario Power Generation (OPG) is proposing to build a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste (L&ILW) near the existing Western Waste Management Facility (WWMF) at the Bruce nuclear site in the Municipality of Kincardine, Ontario. The Nuclear Waste Management Organization (NWMO), on behalf of OPG, is preparing the Environmental Impact Statement (EIS) and Preliminary Safety Report (PSR) for the proposed repository.

The objectives of this report are to assess the hazard due to Radon-222 (hereon referred to as radon) emanation from the surrounding host rock and from the waste during construction and operations, and to recommend whether radiation protection (action level) and radiation monitoring will be required for radon during these periods.

This report estimates radon emanation rate from the DGR surrounding host rock, based on rock properties of the Cobourg formation from the site characterization (INTERA 2011), and the preliminary design of the DGR (OPG 2011). Radon characteristics and criteria, and relevant information on DGR construction and operations are given in Chapter 2. The methodology to estimate the radon emanation rate, together with the calculated value, is given in Chapter 3. In Chapter 4, radon concentrations during the construction and operations phases are calculated. The estimated radon concentrations are then compared to applicable criteria, and a recommendation is made on whether radiation protection (action level) and radiation monitoring is required.

2. BACKGROUND

2.1 Radon Characteristics

Radon is a naturally occurring member of the uranium, thorium and actinium series. Most of the uranium series elements are solids; however, radon is a gas. Upon generation of radon from its precursor, radon can escape from the crystalline structure of rock and diffuse towards the free atmosphere. Naturally occurring radon emanates constantly from rock and is dissolved in, and transported by, groundwater. Radon is also generated from the decay of radium in the radioactive waste.

The most abundant form of radon is Rn-222, with a half life of 3.82 days. As such, this is the radon isotope that is considered in this analysis. 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 occurs at low levels in virtually all rock, soil, water, plants, and animals.

Radon decay products are divided into two groups: the short-lived radon progeny Po-218 (3.05 min), Pb-214 (26.8 min), Bi-214 (19.7 min), and Po-214 (164 micro s) with half-lives below 30 min; and the long-lived radon decay products Pb-210 (22.3 years), Bi-210 (5.01 d), and Po-210 (138.4 d) (Porstendorfer 1994). Radon progeny concentration in air 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 x 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 h working hours per month, the cumulative exposure of any individual may be calculated as (Section 13.3.3, McPherson 1993):

$$\text{WLM} = \frac{\sum(WL \times hours\ of\ exposure)}{170} \tag{2.1}$$

As per the Canadian Guidelines for Management of Naturally Occurring Radioactive Materials (NORM) (Health Canada 2000), a radon progeny concentration of 0.2 WLM is equivalent to a radon concentration of approximately 150 Bq/m^3 and gives a dose of 1 mSv/year, based on occupational exposure (2000 hours per year).

Across Canada, the average internal public dose from inhalation of natural radon is about 1 mSv/year; 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/year but in Winnipeg it is 2.2 mSv/year (Health Canada 2000). Bruce Power, in its annual radiological monitoring report, reports an inhalation dose of 1 mSv/year from background radon (Bruce Power 2010). Radon released from soil beneath a building gives rise to an average indoor background concentration of about 50 Bq/m^3 (Health Canada 2000).

In open air, the concentration of radon gas is very small. In confined spaces, such as a mine, radon gas can accumulate and reach relatively high concentration levels, and become a health hazard. Two of radon’s progeny, Po-218 and Po-214, decay rapidly themselves, and emit alpha particles. When alpha particles hit an object, the energy in them 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, Health Canada 2009).

2.2 Radon Assessment Criteria

The radiation protection criteria applicable to DGR during construction and operation are in accordance with the Radiation Protection Regulations promulgated under the Nuclear Safety and Control Act. The Canadian Nuclear Safety Commission (CNSC) regulatory dose limits for the public and Nuclear Energy Workers (NEWs) are shown in Table 2.1.

Table 2.1: CNSC Effective Dose Limits

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 ensure that the above limits are met, specific constraints are in place and radiation protection programs are usually developed to address potential exposure to various levels of radon concentration. The development of any management program for the NORM (such as radon) is based on Health Canada Guidelines (Health Canada 2000). These programs, based on the highest individual dose received by the workers and the general public, can be divided into three classifications, as described below.

- Unrestricted – The concentration of radon is less than 150 Bq/m^3. The estimated incremental annual effective dose is less than 0.3 mSv/year to the public and less than 1 mSv/year to the worker. No further action is needed to control doses or materials.
- NORM Management – The concentration of radon is between 150 and 800 Bq/m^3. The estimated incremental annual effective dose to the members of the public or incidental workers is greater than the investigation threshold of 0.3 mSv/year. The estimated annual dose to workers is less than 5 mSv/year. Public access would need to be restricted. However, worker access would be unrestricted.
- Radiation Protection (Dose) Management – The concentration of radon is greater than 800 Bq/m^3. The estimated incremental annual effective dose to an occupationally exposed worker is greater than 5 mSv/year.

To assist in the assessment of the doses, Derived Working Limits (DWLs) are determined based on the annual dose limits (Health Canada 2000). The DWLs provide estimates of doses from quantities that may be directly measured in the workplace.

The radon criterion for workers adopted for this assessment is a DWL of 150 Bq/m^3 (Health Canada 2000), corresponding to the unrestricted classification. This criterion is used to determine if radiation monitoring and specific action levels are required for radon during construction and operation of the DGR.

It should be noted that 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.

2.3 DGR Construction and Operations Summary

2.3.1 DGR Construction

The construction approach for the DGR is outlined in Chapter 9 of the PSR (OPG 2011). The first step in construction will be site preparation activities and construction of key surface facilities, including the headframe. Shaft sinking will commence once some preparation steps are completed. The main and ventilation shaft will be sunk simultaneously. Once shaft sinking reaches approximately 680 mBGS, the horizon of the repository will be developed and the two shafts will be connected to establish a ventilation circuit.

Initially, lateral development will be limited by the space available for excavation equipment and the number of rock faces available. As development progresses, there will be a build-up of equipment, and the rate of rock extraction will increase. The rock extraction rates during DGR lateral development are summarized in Table 2.2.

Table 2.2: Rock Extraction Rates during DGR Lateral Development

Lateral Development Phase	Estimated Daily Extraction Rate (tonnes/day)	Approximate Volume Excavated (m^3)
Phase 1	900	30,000
Phase 2	1,400	50,000
Phase 3	2,100	510,000

2.3.1.1 Waste Rock Pile

Waste rock generated by the excavation of the DGR will be managed on site at the Waste Rock Management Area (WRMA). Some of the rock excavated during construction will be temporarily stored at the WRMA, and eventually used in the construction of berms and roadways. Only the limestone will be managed at the WRMA in the long-term, creating a pile of approximately 832,000 m^3. The estimated quantities of excavated materials are shown in Table 2.3 (OPG 2011).

Table 2.3: Estimated Quantites of Excavated Materials

Material Type	Temporary/ Long-term	Material Quantity (in situ) (m^3)	Material Quantity (Bulked) (m^3)
Overburden	Temporary	1,400	2,000
Dolostones	Temporary	29,400	41,200
Shales	Temporary	26,100	36,500
Argillaceous Limestone	Long-term	594,200	832,000

The limestone rock pile covers a surface area of 8.7 ha and is 15 m tall. For the purpose of this assessment, it is assumed that the waste rock pile is a square shaped, flat-top pile. The waste rock pile is 15 m tall at its highest point, and the base covers a 290 m x 290 m area.

2.3.2 DGR Operations

The underground layout of the DGR will contain two panels as shown in Figure 2.1 (Chapter 6, OPG 2011). Panel 2 will be filled first, primarily with low level waste (LLW) materials and is the furthest away from the shaft area. The furthest nine rooms of Panel 1 will be filled next, receiving a mix of LLW and intermediate level waste (ILW). The closest five rooms (in Panel 1) will be filled last, primarily with ILW materials.

The DGR is designed with the intention that a block of rooms that is filled to capacity can be closed off. Upon a block of rooms reaching capacity and after a suitable monitoring period, ventilation will be disconnected and those rooms will be permanently sealed by the construction of closure walls in the panel access tunnel and the ventilation exhaust tunnel.

The surface areas of the DGR emplacement rooms, access tunnels, and shaft and services area are presented in Table 2.4 (NWMO 2010). These surface areas include the walls, floor and ceiling of the repository. The volume of the repository is shown in Table 2.5 (NWMO 2010). When the repository has reached maximum waste capacity, the average free volume in emplacement rooms will be 60% in Panel 1 and 40% in Panel 2 (NWMO 2010).

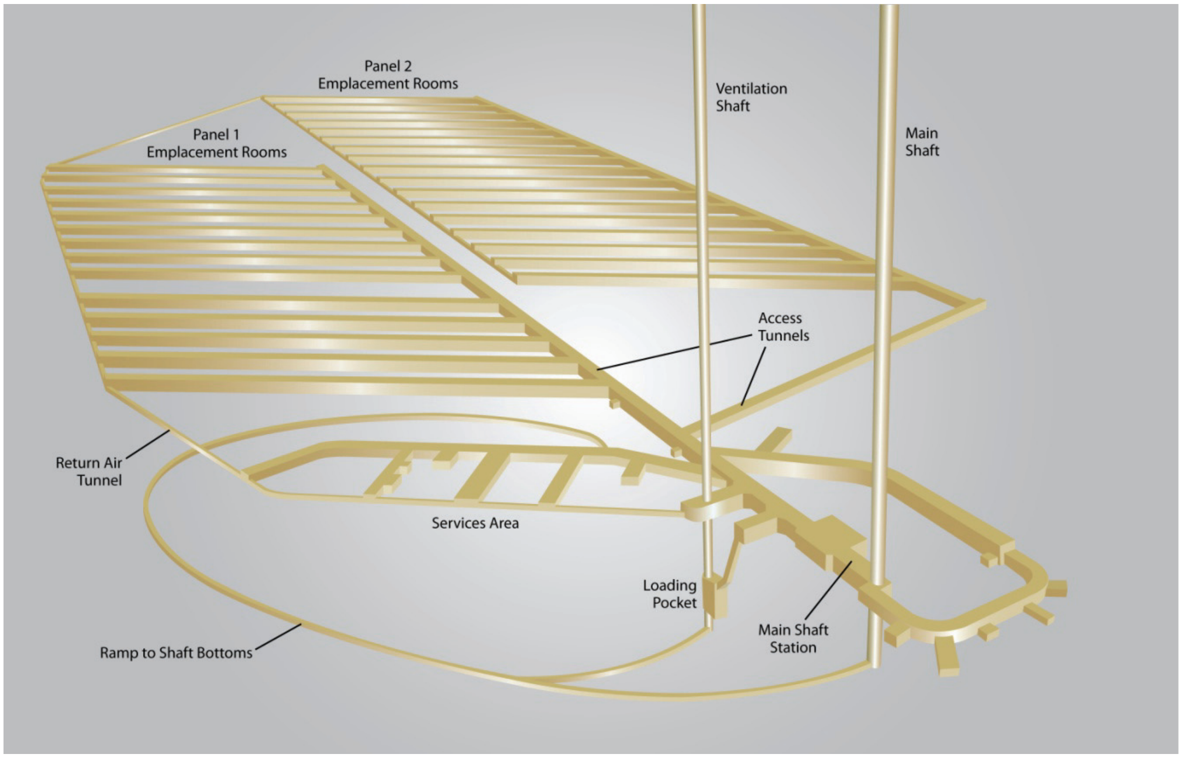

Figure 2.1: DGR Underground Layout

Table 2.4: DGR Surface Area

Location	Surface Area (m^2)
Emplacement Rooms	2.4E+05
Access Tunnels (outside shaft and services area)	5.8E+04
Shaft and Services Area	4.0E+04
Total	**3.4E+05**

Table 2.5: DGR Volume

Location	Volume (m^3)
Emplacement Rooms	4.4E+05
Access Tunnels (outside shaft and services area)	7.9E+04
Shaft and Services Area	5.6E+04
Total	**5.7E+05**

2.3.3 Ventilation System

The ventilation model for the DGR is described in the PSR (OPG 2011). The total volume of air supplied to the DGR will be periodically adjusted throughout the life cycle of the facility based on the nature of work being performed. During the operations phase, the number of active and non-active rooms will affect the volume of air required.

The DGR is designed to be a “flow-through” ventilation system. Ventilation flow through the facility will be facilitated primarily by the action of maintaining the underground facility under a negative pressure such that air flows from the main shaft and through the repository level to the ventilation shaft. From the main shaft, fresh air will be directed to the access tunnels through the use of booster fans located adjacent to the shaft. The balance of fresh air will flow freely across the main shaft station to the ventilation shaft to provide for diesel equipment and personnel unloading the main cage and the staging area. The distribution of air underground will be mainly controlled by the main exhaust fans located at the ventilation shaft on the repository level and regulators at the ends of the emplacement rooms. The exhaust air leaving the emplacement rooms will travel through ventilation exhaust tunnels to the ventilation shaft, and back to the surface.

2.3.3.1 Ventilation during Construction

Lateral development will employ a drill and blast technique for face advancement. A typical drill and blast excavation cycle is shown in Figure 2.2 (Chapter 9, OPG 2011). Ventilation will be required for all phases of the drill and blast cycle.

A room under construction will use both an exhausting duct and fan system along with a fresh air delivery fan and duct system. As the development face progresses, the end of the temporary duct will be extended so that fresh air is kept close to the working personnel. The exhaust/intake arrangement is shown in Figure 2.3 (Chapter 9, OPG 2011).

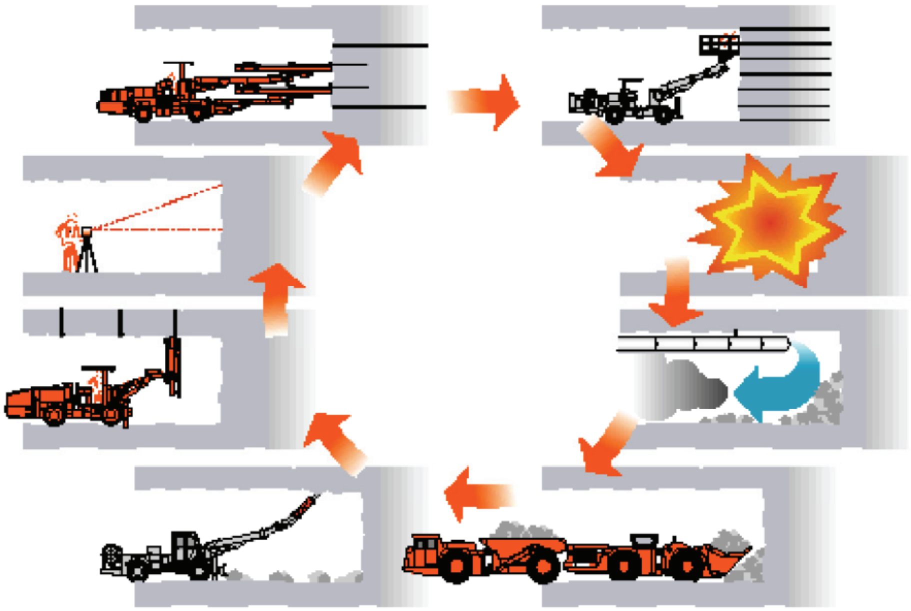

Figure 2.2: Typical Drill and Blast Excavation Cycle

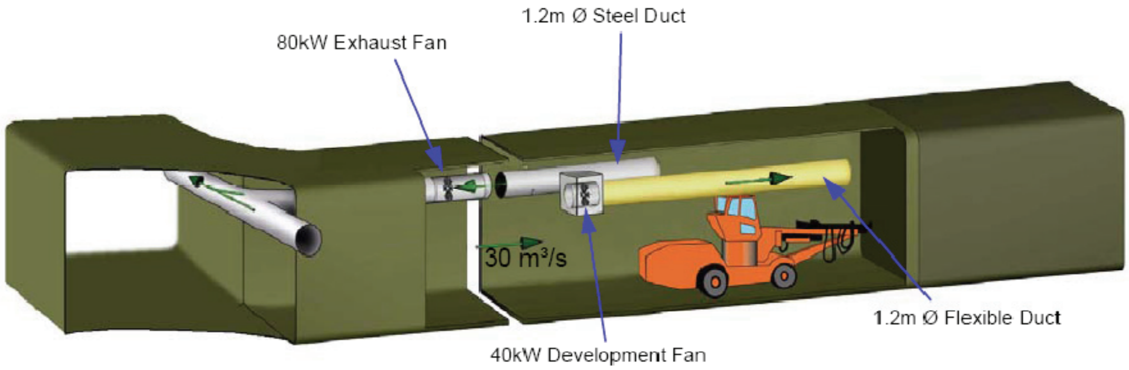

Figure 2.3: Ventilation during Construction

Ventilation during the construction phase is described in the PSR (Chapter 9, OPG 2011). The air requirement is based on the maximum amount of diesel equipment usage in the repository.

It is assumed that lateral development of the DGR will be carried out 24 hours per day, 7 days per week. The ventilation will, therefore, remain constant, as there will be no decreased activity over a 24 hour period.

2.3.3.2 Ventilation during DGR Operations

The primary driver for the total airflow requirements in the operations phase will be the amount of diesel equipment in operation underground and the need to ensure that the air levels of any contaminants are low. The general ventilation levels for emplacement rooms are described below (Chapter 7, OPG 2011).

- Active (i.e., rooms in the process of being filled) emplacement rooms will be ventilated at a rate of 18 m^3/s during the day and 3 m^3/s at night.
- Empty emplacement rooms will not be ventilated. They will be equipped with an entry barricade and signed.
- Filled emplacement rooms will be ventilated at a rate of approximately 1 m^3/s. A wall will be installed at the entrance to the room, but will still allow for ventilation.

Taking into account these ventilation levels and the number of emplacement rooms, and the need for additional air for other locations (especially the shaft station and maintenance bays), the airflow requirements for the DGR are expected to be approximately 100 m^3/s during the day, and about 50 m^3/s at night. The actual values will vary somewhat depending on the specific operating conditions and activities, as well as surface conditions.

3. ESTIMATION OF RADON EMANATION ROCK FROM 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.

3.1 Rock Properties

The radon emanation rate is based on properties of the host rock, which have been obtained by site characterization. The properties of interest include the rock porosity, the effective diffusion coefficient of gases in the rock and the uranium content.

Based on the site characterization data, the uranium concentration in the Cobourg formation is summarized in Table 3.1. The average concentration of uranium in the Cobourg is used for subsequent analysis in the present report.

The radium concentration in the host rock is assumed to be in secular equilibrium with uranium. Based on this assumption and taking the uranium concentration in the host rock to be 1.2 ppm (Table 3.1), the radium concentration is calculated as 4.1×10^4 Bq/m^3. The details of this calculation are shown in Appendix A.

Based on site characterization date, the Cobourg formation porosity is approximately 2% (INTERA 2011), and this porosity is mostly saturated. Tests indicate that the gas saturation in the Ordovician limestone is in the range 0-30% (INTERA 2011).

The diffusion coefficient of radon in the DGR host rock is estimated using the Millington and Shearer model (Aachib et al. 2002). This method predicts the diffusion of radon for partially saturated, porous materials, like the DGR host rock. The effective diffusion coefficient for radon is calculated as 3.0×10^{-10} m^2/s. The details of this calculation are shown in Appendix B.

The presence of water in a porous medium significantly decreases the diffusion of radon (Fournier et al. 2005). The diffusion coefficient for radon in the Cobourg formation is similar to that for mud with high moisture content; the effective diffusion coefficient in the pores of this mud material is on the order of 10^{-10} m^2/s (Chapter 2, Sengupta 1990).

3.2 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 soils range from 5 to 70% (Schumann and Gundersen 1996). Five samples of limestone bedrock from various world localities yielded emanation coefficients ranging from 0.6 to 2.2% (Barretto 1975).

Table 3.1: Uranium Concentration in the Cobourg Formation

Borehole	Sample Number	Uranium Concentration (ppm)	Reference
DGR-2	DGR2-659.31	1.54	Skowron and Hoffman 2009
	DGR2-669.27	1.51	
	DGR2-677.93	0.84	
DGR-3	DGR3-665.86	2.5	Wigston and Jackson 2010a
	DGR3-674.87	0.91	
	DGR3-684.23	1.1	
	DGR3-691.32	0.91	
	DGR3-699.62	1.4	
DGR-4	DGR4-655.14	2.2	Wigston and Jackson 2010b
	DGR4-667.94	0.77	
	DGR4-677.48	0.72	
	DGR4-682.41	0.66	
DGR-5	DGR5-704.99	1.1	Jackson and Murphy 2011
	DGR5-715.40	1.3	
	DGR5-725.33	0.88	
DGR-6	DGR6-750.80	1.4	Jackson and Murphy 2011
	DGR6-761.76	1.2	
	DGR6-768.58	1	
Average	-	1.2	-

Due to the low porosity of the Cobourg formation, an emanation coefficient of 2.2% is assumed (i.e., 2.2% of the radon generated would be released into the pore space, with the remainder staying in the grains of the host rock), based on the upper end of the emanation coefficient range in limestone samples (Barretto 1975).

3.3 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:

$$\beta = \alpha A_{Ra226} \lambda_{Rn} \qquad (3.1)$$

where α is the emanation coefficient (-), as discussed in Section 3.2, A_{Ra226} is the activity of radium per unit rock volume which decays to produce radon (Bq/m^3) and λ_{Rn} represents the decay rate for radon (1/s).

From Equation 3.1, the radon emanation power is 1.9 x 10^{-3} Bq/m^{3}s. The details of this calculation are shown in Table 3.2.

Table 3.2: Radon Emanation Power

Emanation coefficient (-)	2.2E-02
Ra-226 Activity (Bq/m^3)	4.1E+04
Decay Rate of Radon (1/s)	2.1E-06
Emanation power (Bq/m^{3}s)	1.9E-03

3.4 Emanation Rate

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

$$E = \beta\sqrt{\frac{D_e}{\lambda_{Rn}\phi}} \tag{3.2}$$

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) (-).

From Equation 3.2, the radon emanation rate is 1.6 x 10^{-4} Bq/m^{2}s. The details of this calculation are shown in Table 3.3.

A radon emanation rate of 1.6 x 10^{-4} Bq/m^{2}s, as calculated in Table 3.3, is well below the average measured radon emanation rate of 2.6 x 10^{-1} Bq/m^{2}s 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 uranium in the Cobourg formation). Ore grade is expected to relate to radon gas emanation, as radium is in secular equilibrium with uranium.

Table 3.3: Radon Emanation Rate

Emanation Power (Bq/m^{3}s)	1.9E-03
Effective Diffusion Coefficient (m^2/s)	3.0E-10
Decay Rate of Radon (1/s)	2.1E-06
Rock Porosity (-)	2.0E-02
Emanation Rate (Bq/m^{2}s)	1.6E-04

4. RADON ASSESSMENT

In order to assess the radon hazard in the DGR, both the construction phase and operations phase of the DGR are examined. As well, various levels of ventilation are considered. Due to very low permeability of host rock and very low uranium content in the host rock, there is very little radon-dissolved water influx from the host rock.

The radon concentration in the DGR during the construction and operations phases is compared to the DWL of 150 Bq/m^3 in order to determine whether further action is necessary (as discussed in Section 2.2). Doses due to inhalation of radon gas are given.

4.1 Maximum Concentration of Radon in the Host Rock Pore 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):

$$C_{max} = \frac{\beta}{\lambda_{Rn}\phi} \tag{4.1}$$

The calculated radon concentration in the Cobourg limestone host rock pore spaces (the maximum radon concentration) is, therefore, 4.5 x 10^4 Bq/m^3, approximately 300 times greater than the DWL of 150 Bq/m^3. It is emphasized that this concentration is strictly within the pore spaces in the rock, and is not reached in the DGR as there will be ventilation in the DGR which is not accounted for in the above calculation.

4.2 Estimated Radon Concentration and Doses in the DGR during Construction Phase

Radon is released from the rock at the working face as a result of drilling, and by diffusion from the already excavated areas. 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 from the surrounding host rock and from the temporary waste rock pile inside the DGR.

The concentration of radon in the DGR (C_i) can be estimated according to Equation 4.2:

$$C_i = \frac{\left(E\cdot SA_{walls}+E\cdot SA_{waste\,rock}+C_{pore\,space}\cdot V_R\cdot\phi\right)\left(1-e^{\left(-(\lambda_{Rn}+\lambda_v)(t_i-t_{i-1})\right)}\right)}{V_{rep}(\lambda_{Rn}+\lambda_v)} + C_{i-1}e^{\left(-(\lambda_{Rn}+\lambda_v)(t_i-t_{i-1})\right)} \tag{4.2}$$

where (t_i-t_{i-1}) represents a time step over which the concentration change is calculated (s), SA is the surface area of the repository or the waste rock (m^2), $C_{pore\ space}$ is the concentration of radon in the host rock pore space, as calculated by Equation 4.1 (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), and λ_v is the ventilation rate (1/s). The derivation of this equation can be seen in Appendix C.

The concentration of radon in the host rock pore space is 4.5 x 10^4 Bq/m^3, as shown in Section 4.1, and the mass of excavated rock per day is given in Table 2.2 for each stage of development. The surface area and volume of the repository increase as lateral development progresses. It is assumed that the underground temporary waste rock pile has a constant mass of 400 Mg, the capacity of the waste rock pile holding area.

The daily excavation increases over the course of the development, because more rock faces become available for excavation. Initially, development will only proceed at one rock face. In stage two, development will proceed at two rock faces. In stage three, multiple rock faces will be developed upon. The schedule for development, as shown in Table 2.2, is used to calculate the repository volume during the construction phase.

The ventilation rate during the construction phase is nominally 100 m^3/s, driven by the presence of diesel powered equipment used for development. The concentration of radon in the DGR for the three stages of lateral development is shown in Figure 4.1. This figure shows the full estimated lateral development period.

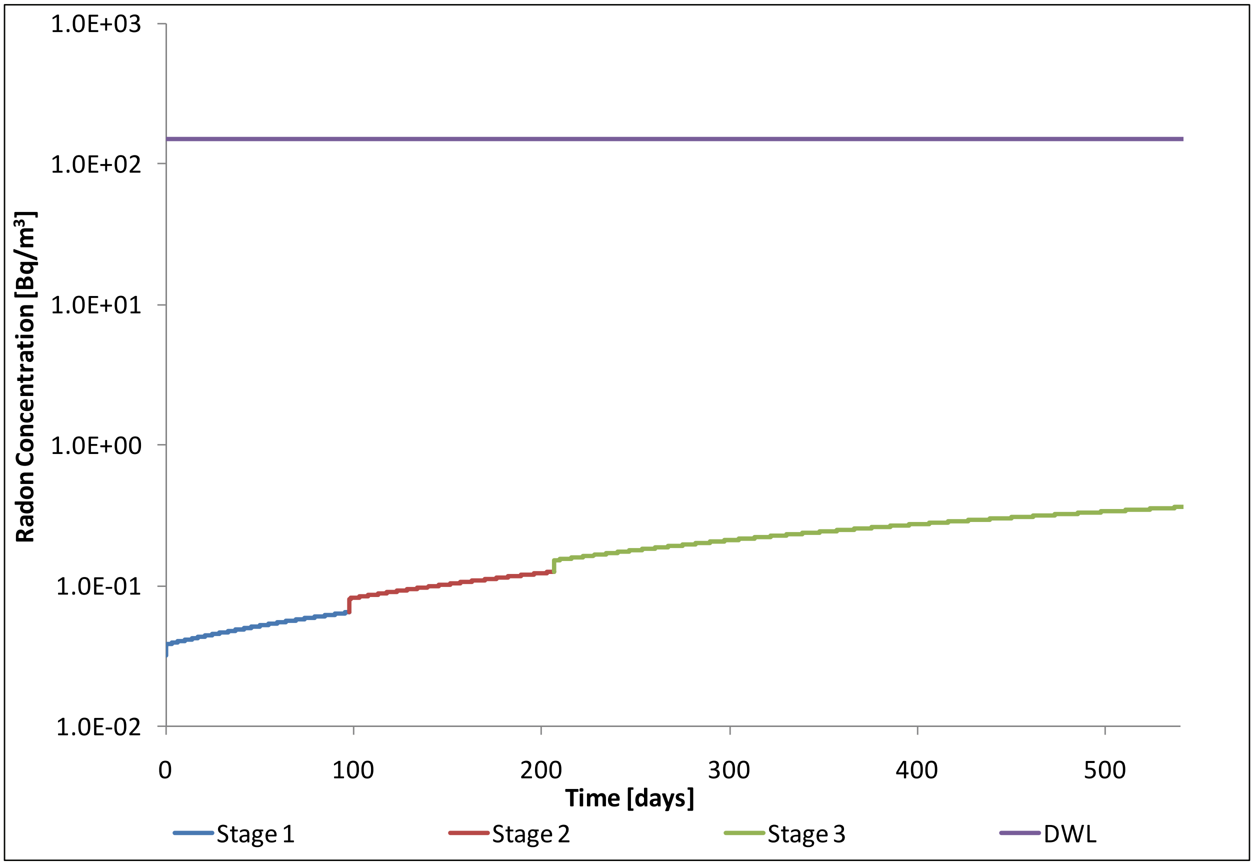

Figure 4.1: Average Radon Concentration in the DGR during Construction

The maximum concentration observed in the DGR during the construction phase is 0.38 Bq/m^3 (end of phase three of lateral development), more than two orders of magnitude less than the DWL of 150 Bq/m^3. As per the Canadian Guidelines for Management of NORM (Health Canada 2000), a radon concentration of approximately 150 Bq/m^3 is equivalent to a radon progeny concentration of 0.2 WLM and gives a dose of 1 mSv/year, based on occupational exposure (2000 hours per year). Hence the radon progeny concentration is approximately 5.1×10^{-4} WLM and the inhalation dose to workers in the DGR due to radon and its progeny is approximately 2.5×10^{-3} mSv/year. This does not take into account that there will likely be as much as an hour following a blast to clear blast fumes, during which time no workers will be present.

4.2.1 Estimated Radon Release from Above-Ground Waste Rock Pile

In this section, radon emissions from the limestone waste rock pile are estimated. The other waste rock piles are not examined, as they are much smaller and will only be at the WRMA temporarily.

The properties of the limestone waste rock pile are significantly different from those of the limestone underground in the DGR. As such, a new emanation rate is estimated.

An average moisture content of 8% is typical of limestone stock piles. 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):

$$D_e = 0.66\phi_{WRP}D_a^o \tag{4.3}$$

where $D°_a$ represents the open air diffusion coefficient (m^2/s) and ϕ_{WRP} is the porosity (fraction) of the waste rock pile (-). The diffusion coefficient of radon in open air is 1.2×10^{-5} m^2/s (Chapter 2, Sengupta 1990). Based on a bulked volume of limestone of 8.3×10^5 m^3, and an in situ volume of limestone of 5.9×10^5 m^3, the porosity of the waste rock pile is approximately 30%.

The emanation rate can be estimated for the waste rock pile using Equations 3.1 and 3.2. An emanation coefficient of 50% is conservatively assumed. The details of this calculation are shown in Table 4.1.

Table 4.1: Radon Emanation Power and Emanation Rate from the Waste Rock Pile

Emanation Coefficient (-)	5.0E-01
Activity of Radium (in bulked rock) (Bq/m^3) [a]	2.9E+04
Decay Rate of Radon (1/s)	2.1E-06
Emanation Power (Bq/m^3s)	**3.1E-02**
Diffusion of Radon in Air (m^2/s)	1.2E-05
Porosity of Waste Rock Pile (-)	2.9E-01
Emanation Rate (Bq/m^2s)	**6.0E-02**

Note: 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 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 concentration of radon in the atmospheric compartment above the pile (C) can be estimated according to Equation 4.4:

$$C = \frac{E\, SA_1}{V_{wind} SA_2 + \lambda_{Rn} V_C} \tag{4.4}$$

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 annual average wind velocity at the Bruce nuclear 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 D.

The size of the limestone rock pile has been discussed in Section 2.3.1.1. The atmospheric compartment considered for this analysis measures 2 m x 210 m x 210 m (the area at the top of the waste rock pile). A drawing of this compartment can be seen in Appendix D.

The annual average wind velocity at the Bruce nuclear site is 11.8 km/h (or 3.3 m/s), predominantly to the south (Table 5.3.4-1, GOLDER 2011). A wind speed of 2 m/s will be used in this analysis, in order to protect workers during periods of low winds.

The average concentration of radon in the atmospheric compartment on top of the waste rock pile is 3.1 Bq/m^3. A worker inhalation dose of 0.021 mSv/year due to radon is estimated, conservatively assuming 2000 hours are spent near the waste rock pile.

For the case of a worker standing down-wind of the waste rock pile, radon enters the atmospheric compartment by radon emanation from the waste rock pile and by wind which has collected radon flowing over the top of the waste rock pile. Radon leaves by decay and wind transport.

The concentration of radon in the atmospheric compartment downwind of the pile (C) can be estimated according to Equation 4.5:

$$C = \frac{E\, SA_3 + f V_{wind} SA_4 C_{initial}}{f V_{wind} SA_4 + \lambda_{Rn} V_C} \tag{4.5}$$

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 fact that there is a wake region on the down-wind side of a pile and only a fraction of the nominal wind velocity proceeds into this compartment (-), SA_4 represents the surface area of the compartment perpendicular to the direction of wind flow (m^2), and $C_{initial}$ 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 E.

The atmospheric compartment for this analysis measures 2 m thick (perpendicular distance from the slope of the waste rock pile to the parallel boundary of the compartment), and extends 290 m (the estimated length of the waste rock pile) to the top of the slope (15 m off the ground, with a slope length of 43 m). This compartment is shown in Appendix E.

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 analysis, 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 Bruce nuclear site (i.e., f is equal to 0.2).

The average concentration in the atmospheric compartment down-wind of the waste rock pile is 6.3 Bq/m^3. A worker inhalation dose of 0.042 mSv/year due to radon is estimated, conservatively assuming the worker spends 2000 hours near the waste rock pile.

In order to assess the impact of radon on the public, air dispersion effects are considered. The effect of air dispersion was estimated in the WWMF Derived Release Limit (DRL) calculations using Atmospheric Dilution Factors (ADFs) (OPG 2003). The WWMF DRLs are based on a single ground level release source for airborne radionuclide releases. The ADFs were developed using the model in the DRL Guidance document. Meteorological data used were triple joint frequencies of wind direction, speed and stability class from average data over 1998 to 2002 obtained from the on-site meteorological tower at the 10 m elevation. The receptors are offsite, and all greater than 1 km distant.

It is assumed that this atmospheric dispersion model is also applicable to radon release from the WRMA. An ADF of 2.05 x 10^{-7} s/m^3 (OPG 2003) in particular is used for this analysis. This ADF corresponds to the nearest group of inland residences, approximately 2.7 km south-southeast of the WWMF. This is the most conservative ADF predicted for all of the receptors considered (OPG 2003).

The maximum radon concentration in the vicinity of the public receptor is summarized in Table 4.2.

Table 4.2: Radon Concentration in the Vicinity of the Public

Emanation Rate (Bq/m^{2}s)	6.0E-02
Approximate Surface Area of Waste Rock Pile (m^2)	8.7E+04
Average Rate of Emission (Bq/s)	5.2E+03
ADF (s/m^3)	2.1E-07
Maximum Radon Concentration in vicinity of public (Bq/m^3)	1.1E-03

The maximum estimated radon concentration from the WRMA at a continuous public receptor location is 1.1 x 10^{-3} Bq/m^3. This is significantly less than the average indoor and outdoor radon concentrations in Canada, 50 Bq/m^3 and 10 Bq/m^3, respectively (CNSC 2011, Health Canada 2000, Health Canada 2007). The Health Canada guideline for radon levels in indoor air is 200 Bq/m^3 (CNSC 2011).

A dose coefficient of 2.4 x 10^{-9} (Sv/ h)/(Bq/ m^3) is recommended for external irradiation and inhalation of Rn-222 gas by the International Commission on Radiological Protection (ICRP 1993). As such, the maximum public dose due to radon emanation from the waste rock pile is approximately 0.02 μSv/year (based on 8760 hours per year).

The average rate of emission from the waste rock pile of 5.2 x 10^3 Bq/s, as shown in Table 4.2, is equivalent to 0.4 GBq/day. In comparison, the radon release from the waste rock pile at the Rum Jungle uranium mining site in Australia has been measured as 25 GBq/day (Mudd 2008). The Rum Jungle rock pile has a U ore grade of 0.01% and covers an area of 26 ha. If the radon release from the Rum Jungle rock pile is scaled to the size and U content of the WRMA rock pile, then a release rate of 0.2 GBq/day is estimated, approximately consistent with the present estimated WRMA radon release rate.

4.3 Estimated Radon Concentration and Doses in the DGR during Operations Phase

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

4.3.1 Underground Tunnel

The radon level in the DGR varies depending on location. Air entering through the main shaft is free of radon. As air travels from the main shaft, through the repository and out the ventilation shaft, radon builds-up. Thus, the air leaving through the ventilation shaft contains the highest concentration of radon.

The radon concentration as a function of location can be estimated by treating the DGR as one long tunnel. The radon concentration can be calculated from Equation 4.6.

$$C_i = \frac{E \cdot (2w+2h)\left(1-e^{\left(-\frac{\lambda_{Rn} wh}{Q}(x_i - x_{i-1})\right)}\right)}{\lambda_{Rn} wh} + C_{i-1} e^{\left(-\frac{\lambda_{Rn} wh}{Q}(x_i - x_{i-1})\right)} \tag{4.6}$$

where (x_i-x_{i-1}) represents the iteration interval (a distance) over which the concentration change is calculated (m), Q 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 F.

One pathway of air, from the entry of air into the DGR by the main shaft to the end of an emplacement room, can be represented by a tunnel. The longest pathway for the initial DGR conditions is modelled. This is also the path where workers are present. No waste is included in this analysis, as the model follows the flow of ventilation air, and the workers are always in fresh air, on the upwind side of the waste packages. (A worker standing in the ventilation exhaust tunnel will be considered separately, as this worker will be on the downwind side of a waste package.) This pathway is shown in Figure 4.2. The tunnel can be divided into five parts: the west services tunnel, south services tunnel, Panel 2 (south) access tunnel, Panel 2 room access tunnel and emplacement room. The maximum radon concentration in this path will occur at point A (Figure 4.2). The properties for each section are listed in Table 4.3. The radon emanation rate was determined in Section 3.4.

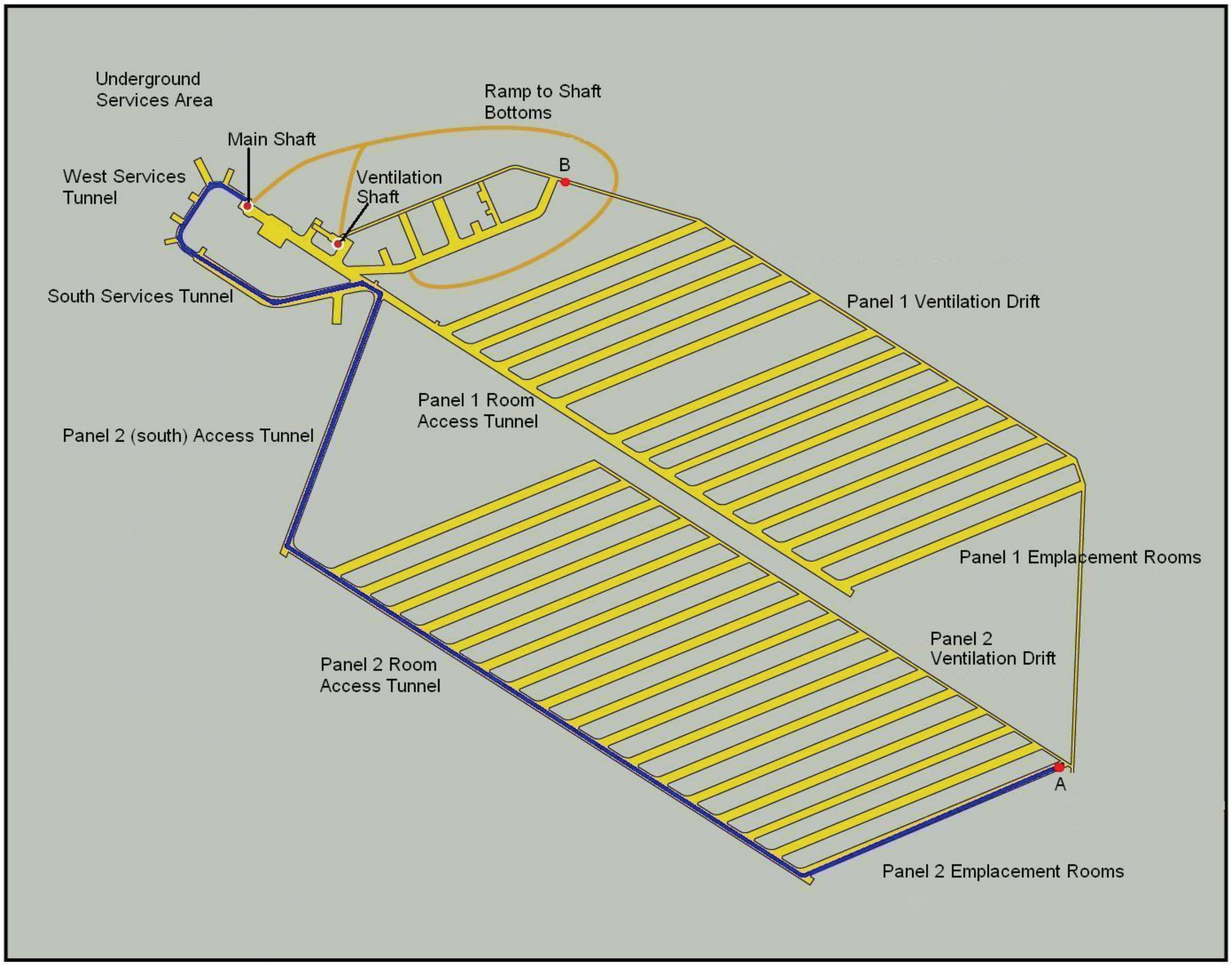

Figure 4.2: DGR Layout with Ventilation Path of Radon Concentration Analysis

Table 4.3: DGR Properties by Location

Property	West Services Tunnel	South Services Tunnel	P2 (South) Access Tunnel	P2 Room Access Tunnel	Profile 1 Emplacement Room
Length (m)	95 [a]	150	260	560	250
Width (m)	4.5	8.1	5.9	5.4	8.6
Height (m)	4.5	6.4	6.4	6.4	7
Volume (m^3)	2.9E+03	7.8E+03	9.8E+03	1.9E+04	1.5E+04
Ventilation Rate (m^3/s)	78	78	55	55	18

Notes: a - Side room volume is estimated as 50% extra length of main tunnel

The maximum radon concentration reached in the DGR for the pathway shown in Figure 4.2 (point A) is 0.14 Bq/m^3, occurring at the end of an active (and ventilated) emplacement room. This concentration is a factor of 1000 less than the DWL of 150 Bq/m^3. A worker dose of 9.3 x 10^{-4} mSv/year due to radon is estimated.

4.3.2 Empty Emplacement Room

The average concentration of radon in an emplacement room (or in the DGR) (C_i) can be estimated according to:

$$C_i = \left(\frac{E \cdot SA_{walls}}{V_{rep}} + R_w\right)\frac{\left(1 - e^{\left(-(\lambda_{Rn}+\lambda_v)(t_i - t_{i-1})\right)}\right)}{(\lambda_{Rn}+\lambda_v)} + C_{i-1}e^{\left(-(\lambda_{Rn}+\lambda_v)(t_i - t_{i-1})\right)} \quad (4.7)$$

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 emplacement room (or DGR) (m^2), V_{rep} is the excavated volume of the emplacement room (or DGR) (m^3) and R_w is the radon emissions from waste (Bq/m^{3}s). The details of derivation of this equation can be seen in Appendix G. Note that this does not take any credit for the effectiveness of concrete floors and shotcrete on walls in reducing the diffusion rate of radon into the DGR. In an empty emplacement room, there is no waste present. As such, there are no radon emissions from waste (i.e., R_w=0).

The dimensions of an emplacement room are summarized in Table 4.3. The ventilation rate in an empty emplacement room is listed in Section 2.3.3.2.

The maximum concentration during the operation of the DGR due to radon from the host rock is 40 Bq/m^3 in an empty, unventilated emplacement room. This is less than a third of the DWL of 150 Bq/m^3 (and approximately 0.05 WLM). However empty rooms are barricaded and workers are not permitted to enter an unventilated room. Loss of radon by diffusion from the empty room is possible, depending on the barrier but was conservatively not considered in the room concentration.

4.3.3 Ventilation Shaft

The average radon concentration in the DGR ventilation shaft can be estimated from Equation 4.7. The radon emanation rate was determined in Section 3.4. The calculation considers the entire DGR surface area and volume (Tables 2.4 and 2.5). The ventilation rates for the DGR are listed in Section 2.3.3.2. Ventilation rates of 100 m^3/s during the day and 50 m^3/s at night are considered.

During operations, waste packages emplaced in the DGR may be another source of radon. Specifically, used radium sealed sources are placed in dedicated non-processible waste packages. Uranium in the wastes comes mostly from fuel sources, and therefore the uranium would not have decayed enough for radium and radon to be present in significant amounts.

The radon concentration due to emissions from waste packages (R_w) is calculated by dividing the generation rate of radon from radium by the void space in an emplacement room. The generation rate of radon from radium can be calculated using Equation 3.1. The inventory of radium in ventilated emplacement rooms in the DGR is approximately 2.8 x 10^9 Bq, not taking credit for the closure of rooms (OPG 2010). Sealed sources are stored inside of instruments or (metal or plastic) pails, and placed inside a dedicated non-processible waste bin. It is assumed that only 10% of the generated radon escapes from the waste packages (i.e., α=0.1) because sealed sources are stored inside multiple layers of packaging.

The estimated average radon concentration in the ventilation shaft over 10 days of operations is shown in Figure 4.3. This figure shows that the average radon levels quickly reach equilibrium levels, and are less than the DWL of 150 Bq/m^3.

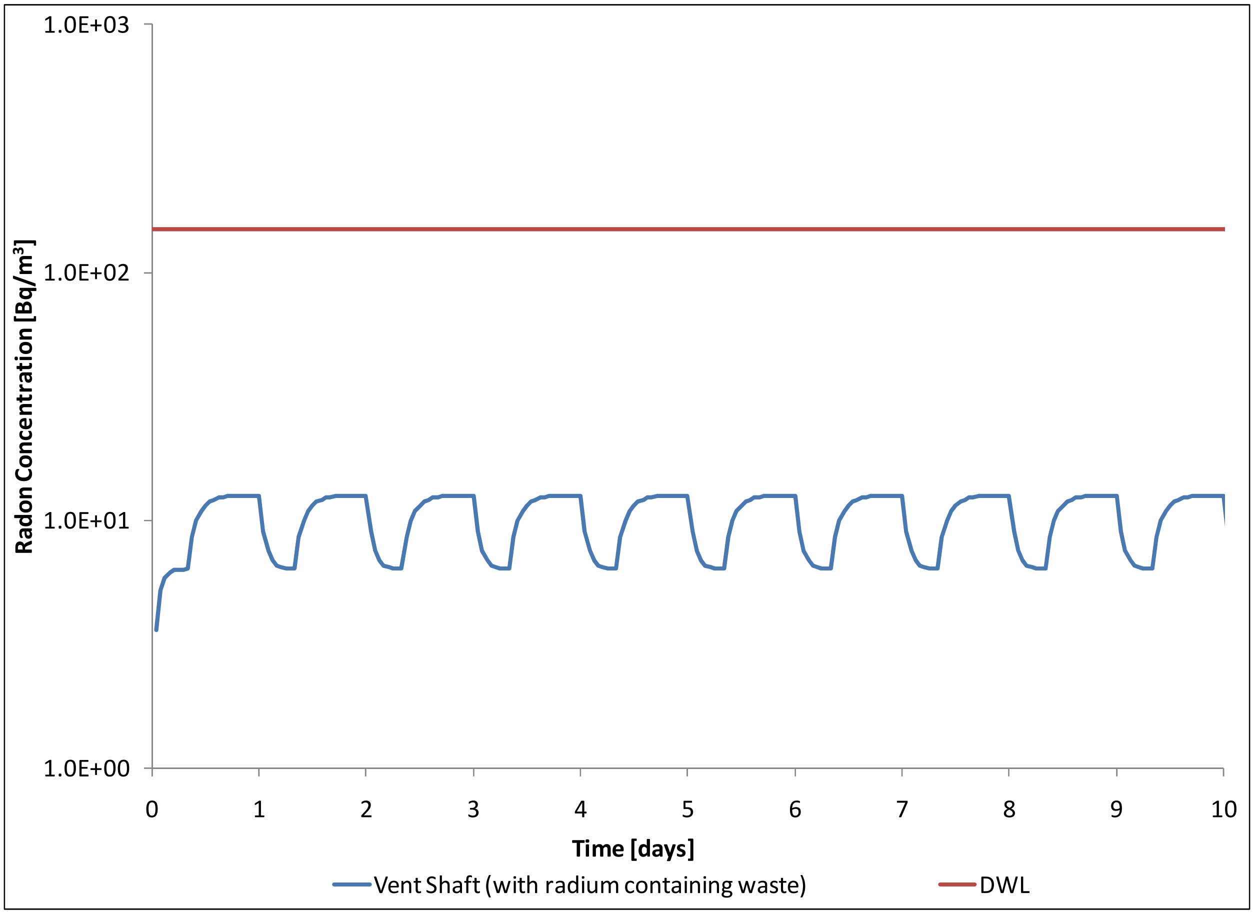

Figure 4.3: Average Radon Concentration in the DGR Ventilation Shaft during Operations

The maximum concentration observed in the DGR ventilation shaft during the operations phase is 13 Bq/m^3 (at night), a factor of 12 less than the DWL of 150 Bq/m^3. The radon concentration in the ventilation shaft during daytime hours is 6.4 Bq/m^3. The dose to a worker in the ventilation shaft (for inspection and maintenance) is approximately 5.5 x 10^{-3} mSv/year (based on 260 hours per year in the shaft conducting weekly/monthly inspections).

The dose to a public receptor due to radon release from the DGR during the operations phase is 2.7 x 10^{-3} μSv/year, based on an ADF of 2.05 x 10^{-7} s/m^3 (OPG 2003) and a dose coefficient of 2.4 x 10^{-9} (Sv/ h)/(Bq/m^3) for external irradiation and inhalation of Rn-222 gas (ICRP 1993).

For workers in the ventilation drift, the radon concentration will be greater than that in the ventilation shaft at certain times during the repository evolution, due to radon releases from the waste and the lower ventilation rate in the exhaust tunnel as compared to the ventilation shaft. The location of maximum radon concentration is shown in Figure 4.2 (point B). The radon concentration at point B can be calculated by scaling the radon concentration in the ventilation shaft based on the air flow rate.

The radon concentration in the ventilation shaft during the day has been calculated as 6.4 Bq/m^3, based on an air flow rate of 100 m^3/s. A ventilation rate of 69 m^3/s during the day is considered for the ventilation exhaust tunnel, based on the requirements for full and active emplacement rooms in Panel 2 and a nominal flowrate of 1 m^3/s in Panel 1.

The radon concentration in the ventilation drift will be approximately 9.3 Bq/m^3. The dose to a worker in the ventilation drift is approximately 8.0 x 10^{-3} mSv/year (based on 260 hours per year in the ventilation drift conducting weekly/monthly inspections).

5. CONCLUSION

An assessment of the radon hazard during construction and operation of the DGR has been performed to determine whether there is a need for radon monitoring or development of any action levels in order to be in compliance with the applicable regulatory requirements.

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 rock properties, and the low concentration of radium in the waste, the concentration of radon in the repository remains low during all phases of development. The estimated steady state concentrations of radon during various phases of the DGR are summarized in Table 5.1.

The highest concentration in an area where workers may be present is on or near the waste rock pile or in the ventilation exhaust tunnel. There will be no person working in the empty, unventilated emplacement room.

Considering the Derived Working Limit from the Canadian Guidelines for Management of Naturally Occurring Radioactive Materials of 150 Bq/m^3, there is no need for routine radon monitoring or development of an action level. Radon concentrations should be checked during construction, and then periodically during operation as part of routine air quality and radiological surveys to assess its importance.

Table 5.1: Summary of Radon Concentration and Dose in the DGR

		Maximum Radon Concentration (Bq/m^3)	**Maximum Dose Rate (mSv/year)**
Cobourg Host Rock Pore Space		4.5E+04	n/a
Construction Phase	Lateral Development - Stage 1	6.5E-02	4.3E-04 [a]
	Lateral Development - Stage 2	1.3E-01	8.4E-04 [a]
	Lateral Development - Stage 3	3.8E-01	2.5E-03 [a]
Waste Rock Pile	Worker (standing on pile)	3.1E+00	2.1E-02 [a]
	Worker (leeward side of pile)	6.3E+00	4.2E-02 [a]
	Public	1.1E-03	2.2E-05 [b]
Operations Phase	Underground Tunnel	1.4E-01	9.3E-04 [a]
	Empty, Unventilated Room	4.0E+01	n/a
	Ventilation Shaft	6.4E+00	5.5E-03 [c]
	Ventilation Exhaust Tunnel	9.3E+00	8.0E-03 [c]
	Public	1.3E-04	2.7E-06 [b]
Derived Working Limit		1.5E+02	1

Notes: a- Based on 2000 working hours per year; b- Based on 8760 hours per year; c- Based on 260 working hours per year

6. REFERENCES

Aachib, M., M. Aubertin and M. Mbonimpa. 2002. Laboratory Measurements and Predictive Equations for Gas Diffusion Coefficient of Unsaturated Soils. Canadian Geotechnical Society/International Association of Hydrogeologists Conference. Niagara Falls, Canada.

Barretto, P.M.C. 1975. Radon-222 Emanation Characteristics of Rocks and Minerals. Panel Proceedings Radon in Uranium Mining. International Atomic Energy Agency STI/PUB/391. Vienna, Austria.

Billman, B.J. and S.P.S. Arya. 1985. Windbreak effectiveness for storage-pile fugitive-dust control: a wind tunnel study. Research Triangle Park, N.C.: U.S. Environmental Protection Agency, Atmospheric Sciences Research Laboratory. EPA/600/S 3-85/059. USA.

Bruce Power. 2010. Annual Summary and Assessment of Environmental Radiological Data for 2009. Bruce Power Report B-REP-03419-00010 R000. Kincardine, Canada.

CNSC. 2011. Radon and Health. Canadian Nuclear Safety Commission INFO-0813. Ottawa, Canada.

Fournier, F., J.E. Groetz, F. Jacob, J.M Crolet and H. Lettner. 2005. Simulation of radon transport through building materials: influence of the water content on Radon exhalation rate. Transport in Porous Media 59, 197-214.

GOLDER. 2011. Atmospheric Environment Technical Support Document. Golder Associates Ltd. Report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-02 R000. Toronto, Canada.

Health Canada. 2000. Canadian Guidelines for the Management of Naturally Occurring Radioactive Materials (NORM). Ottawa, Canada. (http://www.hc-sc.gc.ca/ewh-semt/alt_formats/hecs-sesc/pdf/pubs/contaminants/norm-mrn/00ehd245.pdf). Accessed June 2010.

Health Canada. 2007. Radon: A Guide for Canadian Homeowners. Ottawa, Canada. (http://www.cmhc-schl.gc.ca/odpub/pdf/61945.pdf). Accessed November 2010.

Health Canada. 2009. It's your health: radon. Ottawa, Canada. (http://www.hc-sc.gc.ca/hl-vs/iyh-vsv/environ/radon-eng.php). Accessed September 2010.

ICRP. 1993. Protection against Radon-222 at Home and Work. International Commission on Radiological Protection Publication 65, Annals of the ICRP Volume 23, Number 2. Oxford, United Kingdom.

INTERA. 2011. Descriptive Geosphere Site Model. Intera Engineering Ltd. Report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-24 R000. Ottawa, Canada.

Jackson, R. and S. Murphy. 2011. Mineralogical and Lithogeochemical Analyses of DGR-5 and DGR-6 Core. Intera Engineering Ltd. Report TR-09-06. Ottawa, Canada.

McPherson, M.J. 1993. Subsurface Ventilation and Environmental Engineering. Chapman and Hall, London, United Kingdom.

Mudd, G.M. 2008. Radon releases from Australian uranium mining and milling projects: assessing the UNSCEAR approach. Journal of Environmental Radioactivity 99, 288-315.

NWMO. 2010. L&ILW DGR Project Data Clearance: Design Information for Postclosure Safety Assessment. Nuclear Waste Management Organization Report DGR-REF-01929-23736. Toronto, Canada.

OPG. 2003. Derived Release Limits for the Western Waste Management Facility. Ontario Power Generation Report 0125-REP-03482.00002-R00. Toronto, Canada.

OPG. 2010. Reference Low and Intermediate Level Waste Inventory for the Deep Geologic Repository. Ontario Power Generation Report 00216-REP-03902-00003-R003. Toronto, Canada.

OPG. 2011. Deep Geologic Repository for Low and Intermediate Level Waste – Preliminary Safety Report. Ontario Power Generation Report 00216-SR-01320-00001 R000. Toronto, Canada.

Porstendorfer, J. 1994. Properties and behaviour of radon and thoron and their decay products in air. Journal of Aerosol Science 25, 219-263.

Przylibski, T.A. 2000. Estimating the radon emanation coefficient from crystalline rocks into groundwater. Applied Radiation and Isotopes 53, 473-479.

Schumann, R.R. and L.C.S. Gundersen. 1996. Geologic and climatic controls on the radon emanation coefficient. Environment International 22, S439-S446.

Sengupta, M. 1990. Mine Environmental Engineering Volume 1. CRC Press Inc., Boca Raton, USA.

Skowron, A. and E. Hoffman. 2009. Geochemical and SEM/EDS Analysis of DGR-1 and DGR-2 Core. Intera Engineering Ltd. Report TR-08-02. Ottawa, Canada.

Wigston, A. and R. Jackson. 2010a. Mineralogy and Geochemistry of DGR-3 Core. Intera Engineering Ltd. Report TR-08-22. Ottawa, Canada.

Wigston, A. and R. Jackson. 2010b. Mineralogy and Geochemistry of DGR-4 Core. Intera Engineering Ltd. Report TR-08-23. Ottawa, Canada.

7. ABBREVIATIONS AND ACRONYMS

ADF	Atmospheric Dilution Factor
Bi-210	Bismuth-210
Bi-214	Bismuth-214
CNSC	Canadian Nuclear Safety Commission
DGR	Deep Geologic Repository
DWL	Derived Working Limit
EIS	Environmental Impact Statement
ICRP	International Commission on Radiological Protection
ILW	Intermediate Level Waste
L&ILW	Low and Intermediate Level Waste
LLW	Low Level Waste
NEW	Nuclear Energy Worker
NORM	Naturally Occurring Radioactive Materials
NWMO	Nuclear Waste Management Organization
OPG	Ontario Power Generation Inc.
PSR	Preliminary Safety Report
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
WLM	Working Level Month
WRMA	Waste Rock Management Area
WWMF	Western Waste Management Facility

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APPENDICES

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APPENDIX A: CONCENTRATION OF RADIUM IN HOST ROCK

The radium concentration in the host rock is expected to be in secular equilibrium with the uranium since the sediments have been in place for millions of years. Therefore, the radium concentration is calculated as 4.1 x 10^4 Bq/m^3, same as U-238 concentration. The details of this calculation are shown below:

Radium in host rock:

Uranium in host rock	1.2	ppm
Density of host rock	2.7	g/cm^3 (INTERA 2011)
Amount of uranium	1.4E-02	mol/m^3
Fraction U-238/Uranium	99.3	%
Amount of U-238	1.4E-02	molU238/m^3
Activity of U-238	4.0E+04	Bq/m^3
Half life uranium	4.5E+09	year
Half life radium	1.6E+03	year
Amount of radium	4.9E-09	molRa226/m^3
Activity of Ra-226	4.1E+04	Bq/m^3

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APPENDIX B: DIFFUSION COEFFICIENT

For the present analysis, the diffusion model considers diffusion of radon through the air and water phases in a partially saturated porous medium (Aachib et al. 2002). Using this approach, one can express D_e as follows:

$$D_e = D_a + HD_w \tag{B.1}$$

where D_e represents the effective diffusion coefficient (m^2/s), H represents the Henry's law coefficient for radon (-), and D_w and D_a represent the diffusion of radon in the gas and water phase, respectively (m^2/s).

D_a is given by:

$$D_a = \theta_a \tau_a D_a^o \tag{B.2}$$

where θ_a represents the volumetric air content (-), τ_a represents the gas-phase tortuosity (-) and $D°_a$ represents the open air diffusion coefficient (m^2/s).

D_w is given by:

$$D_w = \theta_w \tau_w D_w^o \tag{B.3}$$

where θ_w represents the volumetric water content (-), τ_w represents the water-phase tortuosity (-) and $D°_w$ represents the open water diffusion coefficient (m^2/s).

The volumetric air and water contents can be estimated based on saturation and porosity:

$$\theta_a = n(1 - S_r) \tag{B.4}$$

$$\theta_w = nS_r \tag{B.5}$$

where n represents the porosity of the host rock (-), and S_r represents the degree of saturation (-).

For this model, the tortuoisty parameters depend on porosity, connectivity and shape of the pore canals. The tortousity can be calculated as follows:

$$\tau_a = \frac{\theta_a^{2x+1}}{n^2} \quad \text{and} \quad \tau_w = \frac{\theta_w^{2y+1}}{n^2} \tag{B.6}$$

with x and y defined in terms of the following equations:

$$\theta_a^{2x} + (1 - \theta_a)^x = 1 \quad \text{and} \quad \theta_w^{2y} + (1 - \theta_w)^y = 1 \tag{B.7}$$

Tortuosity is calculated by first solving for x and y:

Table B.1: Radon Tortuosity in Air and Water

Parameter	Symbol	Value	Reference
Porosity (-)	n	2.0E-02	INTERA 2011
Degree of Saturation (-)	S_r	8.6E-01	INTERA 2011
Volumetric Air Content (-)	θ_a	2.8E-03	-
Calculation parameter	x	5.5E-01	-
Radon Tortuosity in Air Phase (-)	$\boldsymbol{\tau_a}$	**1.1E-02**	**-**
Volumetric Water Content (-)	θ_w	1.7E-02	-
Calculation parameter	y	5.7E-01	-
Radon Tortuosity in Water Phase (-)	$\boldsymbol{\tau_w}$	**4.2E-01**	**-**

The diffusion coefficients for the air and water phases can now be calculated:

Table B.2: Diffusion of Radon in the Air Phase

Parameter	Symbol	Value	Reference
Volumetric Air Content (-)	θ_a	2.8E-03	-
Tortuosity (gas phase)	τ_a	1.1E-02	-
Diffusion of Radon in Open Air (m^2/s)	D_a^o	1.2E-05	Sengupta 1990
Diffusion of Radon in Air Phase (m^2/s)	D_a	3.0E-10	-

Table B.3: Diffusion of Radon in the Water Phase

Parameter	Symbol	Value	Reference
Volumetric Water Content (-)	θ_w	1.7E-02	-
Tortuosity (aqueous phase)	τ_w	4.2E-01	-
Diffusion of Radon in Open Water (m^2/s)	D_w^o	1.1E-09	Sengupta 1990
Diffusion of Radon in Water Phase (m^2/s)	D_w	8.2E-12	-

The diffusion coefficient (D_e) for the current analysis has been calculated as **3.0 x 10^{-10} m^2/s**, as shown below:

Table B.4: Effective Diffusion Coefficient for Radon

Parameter	Value
Diffusion of Radon in Air Phase (m^2/s)	3.0E-10
Diffusion of Radon in Water Phase (m^2/s)	8.2E-12
Henry's law constant for radon (-)	2.3E-01
Effective Diffusion Coefficient (m^2/s)	**3.0E-10**

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APPENDIX C: DERIVATION OF EQUATION USED TO ESTIMATE THE RADON CONCENTRATION IN THE DGR DURING THE CONSTRUCTION PHASE (EQUATION 4.2)

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).

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

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.

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

where E is the emanation rate (Bq/m^{2}s), SA is the surface area of the repository or the waste rock (m^2), V_{rep} is the 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 $$m = \frac{E \cdot SA_{walls}}{V_{rep}} + \frac{E \cdot SA_{waste\,rock}}{V_{rep}} + \frac{C_{pore\,space} \cdot V_R \cdot \phi}{V_{rep}} \quad \text{and} \quad n = \lambda_{Rn} + \lambda_v \tag{C.3}$$

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

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

We will integrate Equation C.5 over a time step defined as: $t_i - t_{i-1}$. At time t_i the radon concentration averaged over the DGR will be C_i and at time t_{i-1} the radon concentration will be C_{i-1}.

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

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

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

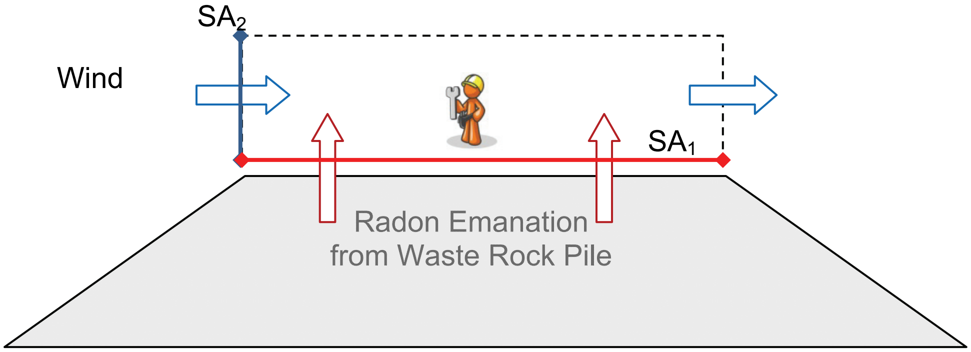
APPENDIX D: DERIVATION OF EQUATION USED TO ESTIMATE THE RADON CONCENTRATION IN AN ATMOSPHERIC COMPARTMENT ON TOP OF THE WASTE ROCK PILE (EQUATION 4.4)

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) in the atmospheric compartment is equal to the amount entering (IN) less the amount leaving (OUT).

$$\frac{\partial C}{\partial t} = IN - OUT \qquad \text{(D.1)}$$

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.



$$\frac{\partial C}{\partial t} = E\,SA_1 - V_{wind}SA_2C - \lambda_{Rn}V_CC \qquad \text{(D.2)}$$

where E represents the emanation 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 the Bruce nuclear 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 represents the concentration of radon in the atmospheric compartment (Bq/m^3).

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

$$\frac{\partial C}{\partial t} = m - nC \qquad \text{(D.3)}$$

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

$$\frac{\partial C}{\partial t} = m - nC \quad = 0 \qquad \text{(D.4)}$$

$$C = \frac{m}{n} \qquad \text{(D.5)}$$

$$C = \frac{E\,SA_1}{V_{wind}SA_2 + \lambda_{Rn}V_C} \qquad \text{(D.6)}$$

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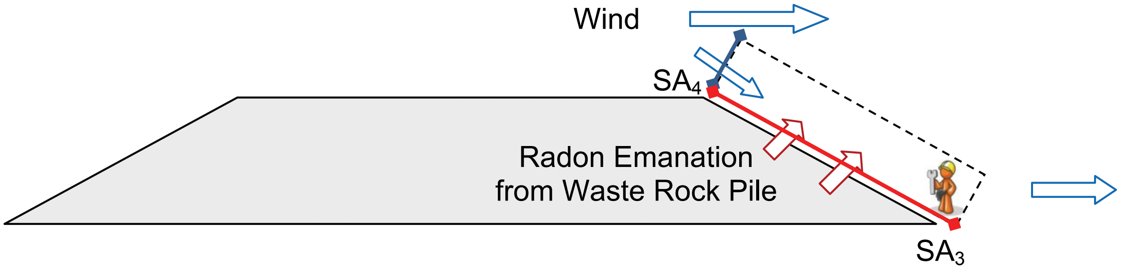
APPENDIX E: DERIVATION OF EQUATION USED TO ESTIMATE THE RADON CONCENTRATION IN AN ATMOSPHERIC COMPARTMENT DOWN-WIND OF THE WASTE ROCK PILE (EQUATION 4.5)

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) in the atmospheric compartment is equal to the amount entering (IN) less the amount leaving (OUT).

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

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.



$$\frac{\partial C}{\partial t} = E\,SA_3 + fV_{wind}SA_4C_{initial} - fV_{wind}SA_4C - \lambda_{Rn}V_CC \tag{E.2}$$

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 the Bruce nuclear 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$_{initial}$ 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 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 $m = E\,SA_3 + fV_{wind}SA_4C_{initial}$ and $n = fV_{wind}SA_4 + \lambda_{Rn}V_C$

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

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

$$\frac{\partial C}{\partial t} = m - nC = 0 \tag{E.4}$$

$$C = \frac{m}{n} \tag{E.5}$$

$$C = \frac{E\,SA_3 + fV_{wind}SA_4C_{initial}}{fV_{wind}SA_4 + \lambda_{Rn}V_C} \tag{E.6}$$

APPENDIX F: DERIVATION OF EQUATION USED TO ESTIMATE THE RADON CONCENTRATION IN THE DGR DURING OPERATIONS PHASE AS A FUNCTION OF TUNNEL LENGTH (EQUATION 4.6)

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).

$$\frac{\partial C}{\partial x} = IN - OUT \qquad \text{(F.1)}$$

$$\frac{\partial C}{\partial t} = \frac{E\cdot(2w+2h)}{Q} - \frac{\lambda_{Rn}wh}{Q}C \qquad \text{(F.2)}$$

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), Q is the volumetric flow rate through the DGR (m^3/s), and λ_{Rn} is the decay rate of Radon-222 (1/s).

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

$$\frac{\partial C}{\partial x} = m - nC \qquad \text{(F.3)}$$

$$\frac{\partial C}{m - nC} = \partial x \qquad \text{(F.4)}$$

We will integrate Equation F.4 over a time step defined as: x_i- x_{i-1}.

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

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

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

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APPENDIX G: DERIVATION OF EQUATION USED TO ESTIMATE THE RADON CONCENTRATION IN AN EMPLACEMENT ROOM OR THE DGR DURING OPERATIONS PHASE (EQUATION 4.7)

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).

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

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

where E is the emanation rate (Bq/m^{2}s), SA$_{wall}$ is the surface area inside an emplacement room or the entire DGR (m^2), V$_{rep}$ is the excavated volume of an emplacement room or the entire DGR (m^3), R$_w$ is the radon emissions from the waste (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 $n = \lambda_{Rn} + \lambda_v$

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

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

We will integrate Equation G.4 over a time step defined as: t$_i$- t$_{i-1}$.

At time t$_i$ the radon concentration averaged over the DGR will be C$_i$ and at time t$_{i-1}$ the radon concentration will be C$_{i-1}$.

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

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