



WORKER DOSE ASSESSMENT

FOR THE WHEELER RIVER PROJECT

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EXECUTIVE SUMMARY

The Wheeler River Project proposes the development of the high-grade Phoenix uranium deposit as an in-situ recovery (ISR) mining operation with on-site processing. This worker dose report provides technical detail regarding radiological doses to workers involved in the ISR operations, and supports the Human Health Assessment, which is part of the Wheeler River Environmental Assessment (EA).

The ISR operations involve a wellfield, where uranium is extracted from the ore body in a circulating lixiviant solution, and the ISR Plant, where uranium is precipitated out of solution to make the yellowcake product. The fresh yellowcake will be dried and calcined, and then packaged for transport.

Prior to uranium precipitation, unwanted constituents, particularly iron (Fe) and radium (Ra), will be removed from solution by precipitation. The process precipitate sludge will contain enough uranium to be considered an asset and it is expected to be sent offsite for processing at an eligible licensed facility. Secondary options include offsite disposal, long term reclamation and storage in place on surface or re-slurry and injection below ground at the end of mining.

Other stored waste includes drill cuttings from the wellfield. Drill cuttings from the ore body will be segregated and stored at a special waste pad. The intent is to convey this ore material to a conventional uranium mill for processing, during operations and/or at the end of mining. As a secondary option, the material may be contained and reclaimed on site for long term storage.

Workers engaged in the operation of the Wheeler River Project will be occupationally exposed to radiation sources in several work areas in the process of drilling, lixiviant recovery and processing to yellowcake. Expected exposure pathways are through inhalation of dust and radon, as well as external exposure to gamma radiation from process solids and liquids containing radionuclides of the U-238 decay chain.

Radon (and short-lived progeny) are of primary concern at the front end of the ISR process, where solutions and precipitates bearing Ra-226 and daughter Rn-222 are present. Gaseous Rn-222 grows rapidly from decay of Ra-226. When lixiviant is initially brought from the ore body to the land surface, Rn-222 gas is supersaturated in the solution, and will off-gas rapidly when exposed to air. Venting is undertaken initially to facilitate off-gassing to the open atmosphere. Within the ISR plant, Rn-222 in solution is supported by ingrowth from Ra-226, and Rn-222 gas can partition from open solutions or precipitates to indoor air.

Long-lived radioactive dust is of primary concern at the back end of the ISR process, since the process is wet until the yellowcake product (uranium oxides) is precipitated out of solution and dried. The long-lived species of concern at that point are U-238 and U-234. Both species can be inhaled from air in drying and packaging areas.

Ore dust is also of potential concern when handling ore material that is subject to drying. The drilling process is wet, but cores may become dry. In ore material, all the radionuclides of the U-238 series are present, and all may contribute to worker dose if dust is inhaled.

External gamma exposure is of potential concern throughout the ISR process, when workers spend time in close proximity to a source, particularly a large volume with high concentrations of U-238 series radionuclides. Container materials may provide shielding and thereby reduce the radiation dose.

Doses to workers at the Wheeler River Project are expected to be within the annual dose limit of 20 mSv/a (as a 5-year average) for nuclear energy workers (NEWs), assuming use of powered air purifying respirators (PAPR) in the drying and packaging/loading areas. Uranium dust levels in these areas should be monitored and kept as low as reasonably achievable (ALARA).

Dust inhalation is also a potentially significant component of dose at the core shack. At this location, PAPR will not be required; however, dust levels should be monitored, and it may be possible to increase air exchange in the core shack, above the planned 6 exchanges per hour, should this be necessary. This would help also with radon exposure in the core shack.

For external radiation exposure, the most significant sources are ore cuttings in drums on the wellfield and bags of filter cake in the process precipitate removal area. Doses from external sources can be most effectively reduced by minimizing time at close distance. In the first case of the drums on the wellfield, increasing the distance to the drum is a readily available option. For exposure to bags of filter cake in the ISR plant, external dose from this source can be minimized by managing the quantity of filter cake in the work area, as well as worker proximity.

External doses from ore cuttings stored at the special waste pad were assumed to be mitigated by a berm around the pad, which provides shielding. However, this area is a potentially significant source of external dose, and work inside the berm should be minimized.

In general, it will be necessary to manage work sequence and schedule to avoid prolonged exposures close to identified sources, especially those identified as being significant to worker dose. Doses can be most effectively reduced by reducing exposure times and maximizing distances from the source, as well as by use of protective shielding.

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1.0 Introduction

1.1 Wheeler River Project

The Wheeler River Project proposes the development of the high-grade Phoenix uranium deposit as an in-situ recovery (ISR) mining operation with on-site processing. Denison Mines Corp. (Denison) is the operator of the Wheeler River Joint Venture and holds a 90% interest (directly or through its subsidiaries). JCU (Canada) Exploration Company Ltd. owns the remaining 10% of the joint venture. As of August 3, 2021, Denison acquired 50% of JCU. The Project is located approximately 35 km north-northeast of Cameco's Key Lake Operation and 35 km southwest of Cameco's McArthur River Operation in the eastern portion of the Athabasca Basin region in northern Saskatchewan.

Denison has prepared the Wheeler River Environmental Assessment (EA) to evaluate the potential effects of the Project on the environment and human health. This worker dose report provides technical detail regarding radiological doses to workers involved in the ISR operations, and supports the Human Health Assessment, which is part of the EA.

The ISR operations involve a wellfield, where uranium is extracted from the ore body in a circulating lixiviant solution, and the ISR Plant, where uranium is precipitated out of solution to make the yellowcake product. The fresh yellowcake will be dried and potentially calcined, and then packaged for transport. Figure 1.1 shows a schematic overview of the process.

Prior to uranium precipitation, unwanted constituents, particularly iron (Fe) and radium (Ra), will be removed from solution by precipitation. The process precipitate sludge will contain enough uranium to be considered an asset and is expected to be sent offsite for processing at an eligible licensed facility. Secondary options include offsite disposal, long term reclamation and storage in place on surface or re-slurry and injection below ground at the end of mining.

Other stored waste includes drill cuttings from the wellfield. Drill cuttings from the ore body will be segregated and stored at a special waste pad. The intent is to convey this ore material to a conventional uranium mill for processing, during operations and/or at the end of mining. As a secondary option, the material may be contained and reclaimed on site for long term storage.

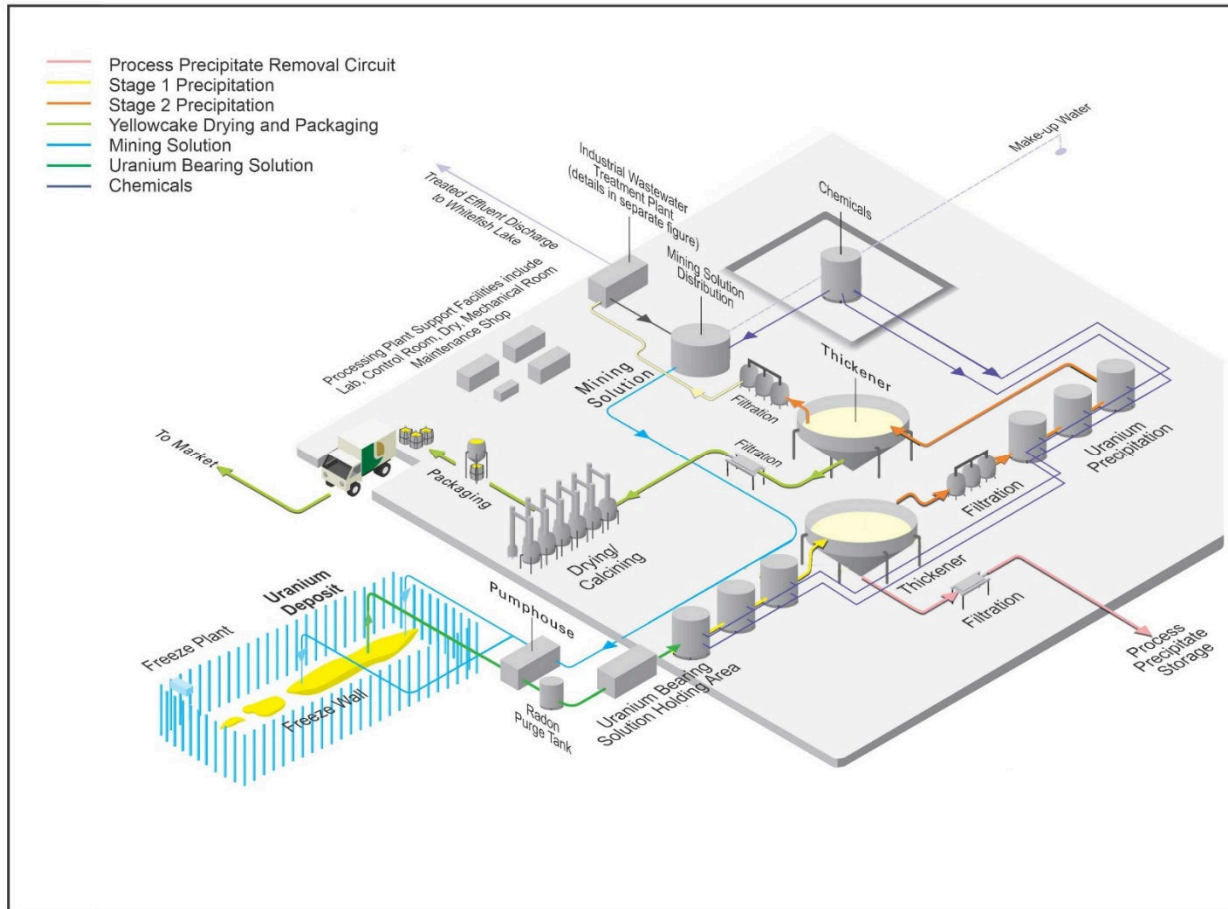


Figure 1.1: Schematic Overview of the ISR Process

1.2 Worker Component of Human Health Assessment

The Human Health component of the EA will address radiological and non-radiological exposures to members of the public, and to workers involved in the ISR process.

This worker dose report specifically addresses the radiological dose to workers, and will provide this information to the Human Health component of the EA. In addition, the worker dose information will inform the development of the Radiation Protection Plan, which will be prepared as a mitigation measure in order to control worker exposure and dose.

Information on the Project operations and work activities was provided by Denison. Based on this, EcoMetrix identified important work areas, sources and exposure pathways by which workers are likely to receive radiation doses, and requested from Denison detailed information needed to develop radiation exposure scenarios for each job category. The information, such as radionuclide concentrations in source materials, source shapes and volumes, container materials, building volumes and air exchange rates, and worker time spent near sources, was provided by Denison and outlined by Ecometrix in a memo (Ecometrix, 2022), for confirmation by Denison,

and is described in Section 3, below. EcoMetrix then applied standard methodology to calculate worker doses, as described in Section 4, presented dose results and discussed radiation protection strategies.

2.0 Regulatory Context

The EA for the Project is subject to federal and provincial approval under the *Canadian Environmental Assessment Act 2012*. The Canadian Nuclear Safety Commission (CNSC) is the responsible authority for the environmental assessment, since the Project will be regulated under the *Nuclear Safety and Control Act* (NSCA). Following EA approval, the Project will be subject to licensing under the NSCA, and the CNSC will be the regulatory body.

The *Radiation Protection Regulations* under the NSCA outline the regulatory requirements with respect to control of radiation doses to both workers and members of the public. Workers subject to radiation exposure from the Project will be designated as Nuclear Energy Workers (NEWs) and as such their radiation doses will be monitored and controlled so as not to exceed radiation dose limits for workers. These dose limits are:

- 50 mSv/a annual effective dose in any year
- 100 mSv as a 5-year effective dose (implies 20 mSv/a average annual effective dose)
- 50 mSv/a equivalent dose to lens of eye
- 500 mSv/a equivalent dose to skin

In addition, the CNSC has proposed a 100 mSv 5-year equivalent dose to lens of eye, in accordance with recent recommendations of the International Commission for Radiological Protection (ICRP, 2012a). This implies an average annual equivalent dose to lens of 20 mSv/a and will be considered as an applicable dose limit for workers.

For any NEW who is pregnant, the effective dose limit is lowered to 4 mSv/a for the balance of pregnancy, after the licensee has been informed, and doses must be managed accordingly.

In uranium mining, the main sources of radiation dose include:

- External gamma radiation, received while in proximity to radioactive sources
- Long-lived radioactive dust (U-238, U-234, Th-230, Ra-226, Pb-210, Po-210)
- Radon (Rn-222) and short-lived progeny (Po-218, Pb-214, Bi-214, Po-214)

The *Radiation Protection Regulations* require monitoring and control of radon exposure, as well as total effective dose and equivalent dose. While radon concentration limits are not specified in the regulation, other workplace standards may be considered relevant. Health Canada (2014) guidelines call for a Radiation Protection Program if annual average radon in the workplace exceeds 800 Bq/m³ and specify that the annual average should not exceed 3,000 Bq/m³.

3.0 Worker Exposure Situations

3.1 Radionuclides and Exposure Pathways

The primary radionuclides that workers may be exposed to include radionuclides of the U-238 decay chain, including radon and short-lived progeny.

Workers engaged in the operation of the Wheeler River Project will be occupationally exposed to radiation sources in several work areas in the process of drilling, lixiviant recovery and processing to yellowcake. Expected exposure pathways are through inhalation of dust and radon, as well as external exposure to gamma radiation from process solids and liquids containing radionuclides of the U-238 decay chain.

Radon (and short-lived progeny) are of primary concern at the front end of the ISR process, where solutions and precipitates bearing Ra-226 and daughter Rn-222 are present. Gaseous Rn-222 grows in rapidly from decay of Ra-226. When lixiviant is initially brought from the ore body to the land surface, Rn-222 gas is supersaturated in the solution, and will off-gas rapidly when exposed to air. Venting is undertaken initially to facilitate off-gassing to the open atmosphere. Within the ISR plant, Rn-222 in solution is supported by ingrowth from Ra-226, and Rn-222 gas can partition from open solutions or precipitates to indoor air.

The short-lived progeny of Rn-222, specifically Po-218, Pb-214, Bi-214 and Po-214, grow in rapidly from the airborne radon, and are more important to dose than radon. Both radon and short-lived progeny can be inhaled from air and contribute to worker dose.

Long-lived radioactive dust is of primary concern at the back end of the ISR process, since the process is wet until the yellowcake product (uranium oxides) is precipitated out of solution and dried. The long-lived species of concern at that point are U-238 and U-234. The uranium mass is almost entirely U-238; on an activity basis, U-238 and U-234 contribute equal activity. Both species can be inhaled from air in drying and packaging areas.

Ore dust is also of potential concern when handling ore material that is subject to drying. The drilling process is wet, but cores may become dry. In ore material, all the radionuclides of the U-238 series are present, and all may contribute to worker dose if dust is inhaled.

External gamma exposure is of potential concern throughout the ISR process, when workers spend time in close proximity to a source, particularly a large volume with high concentrations of U-238 series radionuclides. Container materials may provide shielding and thereby reduce the radiation dose.

3.2 Work Areas and Radiation Sources

Occupational exposure is expected to occur during multiple stages of the ISR process. The following locations and associated sources and worker functions are considered in this assessment:

- Wellfield: Drillers on the wellfield will be exposed to radiation from ore cuttings stored in drums at the well head. Wellfield operators/workers will be exposed to radiation from uranium bearing solution (UBS) in pipes and at the pumphouse and at the UBS storage pond. In addition, wellfield operators may be exposed to radiation from process precipitate slurry in piping at the disposal wellfield, in the event that this material is injected underground (not the preferred option). Both drillers and wellfield operators will be exposed to low levels of radon in outdoor air due to venting at the wellfield, from piping and from the UBS pond.
- The ISR plant consists of 5 areas that each have multiple sources for occupational radiation exposure, as follows:
 - Plant operators/workers in the process precipitate removal area will be exposed to radiation from the UBS feed tank and the process precipitate thickener. Additionally, it is expected that up to three bags of filter cake will be intermittently stored in this area before it is taken to the Process Precipitate pond. Plant operators/workers in the process precipitate removal will be exposed to radon arising from several sources - the open solution in the thickener, and the filter cake.
 - During the yellowcake precipitation, plant operators/workers in this area will be exposed to radiation from the precipitation tank and the yellowcake thickener. Additionally, there will be yellowcake in the conveyor that transports yellowcake to the drying area. Plant operators/workers in the yellowcake precipitation area will be exposed to radon arising from the open solution in the thickener.
 - The water treatment process involves three clarifiers which will be sources of radiation exposure for plant operators/workers in the water treatment area. Precipitated solids from first stage treatment will be conveyed to the Process Precipitate pond; second stage solids will be conveyed to the gypsum pond. Plant operators/workers in the water treatment area will be exposed to radon arising from the open solution in the clarifiers.
 - In the drying area plant operators/maintenance workers will be exposed to radiation from yellowcake in the drier and in the possible calciner. In addition, they will be potentially exposed to radioactive dust in the air from the dried yellowcake product. Workers in this area will be required to wear powered air purifying respirators (PAPR) to reduce/eliminate inhalation exposure.
 - In the packaging area plant operators/workers will be exposed to radiation from drums of yellowcake product in the loading bay. In addition, they will be potentially exposed to radioactive dust in the air from the dried yellowcake product. Workers in this area will be required to wear powered air purifying respirators (PAPR) to reduce/eliminate inhalation exposure.

- Several waste pads and ponds on site are considered as sources of radiation exposure for equipment operators. These include the special waste pad for drill cuttings from the ore zone, and the Process Precipitate Pond. Equipment operators in these areas will also be exposed to radon in outdoor air from various sources, including the wellfield and the Process Precipitate pond.
- The core shack will hold up to 3 cores that will constitute a source of radiation exposure for geologists and geotech loggers working in this area. In addition, the cores will be a source of both radioactive dust and radon to the air in the core shack, resulting in exposures to the workers in this area.

A summary of all exposure situations is presented in Table 3.1.

Table 3.1: Exposure Locations and Sources

Location	Work Area	Source	Worker Function
Wellfield	Wellfield drilling	Cuttings in drum	Driller 1
	Pump houses	UBS in pump house piping	Wellfield Operator 1
	UBS Pond	UBS in storage pond	Wellfield Operator 1
	Wellfield piping	UBS in piping	Wellfield Operator 2 ^a
ISR Plant	Process precipitate removal Area	UBS feed tank	Plant Operator 1 ^a
		Bags of filter cake	
		Process precipitate thickener	
	Yellowcake Precipitation Area	Yellowcake precipitation tank	Plant Operator 2 ^a
		Yellowcake conveyor	
		Yellowcake thickener	
	Water Treatment Area	WTP clarifier	Plant Operator 3 ^a
Drying Area	Yellowcake	Plant Operator 4 ^a	
Packaging Loading Area	Yellowcake	Plant Operator 5 ^a	
Site Ponds Pads	Special Waste Pad	Drill cuttings	Equipment Operator 1
	Industrial Landfill	none	Equipment Operator 1
	Process Precipitate Pond	Process precipitate	Equipment Operator 1
Site infrastructure	Core Shack	3 cores	Geologist/Geotech Loggers

(a) Operator and Maintenance worker have the same exposure characteristics

3.3 Exposure Scenarios and Assumptions

3.3.1 Inhalation Scenarios

Workers at the Wheeler River Project may be exposed to radionuclides through inhalation of dust containing U-238 and its daughters, which can be produced when ore or product is handled. Rn-222 is a gaseous daughter of Ra-226; it will quickly dissipate outdoors, but can become a radiological hazard indoors, mainly due to ingrowth of short-lived progeny.

3.3.1.1 Exposure to Uranium Dust in Air

Radionuclide concentrations in dust and air, as well as worker occupancy in each exposure area, are summarized in Table 3.2. Atmospheric modelling results were used for uranium dust concentrations in outdoor areas, which arise mainly from stacks at the ISR plant (IEC, 2022). Concentrations of radionuclides in dust for indoor locations were estimated as described in this section.

Table 3.2: Concentrations in Dust and Occupancy in Work Area for the Indoor and Outdoor Dust Inhalation Scenarios

Work Area	Worker	Respirable Dust in Air (kg/m ³)	U-238 in Dust (Bq/kg)	Ra-226 in Dust (Bq/kg)	U-238 in Air (Bq/m ³)	Daily Occupancy h/d	Active months per year ^d
Wellfield	Driller 1	-	-		9.49E-04 ^a	11	8
Wellfield	Wellfield Operator 1, 2	-	-		9.49E-04 ^a	8	12
Process Precipitate Removal Area	Plant Operator 1	-	-		3.41E-03 ^a	8	12
Yellowcake Precip Area	Plant Operator 2	-	-		3.41E-03 ^a	8	12
Water Treatment Area	Plant Operator 3	-	-		3.41E-03 ^a	8	12
Drying Area	Plant Operator 4	1.18E-04	9.74E+06		1.15E+03 ^b	8	12
Packaging Loading Area	Plant Operator 5	1.18E-04	9.74E+06		1.15E+03 ^b	8	12
Special Waste Pad	Equipment Operator 1	-	-		6.83E-03 ^a	2	12
Process Precipitate Pond	Equipment Operator 1	-	-		9.95E-04 ^a	4	12
Industrial Landfill	Equipment Operator 1	-	-		4.25E-04 ^a	3	12
Core Shack	Geologist/	6.75E-08	2.99E+06	2.06E+06	2.02E-01 ^c	11	6
	Geotech Logger						

- (a) U-238 (Bq/m³) in air calculated from IEC (2022) µg/m³ in outdoor air at each location, operations phase, with calciner
- (b) U-238 in air shown for drying and packaging areas is an ambient concentration, based on design values for dust in the drying area (Hatch, 2020); the concentrations experienced by workers will be reduced 1000-fold by use of PAPR
- (c) U-238 in air for core shack based on an administrative level for respirable dust equal to ¼ of the ACGIH Threshold Limit Value (TLV); U-238 concentration in dust from ore assays by R and D Enterprises (2018)
- (d) Workers are assumed to work 20 days per month

In the ISR plant, a dust concentration for the drying area was obtained from the design document on emissions from uranium peroxide drying and calcining (Hatch, 2020). The dust concentration selected (148 mg/m^3) was that given for the inflow to the hygiene stack in the area around the dryer and calciner. It is expected that 80% by mass will be of particle sizes smaller than $10 \mu\text{m}$ and as such respirable (EPA, 1980), resulting in a respirable dust in air concentration of 118 mg/m^3 . The dust was assumed to be UO_4 , and the U concentration (all U-238 by mass) was estimated from the atomic weights as $7.88\text{E}+05 \text{ mgU/kg}$. The activity concentration of U-238 was calculated as $9.74\text{E}+06 \text{ Bq/kg}$ using a specific activity of 12.356 Bq/mg U , and U-234 was assumed to be present in secular equilibrium. Workers in the packaging/loading area were assumed to experience the same concentrations as workers in the drying area. Both are assumed to wear PAPR, which is assumed to provide a 1000-fold reduction in dust exposure.

In the core shack, dust was assumed to be uranium ore. Dust levels in the shack will be maintained below $\frac{1}{4}$ of the ACGIH Threshold Limit Value (TLV) of 0.27 mg/m^3 for respirable dust (Verma et al., 2015). The concentration of uranium per unit mass in ore was taken from pilot studies that found uranium concentrations in ore heads to be $2.42\text{E}+05 \text{ mgU/kg}$ (R and D Enterprises, 2018). The activity concentration was calculated using a specific activity of 12.356 Bq/mg U . The Ra-226 concentration was also measured in the aforementioned pilot studies. Core shack workers are assumed not to wear PAPR.

For exposure to ore dust in the core shack, progeny were considered to be in secular equilibrium with U-238 and Ra-226. For U-238, this includes equal concentrations of Th-234, U-234 and Th-230. For Ra-226, the progeny included are Pb-214, Bi-214, Pb-210, Bi-210, Po-210. Radon is considered separately in the following section.

3.3.1.2 Estimation of Radon in Air

Rn-222 concentrations in air, as well as time spent by workers in each considered area, are summarized in Table 3.3. Radon concentrations in outdoor work areas were taken from atmospheric modelling results (IEC, 2022). Radon concentrations were estimated for indoor work areas as described in this section.

Table 3.3: Concentrations of Radon and Occupancy in Work Area for the Indoor and Outdoor Radon Inhalation Scenarios

Work Area	Worker	Source	Rn-222 in Air (Bq/m^3)	Daily Occupancy h/d	Active months per year ^b
Wellfield	Driller 1	Outdoor	$6.75\text{E}+01^a$	11	8
Wellfield	Wellfield Operator 1, 2	Outdoor	$6.75\text{E}+01^a$	8	12
Process Precipitate Removal Area	Plant Operator 1	Outdoor	$1.17\text{E}+02^a$	8	12
		Cake	$2.72\text{E}+01$		
		Thickener	$7.35\text{E}+02$		

Work Area	Worker	Source	Rn-222 in Air (Bq/m ³)	Daily Occupancy h/d	Active months per year ^b
Yellowcake Precip Area	Plant Operator 2	Outdoor	1.17E+02 ^a	8	12
		Thickener	4.96E+02		
Water Treatment Area	Plant Operator 3	Outdoor	1.17E+02 ^a	8	12
		Clarifier	1.28E+02		
Drying Area	Plant Operator 4	Outdoor	1.17E+02 ^a	8	12
Packaging Loading Area	Plant Operator 5	Outdoor	1.17E+02 ^a	8	12
Special Waste Pad	Equipment Operator 1	Outdoor	8.82E+02 ^a	2	12
Process Precipitate Pond	Equipment Operator 1	Outdoor	9.03E+01 ^a	4	12
Industrial Landfill	Equipment Operator 1	Outdoor	2.97E+01 ^a	3	12
Core Shack	Geologist/Geotech Logger	Outdoor	6.75E+01 ^a	11	6
		Cores	1.18E+03		

(a) Rn-222 (Bq/m³) in air taken from IEC (2022) value in outdoor air at each location, operations phase, with calciner

(b) Workers are assumed to work 20 days per month

Two work areas in the ISR Plant are of particular interest with respect to radon partitioning from the circulating uranium bearing solution (UBS) to the indoor air: the Process Precipitate Removal Area and the Yellowcake Precipitation Area, both areas where the solution passes through a thickener that is open to air. In the Process Precipitate Removal Area there is also process precipitate cake that can partition radon to air.

The WTP work area is also of interest with respect to radon partitioning to air, as there will be residual radon in the water being treated, and this water will be open to air in the clarifiers.

The radon concentration in each work area as a result of partitioning from the uranium bearing solution was estimated based on the USNRC (1999) equation for radon transfer from household water to indoor air (USNRC, 1999), as follows:

$$TC = \frac{C_a}{C_w} = UR \times \frac{TE}{(ER \times V)}$$

Where:

TC = transfer coefficient (m³/m³)

C_a = radon (Rn-222) in air (Bq/m³)

C_w = radon (Rn-222) in water (Bq/m³)

UR = water use rate (m³/h)

TE = transfer efficiency (unitless)

ER = air exchange rate (1/h)

V = air volume (m^3)

It was assumed that the Rn-222 concentration in water (UBS) entering the ISR plant equals the Ra-226 concentration in water (3,000 Bq/L). Solution arriving at the UBS Pond is expected to contain 3,700 Bq/L Rn-222 (IEC, 2022) but this would be reduced over the 7-day retention time, due to decay and volatilization, to a level supported by Ra-226. The water use rate was taken to be the process plant feed rate of UBS (30 m^3/h) (Denison Mines, 2021a). Transfer efficiency taken to be 0.55 as recommended by the USNRC. The air exchange rate was the design value of 6 air exchanges per hour. The air volume used was the design volume of each work area – 11,232 m^3 for the Process Precipitate Removal Area, 7,488 m^3 for Yellowcake Precipitation Area, and 13,104 for the WTP Area (Ecometrix, 2022).

Denison completed pilot studies (Ecometrix, 2022), to determine that the maximum Ra-226 in uranium bearing solution entering the Process Precipitate Removal Area was 3,000 Bq/L (3.0E+06 Bq/ m^3). After process precipitate removal, the maximum Ra-226 in the yellowcake precipitation tank solution was 3.2 Bq/L (3.2E+03 Bq/ m^3). The maximum Ra-226 in the WTP was 0.4 Bq/L (4.0E+02 Bq/ m^3). Based on this information, and accounting for Rn-222 loss through the ventilation system (6 air exchanges /h), the Rn-222 in solution will be in excess of that supported by Ra-226 downstream of the Process Precipitate Removal Area – 1,350 Bq/L (1.35E+06 Bq/ m^3) in the Yellowcake Precipitation Area, and 610 Bq/L (6.1E+05 Bq/ m^3) in the WTP Area. Based on these inputs, the Rn-222 in air was estimated to be 735 Bq/ m^3 in the Process Precipitate Removal Area, 496 Bq/ m^3 in the Yellowcake Precipitation Area, and 128 Bq/ m^3 in the WTP Area.

In the Process Precipitate Removal Area, the precipitate cake produced by dewatering the process precipitates may be considered as an additional source of radon release to air. The process precipitate cake taken from the filter press will be bagged and transported from the ISR Plant to the Process Precipitate Pond. The amount of process precipitate in the Process Precipitate Removal Area at any time will be up to 3 bags (1m height, 1m diameter). The IAEA provides radon exhalation rates (Bq/ m^2/s) for thick NORM residues (>2m thick) as a function of Ra-226 content and % saturation (IAEA, 2013). These rates are conservative for a 1m thickness. Assuming a 30% saturation, the radon exhalation rate is estimated at 0.9 Bq/ m^2/s per Bq/g of Ra-226. The radon concentration in air from process precipitate cake can be calculated as:

$$C_a = C_s \times ExRate \times \frac{SA}{(ER \times V)}$$

Where:

- C_a = Radon (Rn-222) in air (Bq/ m^3)
- C_s = Ra-226 in cake (Bq/g fw)
- $ExRate$ = exhalation rate (Bq/ m^2/s)
- SA = open surface area of cake (m^2)
- ER = air exchange rate (1/s)
- V = air volume (m^3)

From the above-mentioned Denison pilot studies, the Ra-226 in process precipitate solids is expected to be 300 Bq/g dw. The ratio of dry weight to fresh weight after dewatering is expected to be 0.8, so the fresh weight concentration of Ra-226 is 240 Bq/g fw. The exhalation rate was 0.9 Bq/m²/s as discussed above. The open surface area for 3 bags of process precipitate cake was 2.355 m². The air exchange rate was the design value of 6 air exchanges per hour, or 0.00167 per second. The air volume used was 11,232 m³ as noted above. Based on these inputs, the Rn-222 in air from process precipitate cake in the Process precipitate Removal Area was estimated to be 27.2 Bq/m³, which is a very small addition to the Rn-222 in air arising from the thickener.

The Core Shack is another work area where radon partitioning to air will be of concern. This concern relates to radon exhalation from core material that is taken from the ore zone.

The Core Shack is a small narrow structure (40' long, 8' wide and 8' high). It will hold up to 3 cores at a time, each 4m long and 8cm in diameter, for examination by the geologist or geotech logger. Each core is housed in a core box, in three segments, with bottom and side walls. The source surface area was estimated as 3 x 0.08m x 4m = 0.96 m². Radon exhalation from core material was estimated using the IAEA exhalation rate for thick NORM residues, with the suggested adjustment for thin layers (IAEA, 2013). Assuming a 10% saturation, and a 0.08m layer thickness, the thick layer exhalation rate of 1.2 Bq/m²/s per Bq/g of Ra-226 was adjusted by $\tanh[\sqrt{\lambda/D} z]$, with $\lambda=2.1E-6 \text{ s}^{-1}$, $D=3.0E-6 \text{ m}^2/\text{s}$ and $z=0.08\text{m}$, giving an estimated exhalation rate of 0.08 Bq/m²/s per Bq/g of Ra-226.

From pilot studies (R and D Enterprises, 2018), the Ra-226 in ore solids was taken to be 2,061 Bq/g dw. The ratio of dry weight to fresh weight was taken to be 0.9 (dry, but not bone dry), so the fresh weight concentration of Ra-226 was 1,855 Bq/g fw. The exhalation rate was therefore $0.08 \times 1,855 \text{ Bq/g} \times 0.96 \text{ m}^2 = 142.5 \text{ Bq/s}$. The air exchange rate was the design value of 6 air exchanges per hour, or 0.001667 volumes per second. The air volume used was 72.5 m³ (12.2m x 2.44m x 2.44m). Based on these inputs, the Rn-222 in air from cores in the Core Shack was estimated to be $142.5 \text{ Bq/s} / 0.1208 \text{ m}^3/\text{s} = 1,180 \text{ Bq/m}^3$.

3.3.2 External Exposure

3.3.2.1 Radionuclide Concentrations

External exposure of workers is dependent on the chemistry of the radiation source. Five source configurations were identified for external exposure of workers:

Ore: Concentration of U-238 and Ra-226 in uranium ore were taken from pilot studies (R and D Enterprises, 2018) and converted to activity concentrations as discussed in Section 3.3.1.1. The progeny are considered in secular equilibrium with U-238 and Ra-226 as summarized in Table 3.4. Fresh weight concentrations are calculated using a dw/fw ratio of 0.9 and 0.7 for uranium ore cores and uranium ore cuttings respectively.

Table 3.4: Concentrations of U-238 and Ra-226 and Progeny in Uranium Ore

Radionuclide	Ore (Bq/kg dw)	Progeny
U-238	2.99E+06	U-234, Th-234, Th 230
Ra-226	2.06E+06	Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210, Po-210

Uranium Bearing Solution (UBS): The chemical composition of UBS was investigated in pilot tests and is summarized in Table 3.5. The daughters are considered to be in secular equilibrium with the parent. An exception to this is Th-234 for which the same activity concentration as Th-230 is assumed, based on similar chemical behaviour in solution.

Table 3.5: Measured Concentrations and Progeny of Radionuclides in the UBS Entering the ISR Plant

Radionuclide	UBS Bq/L	Progeny
Th-232 ^a	1.20E+01	
U-238	4.50E+05	U-234
Ra-228 ^a	5.00E+00	Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212; 64.06% Po-212; 35.94% Tl-208
Th-230	2.20E+05	
Ra-226	3.00E+03	
Rn-222	3.00E+03	Po-218, Pb-214, Bi-214, Po-214
Pb-210	1.70E+03	Bi-210, Po-210

(a) The Th-232 decay series is included in the external dose calculations, however its contribution to external dose is not significant compared to the contribution from the U-238 series.

Process precipitate solids: The chemical composition of the process precipitate solids from pilot testing is summarized in Table 3.6. The daughters are considered to be in secular equilibrium with the parent. An exception to this is Th-234 for which the same activity concentration as Th-230 is assumed. Fresh weight concentrations are calculated using a dw/fw ratio of 0.8, 0.5 and 0.3 for cake, sludge and slurry respectively. Rn-222 and short-lived progeny are assumed to be present in these media at the Ra-226 concentration. The Plant Operator has radiation exposure from slurry in the thickener, and from process precipitate cake. The Equipment Operator has radiation exposure from sludge at the Process Precipitate Pond.

Table 3.6: Measured Concentrations and Progeny of Radionuclides in the Process Precipitate Solids

Radionuclide	Process precipitate Solids (Bq/kg dw)	Process precipitate Pond Solids ^b (Bq/kg dw)	Progeny
Th-232 ^a	2.60E+02	2.10E+02	
U-238	2.90E+05	2.33E+05	U-234
Ra-228 ^a	2.00E+03	1.72E+03	Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb212, Bi-212; 64.06% Po-212; 35.94% Tl-208
Th-230	1.30E+06	1.09E+06	
Ra-226	3.00E+05	2.40E+05	Rn-222, Po-218, Pb-214, Bi-214, Po-214
Pb-210	7.00E+04	5.72E+04	Bi-210, Po-210

(a) The Th-232 decay series is included in the external dose calculations, however its contribution to external dose is not significant compared to the contribution from the U-238 series.

(b) The process precipitate solids will be mixed 80:20 with gypsum solids in the Process Precipitate Pond and therefore have lower concentrations of radionuclides in both U-238 and Th-232 series.

Yellowcake Precipitation Tank Solution: Radionuclide concentrations in the yellowcake precipitation tank as determined in pilot testing are summarized in Table 3.7. The daughters are considered to be in secular equilibrium with the parent. An exception to this is Th-234 for which the same activity concentration as Th-230 is assumed.

Table 3.7: Measured Concentrations and Progeny of Radionuclides in the Yellowcake Precipitation Tank

Radionuclide	Yellowcake Precipitation Tank Solution Bq/L	Progeny
Th-232 ^a	1.00E+01	
U-238	1.62E+05	U-234
Ra-228 ^a	2.00E+00	Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb212, Bi-212; 64.06% Po-212; 35.94% Tl-208
Th-230	1.83E+04	
Ra-226	3.20E+00	
Rn-222	1.35E+03 ^b	Po-218, Pb-214, Bi-214, Po-214
Pb-210	6.00E+01	Bi-210, Po-210

(a) The Th-232 decay series is included in the external dose calculations, however its contribution to external dose is not significant compared to the contribution from the U-238 series.

(b) Rn-222 was calculated to account for loss through the ventilation system in the process precipitate area.

Uranium Peroxide: Uranium peroxide is assumed to contain U-238 with a concentration of 9.74E+06 Bq/kg (dw) as discussed in Section 3.3.1.1. The only progeny included in the dose calculations is U-234 in secular equilibrium. Fresh weight concentrations are determined with a dw/fw ratio of 0.8 and 0.3 for cake in the yellowcake conveyor and slurry in the yellowcake thickener respectively. Yellowcake in the drying area is assumed to be almost dry, with a dw/fw ratio of 0.9, and completely dry in the packaging area, with a dw/fw ratio of 1 when packaged.

Water Treatment Plant Solids: Radionuclide concentrations in the 1st stage clarifier solids as determined in pilot testing are summarized in Table 3.8. Progeny are considered to be in secular equilibrium with the parent. An exception to this is Th-234 for which the same activity concentration as Th-230 is assumed. Fresh weight concentrations are calculated using a dw/fw ratio of 0.3 for slurry. Rn-222 and short-lived progeny are estimated to be present in the slurry at 6.1E+02 Bq/L, accounting for loss through the ventilation system in the Yellowcake Precipitation Area. The WTP Operator receives radiation exposure from slurry in the clarifier.

Table 3.8: Measured Concentrations and Progeny of Radionuclides in the WTP Solids

Radionuclide	Waste Treatment Solids (Bq/kg dw)	Progeny
Th-232 ^a	5.00E+00	
U-238	5.70E+00	U-234
Ra-228 ^a	9.00E+01	Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212; 64.06% Po-212; 35.94% Tl-208
Th-230	4.00E+04	
Ra-226	2.00E+02	Rn-222, Po-218, Pb-214, Bi-214, Po-214
Pb-210	1.40E+03	Bi-210, Po-210

The 1st stage solids will be sent directly to the pPond, as a slurry, without dewatering. Any exposures arising from these solids at the Process Precipitate Pond will be bounded by the calculated exposure from process precipitate solids at that location. The 2nd stage solids are of relatively low activity and will be sent directly to the Gypsum Pond, without dewatering.

The WTP liquid as determined in pilot testing was not used in calculation of WTP Operator exposure. The bounding exposure scenario was considered to be from slurry in the clarifier.

3.3.2.2 Exposure Times

Exposure times for the external exposure scenarios are summarized in Table 3.9. In the ISR Plant one plant operator will be assigned to each of the five areas: process precipitate removal,

yellowcake precipitation, water treatment, drying, and loading. In the process precipitate removal, yellowcake precipitation, and water treatment areas, the operators are assumed to split their time equally between the various sources in each area.

Table 3.9: Exposure Factors for External Exposures.

Location	Source ^a	Worker Function	h/d in area	h/d at 1 m	h/d at 5 m	h/d at 10 m	active months per year
Wellfield	Cuttings in Drum	Driller 1	11	2	4	5	8
	UBS Solution in pump house piping	Wellfield Operator 1	4	2	1	1	12
	UBS solution in storage pond	Wellfield Operator 1	4	2	1	1	12
	UBS Solution in piping	Wellfield Operator 2	8	4	2	2	12
ISR Plant	UBS feed tank	Plant Operator 1	8	6	1	1	12
	Bags of filter cake						
	Process precipitate Thickener						
	Yellowcake precipitation tank	Plant Operator 2	8	6	1	1	12
	Yellowcake conveyor						
	Yellowcake Thickener						
	WTP Clarifier	Plant Operator 3	8	6	1	1	12
	Drying Area, Dryer	Plant Operator 4	8	6	1	1	12
	Drying Area, Calciner						
Packaging/Loading Area	Plant Operator 5	8	6	1	1	12	
Site Ponds Pads	Special Waste Pad	Equipment Operator 1	2	0	2	0	12
	none	Equipment Operator 1	3	0	2	1	12
	Process precipitate Pond	Equipment Operator 1	4	0	3	1	12
Core Shack	3 cores	Geologist/Geotech Loggers	11	2	8	1	6

(a) When there are several sources in one work area, the worker is assumed to divide his time roughly equally among those sources (see Appendix Table A.3).

3.3.2.3 External Exposure Geometries and Shielding

Table 3.10 to Table 3.12 summarize the exposure geometries assumed to apply to workers in the different exposure situations. The tables also include illustrative sketches from the setup in MicroShield reflecting any simplifications to conform with input requirements for the program. In all cases, the source material is modelled as the custom material "soil" with densities reflecting the dw/fw used to calculate the activity concentration discussed in Section 3.3.2.1. The shielding for each exposure situation is noted. Stainless steel shielding is modelled as iron in MicroShield with a material density of 7.82 g/cm³. HDPE piping is modelled as polyethylene with a material density of 0.93 g/cm³ (PNNL, 2006).

All receptors, represented by exposure points in MicroShield, are positioned at 1m above ground. For horizontal geometries the exposure height is conservatively assumed to be at the same level as the source. The modelled distances from the source are 1, 5 and 10 m in accordance with the occupancy information presented in Table 3.9.

Table 3.10: Geometries for External Exposure Scenarios Modelled in MicroShield for Sources in the Wellfield




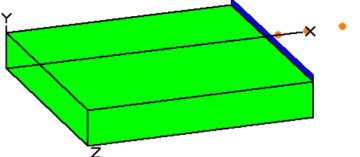
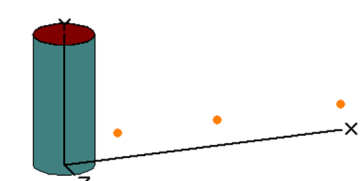

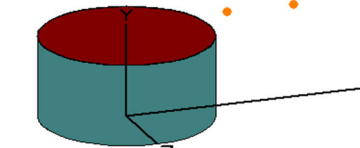
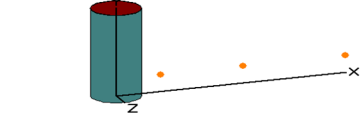
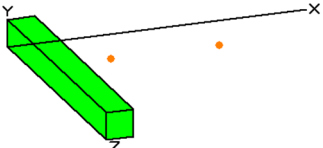
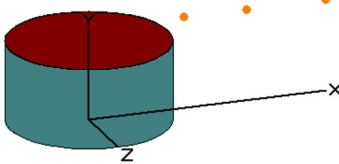
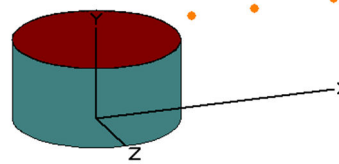
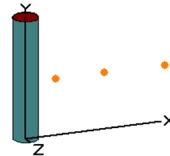
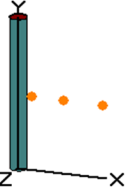
Source	Geometry	Source Type	MicroShield Geometry	Volume (m ³)	Shielding Thickness (mm)	Shielding material	Source form	Density (kg/m ³)
Cuttings in drum	Height: 0.89m, diameter: 0.58m	Ore		2.35E-01	1.20	Steel	Sludge	2.60E+03
Vertical Pipes in Pump House	Vertical pipes on both side walls, width 2.5m, height 2.7m	UBS Feed		1.35E+00	15.5	Polyethylene	Liquid	1.00E+03
Horizontal Pipe in Wellfield piping	Horizontal pipe, 1.2 above grade	UBS Feed		6.28E-01	15.50	Polyethylene	Liquid	1.00E+03
UBS Pond	Dimensions: 1.5m x 59m x 59m	UBS Feed		5.22E+03	6.35	Steel	Liquid	1.00E+03

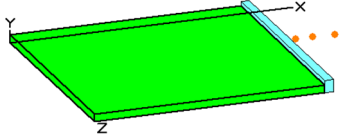
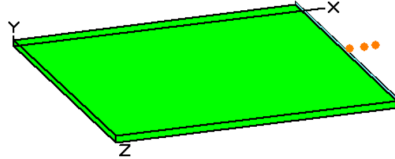

Table 3.11: Geometries for External Exposure Scenarios Modelled in MicroShield for Sources in the ISR Plant

Source	Geometry	Source Type	MicroShield Geometry	Volume (m ³)	Shielding Thickness (mm)	Shielding material	Source form	Density (kg/m ³)
UBS Feed Tank	Height: 5.2m, diameter: 3.3m	UBS Feed		4.45E+01	6.35	Steel	Liquid	1.00E+03
Bags of Filter Cake	3 bags of filter cake, each 1m height, 1m diameter	Process Precipitates		3.00E+00		none	Cake	1.88E+03
Process precipitate Thickener	Height: 5m, Diameter: 10m, drum 1.7m above the floor	Process Precipitates		3.93E+02	6.35	Steel	Slurry	1.30E+03
Precipitation Tank	Height:5.2m, Diameter: 3.3m	Yellowcake Precipitation Solution		4.45E+01	6.35	Steel	Liquid	1.00E+03

Source	Geometry	Source Type	MicroShield Geometry	Volume (m ³)	Shielding Thickness (mm)	Shielding material	Source form	Density (kg/m ³)
Yellowcake in Screw conveyor	Height: 1m, Length: 10m, Width: 1m	UO ₄		1.00E+01	6.35	Steel	Cake	2.40E+03
Yellowcake Thickener	Height: 5m, Diameter: 10m, drum 1.7m above the floor	UO ₄		3.93E+02	6.35	Steel	Slurry	1.30E+03
WTP Clarifier	Height: 5m, Diameter: 10m, drum 1.7m above the floor	NA		3.93E+02	6.35	Steel	Slurry	1.00E+03
Dryer	Horizontal cylinder, Length: 10m Diameter: 2m	UO ₄		3.14E+01	6.35	Steel	powder	2.03E+03
Calciner	Horizontal cylinder, Length: 20m Diameter: 2m	UO ₄		6.28E+01	6.35	Steel	powder	2.03E+03

Source	Geometry	Source Type	MicroShield Geometry	Volume (m ³)	Shielding Thickness (mm)	Shielding material	Source form	Density (kg/m ³)
Drum Storage	350 barrels on a pad, each height: 0.89m, diameter: 0.58m	UO ₄		1.08E+02	1.20	Steel	powder	1.71E+03

Table 3.12: Geometries for External Exposure Scenarios Modelled in MicroShield for Sources in the Site Ponds/Pads and Other Site Infrastructure

Source	Geometry	Source Type	MicroShield Geometry	Volume (m ³)	Shielding Thickness (mm)	Shielding material	Source form	Density (kg/m ³)
Special Waste Pad	Pad with dimensions: width 53m x length 53m, height: 1.8m, Berm 2m wide	Ore		5.06E+03	2000	Sandy soil	sludge	2.60E+03
Process precipitate pond	Dimensions 150m x 150m x 2.3m	Process Precipitates		5.18E+04	6.35	Steel	sludge	1.60E+03
Cores in Shack	3 cores in core boxes, each 0.08m diameter, length 4m, each cut in 3 pieces	Ore		7.72E-02		none	cylindrical solids	3.36E+03

4.0 Dose Calculation Methodology

4.1 Worker Dose from Dust Inhalation

Internal dose from inhalation of radioactive materials is related to the concentration in air through the transfer parameter $P(i)_{19}$ for transfer from air to dose in CSA N288.1-20 (CSA, 2020).

$$P(i)_{19} = I \cdot DCF_i \cdot OF_i$$

Where:

I = inhalation rate ($m^3 \cdot a^{-1}$)

DCF_i = dose coefficient for inhalation ($Sv \cdot Bq^{-1}$)

OF_i = occupancy factor, or fraction of time an individual is exposed to the inhalation hazard (unitless)

Based on ICRP 119 (ICRP, 2012b) the inhalation rate used for workers is $1.2 m^3/h$. The dose coefficients for inhalation are those specified in ICRP Publication 137 as appropriate for occupational intakes of radionuclides in uranium ore (ICRP, 2017). Selected DCFs were for activity median aerodynamic diameter (AMAD) of $5\mu m$ and the lung absorption type M, as indicated in ICRP 137 to be appropriate for uranium ore dust (ICRP, 2017).

The effective dose from inhalation is expressed as:

$$D(i) = P(i)_{19} \cdot A$$

Where:

A = activity of the dust (Bq/m^3)

4.2 Worker Dose from Radon

Dose from Rn-222 inhalation is calculated using the equilibrium fraction method in CSA N288.6-12 (CSA, 2020). For a given concentration of radon, the dose is dependent on the degree of equilibrium (F) between the radon and the short-lived radioactive decay products. The value of F is estimated at 0.18 for indoor work areas, based on 6 air exchanges/hour (10 min air residence time), and at 0.1 for outdoor locations, assuming a 5 min air travel time (Health Canada, 2010). The equation for the calculation of dose (mSv/a) from indoor radon and progeny for workers is:

$$Dose_{Rn} = C_{Rn} \cdot (3700 Bq \cdot m^{-3})^{-1} \cdot F \cdot (ET \cdot (170h)^{-1}) \cdot 5 mSv$$

Where:

C_{Rn} = concentration of radon in air (Bq/m^3)

F = degree of equilibrium between radon and decay products (unitless)

ET = exposure time (h/a)

4.3 Worker Dose from Gamma Radiation

All external dose calculations were done in the Computer Code "MicroShield LT" (Version 12). MicroShield is a comprehensive photon/gamma ray shielding and dose assessment program that is widely used for a number of radiation science applications, e.g. designing shields and estimating source strength from radiation measurements. The dosimetric properties of U-238 and Th-232 decay series radionuclides are included in the database library of MicroShield. The DCF associated with any worker exposure condition depends on the geometry of the radiation source (size and shape), the distance of the worker from the source, and on the nature of any shielding between the worker and the source. MicroShield incorporates solution algorithms for various source geometries and the DCFs are calculated based on the decay energies of each radionuclide including buildup in the source.

The fundamental result of point kernel integration is the photon fluence rate (photons/cm²/s) at the dose point for each energy in each case. This is multiplied by the energy to achieve the energy fluence rate, MeV/cm²/sec. The photon fluence rate is then converted by MicroShield to units of exposure, energy absorption in air (mGy/h), and effective dose (mSv/h). Conversion tables in ICRP Publication 116 (ICRP, 2012b) are used to convert to effective dose (mSv/h) and organ equivalent dose (mSv/a). For the purposes of this report only the effective dose and the equivalent dose to the lens of the eye will be reported. In calculating the effective dose, the MicroShield output includes results for all orientations of the receptor in accordance with geometries provided by ICRP 116. Conservatively, the geometry resulting in the highest effective dose is selected. This is typically the antero-posterior or lateral geometry. For equivalent dose to the lens of the eye the geometry resulting in the largest dose is, in most cases, the right and left lateral geometry. The exposure cases were set up in MicroShield as described in Section 3.3.2.3. The appropriate number of integration slices for the point kernel calculations were selected through a sensitivity analysis.

5.0 Worker Dose Estimates

Predicted doses for the selected exposed workers at the Wheeler River Project are presented in Sections 5.1 to 5.4.

5.1 Dose from Dust Inhalation

Inhalation of U dust will result in appreciable effective dose to workers only in the drying area and in the packaging/loading area of the ISR plant (both 6.91 mSv/a, with PAPR) and in the core shack (6.65 mSv/a, without PAPR). Doses in all considered locations are presented in Table 5.1.

Table 5.1: Internal Annual Dose from Dust Inhalation

Work Area	Worker	Effective Dose from Inhalation U-238 ⁺ (mSv/a)	Effective Dose from Inhalation Ra-226 ⁺ (mSv/a)	Total Effective Dose (mSv/a)
Wellfield	Driller 1	5.21E-03	-	5.21E-03 ^a
Wellfield	Wellfield Operator 1, 2	5.68E-03	-	5.68E-03 ^a
Process Precipitate Removal Area	Plant Operator 1	2.04E-03	-	2.04E-03 ^a
Yellowcake Precip Area	Plant Operator 2	2.04E-02	-	2.04E-03 ^a
Water Treatment Area	Plant Operator 3	2.04E-02	-	2.04E-03 ^a
Drying Area	Plant Operator 4	6.91E+00	-	6.91E+00 ^b
Packaging Loading Area	Plant Operator 5	6.91E+00	-	6.91E+00 ^b
Special Waste Pad	Equipment Operator 1	1.02E-02	-	1.02E-02 ^{ac}
Process Precipitate Pond	Equipment Operator 1	2.98E-03	-	2.98E-03 ^{ac}
Industrial Landfill	Equipment Operator 1	9.54E-04	-	9.54E-04 ^{ac}
Core Shack	Geologist/ Geotech Logger	5.63E+00	1.02E+00	6.65E-00 ^d

(a) Based on outdoor concentration of U dust from IEC (2022); U-238⁺ DCF 2.60E-06 Sv/Bq from ICRP 137 includes U-238+U-234

(b) Based on indoor concentration of U dust, which dominates; U-238⁺ DCF 2.60E-06 Sv/Bq from ICRP 137 includes U-238+U-234

(c) Equipment Operator 1 frequents 3 locations; the 3 doses must be added for this worker

(d) Based on indoor concentration of ore dust, which dominates; U-238⁺ DCF 2.08E-05 Sv/Bq from ICRP 137 includes the entire U-238 series; doses shown for U-238⁺ and Ra-226⁺ reflect the portions from U-238 to Th-230, and from Ra-226 to Po-210, respectively.

5.2 Dose from Radon Inhalation

Inhalation of Rn-222 and its short-lived progeny in air will result in appreciable effective dose to workers in ISR plant areas with open solution (2.27, 1.54 and 0.53 mSv/a in process precipitate removal, Yellowcake Precipitation, and Water Treatment, respectively), at the waste pad/ponds (0.42 mSv/a) and in the core shack (2.3 mSv/a). High radon concentrations in the core shack are due in part to the small volume of the room. Doses in all considered locations are presented in Table 5.2.

Table 5.2: Internal Annual Dose from Radon Inhalation

Work Area	Worker	Source	Dose from Radon in Air (mSv/a)	Total Radon Dose for Worker (mSv/a)
Wellfield	Driller 1	Outdoor	9.44E-02 ^a	9.44E-02
Wellfield	Wellfield Operator 1, 2	Outdoor	1.03E-01 ^a	1.03E-01
Process precipitate Removal Area	Plant Operator 1	Outdoor	1.78E-01 ^a	2.27E+00
		Cake	7.47E-02 ^b	
		Thickener	2.02E+00 ^b	
Yellowcake Precip Area	Plant Operator 2	Outdoor	1.78E-01 ^a	1.54E+00
		Thickener	1.36E+00 ^b	
Water Treatment Area	Plant Operator 3	Outdoor	1.78E-01 ^a	5.30E-01
		Clarifier	3.52E-01 ^b	
Drying Area	Plant Operator 4	Outdoor	1.78E-01 ^a	1.78E-01
Packaging Loading Area	Plant Operator 5	Outdoor	1.78E-01 ^a	1.78E-01
Special Waste Pad	Equipment Operator 1	Outdoor	3.37E-01 ^a	4.23E-01
Process precipitate pond	Equipment Operator 1	Outdoor	6.89E-02 ^a	
Industrial Landfill	Equipment Operator 1	Outdoor	1.70E-02 ^a	
Core Shack	Geologist/	Outdoor	7.08E-02 ^a	2.30E+00
	Geotech Logger	Cores	2.23E+00 ^b	

(a) Based on outdoor concentration of radon from IEC (2022)

(b) Based on an indoor source of radon to indoor air

5.3 Dose from External Exposure

External exposure to gamma radiation from sources in the work area will result in effective dose to workers above 1 mSv/a for Driller 1 in the wellfield (10.16 mSv/a), Plant Operator 1 in the Process Precipitate Removal Area (12.85 mSv/a), Plant Operator 3 in the Water Treatment Area (1.7 mSv/a), Equipment Operator 1 at the waste pad/ponds (5.68 mSv/a) and the Geologist/Geotech Logger in the Core Shack (2.02 mSv/a). External dose for Equipment

Operator 1 at the Special Waste Pad is mitigated by a berm, which provides shielding. Low external dose here depends on the berm.

Doses to the lens of the eye are generally higher by 40% to 60% depending on the exposure geometry. For the above-mentioned workers, the dose to lens of the eye is: Driller 1 (16.4 mSv/a), Plant Operator 1 (19.19 mSv/a), Plant Operator 3 (2.61 mSv/a), Equipment Operator 1 (9.33 mSv/a) and Geologist/Geotech Logger (3.25 mSv/a).

Table 5.3: Effective Dose and Equivalent Dose to the Lens of the Eye for Workers from External Exposure

Work Area	Worker	Source	By Exposure Scenario		By Worker	
			External Dose (mSv/a)	Dose to Lens of Eye (mSv/a)	External Dose (mSv/a)	Dose to Lens of Eye (mSv/a)
Wellfield	Driller 1	Cuttings	10.16	16.40	10.16	16.40
Wellfield	Wellfield Operator 2	Piping	0.05	0.07	0.53	0.81
	Wellfield Operator 1	Pump House Piping	0.24	0.34		
		UBS Pond	0.29	0.47		
Process Precipitate Removal Area	Plant Operator 1	Feed Tank	0.24	0.39	12.85	19.19
		Cake	8.45	13.55		
		Thickener	4.16	5.25		
Yellowcake Precip Area	Plant Operator 2	Precip Tank	0.08	0.13	0.10	0.15
		Cake	0.02	0.02		
		Thickener	0.001	0.001		
Water Treatment Area	Plant Operator 3	Clarifier	1.70	2.61	1.70	2.61
Drying Area	Plant Operator 4	Dryer	0.01	0.01	0.02	0.02
		Calciner	0.01	0.01		
Packaging Loading Area	Plant Operator 5	Drums	0.07	0.07	0.07	0.07
Special Waste Pad	Equipment Operator 1	Waste Pad	<0.0001 ^a	0.0001 ^a	5.68	9.33
Process Precipitate Pond	Equipment Operator 1	Waste Pond	5.68	9.33		
Industrial landfill	Equipment Operator 1	No source	0.000	0.000		
Core Shack	Geologist/ Geotech Logger	Cores	2.02	3.25	2.02	3.25

(a) Dose to Equipment Operator 1 at the Special Waste Pad is mitigated by a 2m wide berm, which provides shielding.

5.4 Total Dose from all Exposures

The total dose from internal as well as external exposure to radioactive material is presented in Table 5.4. Predicted doses range from 0.16 mSv/a for the Wellfield Operator 2 to 16.83 mSv/a for the Plant Operator 1 working in the Process Precipitate Removal Area. In most cases, external radiation is the largest contributor to dose. Radon is most important for Wellfield Operator 2 (although total dose here is low) and for Plant Operator 2 in the Yellowcake Precipitation area. Dust inhalation is the dominant contributor to dose in the Drying and Packaging/Loading areas, and in the Core Shack. All worker doses are expected to be maintained below the average annual dose limit of 20 mSv/a for NEWs.

Table 5.4: Total Dose from Internal and External Pathways for Workers

Work Area	Worker	Internal Dose (mSv/a)		External Dose (mSv/a)	Total Effective Dose (mSv/a)
		Dust	Radon		
Wellfield	Driller 1	5.21E-03	9.44E-02	10.16	10.26
Wellfield	Wellfield Operator 2	5.68E-03	1.03E-01	0.05	0.16
	Wellfield Operator 1	5.68E-03	1.03E-01	0.53	0.64
Process Precipitate Removal Area	Plant Operator 1	2.04E-02	2.27E+00	12.85	15.14
Yellowcake Precip Area	Plant Operator 2	2.04E-02	1.54E+00	0.10	1.66
Water Treatment Area	Plant Operator 3	2.04E-02	5.30E-01	1.70	2.25
Drying Area	Plant Operator 4	6.91E+00 ^a	1.78E-01	0.02	7.10
Packaging Loading Area	Plant Operator 5	6.91E+00 ^a	1.78E-01	0.07	7.15
Special Waste Pad	Equipment Operator 1	1.02E-02	3.37E-01	- ^b	6.11
Process precipitate Pond	Equipment Operator 1	2.98E-03	6.89E-02	5.68	
Industrial Landfill	Equipment Operator 1	9.54E-04	1.70E-02	-	
Core Shack	Geologist/ Geotech Logger	6.65E+00	2.30E+00	2.02	10.97

(a) Dust inhalation dose mitigated by use of PAPR in the Drying and Packaging/Loading areas

(b) External dose mitigated by a berm around the Special Waste Pad, which provides shielding

The actual exposure geometries and shielding factors which will be experienced at the Wheeler River Project Site will be variable, making the predictions made here somewhat uncertain. This is especially true for workers in the ISR plant which are expected to be mobile between different sources of exposure, with various shielding characteristics. Nonetheless, the assumptions made in dose modelling are relatively conservative, and both area monitoring (dust, radon) and individual monitoring of external doses will be carried out, allowing for tracking of worker doses, and ongoing adjustment to minimize doses.

6.0 Radiation Protection Strategies

Doses to workers at the Wheeler River Project are expected to be maintained below the average annual dose limit of 20 mSv/a for NEWs. Several mitigations have been assumed and will be important in keeping doses ALARA. For the drying and packaging/loading areas of the ISR Plant use of PAPR has been assumed. It will be needed in these areas, and it has been planned in these areas to substantially reduce dose from inhalation of uranium dust. Dust levels in these areas should be monitored and kept as low as reasonably achievable.

A protection factor of 1000 is provided by several types of respirators such as Powered Air-Purifying Respirators (PAPR) with a full facepiece or hood, and Supplied-Air Respirators (SAR) in positive-pressure mode or continuous flow mode. Alternatively, a Self-Contained Breathing Apparatus will provide protection factors over 10,000 if used in positive-pressure mode. It should be noted that Air-Purifying Respirators will not offer protection against radioactive gases such as radon.

Dust inhalation is also a potentially significant component of dose at the core shack. At this location, PAPR will not be required; however, dust levels should be monitored here. An administrative level of respirable dust equal to $\frac{1}{4}$ of the ACGIH TLV of $27 \mu\text{g}/\text{m}^3$ has been assumed. It may be possible to increase air exchange in the core shack, above the planned 6 exchanges per hour, should this be necessary. This would help also with radon exposure in the core shack.

For external radiation exposure the most significant sources are ore cuttings in drums on the wellfield and bags of filter cake in the Process Precipitate Removal Area. Doses from external sources can be most effectively reduced by maximizing distances or minimizing time at close distance. In the first case of the drums on the wellfield, increasing the distance to the drum is a readily available option. For exposure to bags of filter cake in the ISR plant it was assumed that 3 bags will be in the area simultaneously at all times. The external dose from this source could be minimized by managing the quantity of filter cake in the work area, as well as worker proximity.

External doses from ore cuttings at the Special Waste Pad were assumed to be mitigated by a berm around the pad, which provides shielding. However, this area is a potentially significant source of external dose, and work inside the berm should be minimized.

In general, it will be necessary to manage work sequence and schedule to avoid prolonged exposures to the identified sources, especially those identified as being significant to worker dose. Doses can be most effectively reduced by reducing exposure times and maximizing distances from the source, as well as by use of protective shielding.

7.0 References

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Appendix A Example Calculations

Table A.1: Dust Inhalation Dose Calculation

Work Area	Worker	U-238 in Air (Bq/m ³)	Exposure Time (h/a)	DCF (Sv/Bq)	Total Effective Dose (mSv/a)
Wellfield	Driller 1	9.49E-04	1760	2.60E-06	5.21E-03
Wellfield	Wellfield Operator 1, 2	9.49E-04	1920	2.60E-06	5.68E-03
Process Precipitate Removal Area	Plant Operator 1	3.41E-03	1920	2.60E-06	2.04E-02
Yellowcake Precip Area	Plant Operator 2	3.41E-03	1920	2.60E-06	2.04E-02
Water Treatment Area	Plant Operator 3	3.41E-03	1920	2.60E-06	2.04E-02
Drying Area	Plant Operator 4	1.15E+00	1920	2.60E-06	6.91E+00
Packaging Loading Area	Plant Operator 5	1.15E+00	1920	2.60E-06	6.91E+00
Special Waste Pad	Equipment Operator 1	6.83E-03	480	2.60E-06	1.02E-02
Process precipitate pond	Equipment Operator 1	9.95E-04	960	2.60E-06	2.98E-03
Industrial Landfill	Equipment Operator 1	4.25E-04	720	2.60E-06	9.54E-04
Core Shack	Geologist/ Geotech Logger	2.02E-01	1320	2.08E-05	6.65E+00

$$\text{Total Effective Dose (mSv/a)} = C_{\text{air}} (\text{Bq/m}^3) \times I (\text{m}^3/\text{h}) \times \text{ET} (\text{h/a}) \times \text{DCF} (\text{Sv/Bq}) \times 1000 (\text{mSv/Sv})$$

Notes:

Concentrations from indoor sources for Drying/Packaging and Core Shack

Concentration in Drying/Packaging reduced 1000-fold by use of PAPR

DCFs (Sv/Bq) from ICRP 137: U238+U234 (2.06E-6); U238 to Po-210 (2.08E-5)

Inhalation Rate (I) from ICRP 119 is 1.2 m³/h

Table A.2: Radon Dose Calculation

Work Area	Worker	Source	Radon in Air (Bq/m ³)	Exposure Time (h/a)	Equilibrium Factor F	Radon Dose (mSv/a)	Total (mSv/a)
Wellfield	Driller 1	Outdoor	6.75E+01	1760	0.10	9.44E-02	9.44E-02
Wellfield	Wellfield Operator 1, 2	Outdoor	6.75E+01	1920	0.10	1.03E-01	1.03E-01
Fe-Ra Removal Area	Plant Operator 1	Outdoor	1.17E+02	1920	0.10	1.78E-01	2.27E+00
		Cake	2.72E+01	1920	0.18	7.47E-02	
		Thickener	7.35E+02	1920	0.18	2.02E+00	
Yellowcake Precip Area	Plant Operator 2	Outdoor	1.17E+02	1920	0.10	1.78E-01	1.54E+00
		Thickener	4.96E+02	1920	0.18	1.36E+00	
Water Treatment Area	Plant Operator 3	Outdoor	1.17E+02	1920	0.10	1.78E-01	5.30E-01
		Clarifier	1.28E+02	1920	0.18	3.52E-01	
Drying Area	Plant Operator 4	Outdoor	1.17E+02	1920	0.10	1.78E-01	1.78E-01
Packaging Loading Area	Plant Operator 5	Outdoor	1.17E+02	1920	0.10	1.78E-01	1.78E-01
Special Waste Pad	Equipment Operator 1	Outdoor	8.82E+02	480	0.10	3.37E-01	4.23E-01
Process Precipitate Pond	Equipment Operator 1	Outdoor	9.03E+01	960	0.10	6.89E-02	
Industrial Landfill	Equipment Operator 1	Outdoor	2.97E+01	720	0.10	1.70E-02	
Core Shack	Geologist/ Geotech Logger	Outdoor	6.75E+01	1320	0.10	7.08E-02	2.30E+00
		Cores	1.18E+03	1320	0.18	2.23E+00	

$$\text{Radon Dose (mSv/a)} = (\text{Cair (Bq/m}^3\text{)} / 3700 \text{ Bq/m}^3 \text{ per WL}) \times F \times (\text{ET (h/a)} / 170 \text{ h per WL}) \times 5 \text{ (mSv/a per WL)}$$

Table A.3: External Dose Calculation

Work Area	Worker	Source	Exposure Time (h/d) at:			Max Effective Dose (mSv/h)			Max Lens Dose (mSv/h)			Exp Days (d/a)	By Exposure Scenario	
			1m	5m	10m	1m	5m	10m	1m	5m	10m		External Dose (mSv/a)	Dose to Lens of Eye (mSv/a)
Wellfield	Driller 1	Cuttings	2	4	5	2.68E-02	1.86E-03	4.84E-04	4.33E-02	3.01E-03	7.82E-04	160	10.16	16.40
Wellfield	Wellfield Operator 1	Piping	4	2	2	4.91E-05	9.10E-06	3.40E-06	6.85E-05	1.26E-05	4.68E-06	240	0.05	0.07
	Wellfield Operator 2	Pump House Piping	2	1	1	4.74E-04	4.13E-05	1.08E-05	6.74E-04	5.81E-05	1.52E-05	240	0.24	0.34
Fe-Ra Removal Area	Plant Operator 1	UBS Pond	2	1	1	4.63E-04	1.80E-04	8.75E-05	7.59E-04	2.94E-04	1.43E-04	240	0.29	0.47
		Feed Tank	2	0.33	0.33	4.35E-04	8.51E-05	2.82E-05	7.13E-04	1.39E-04	4.60E-05	240	0.22	0.36
		Cake	2	0.33	0.33	4.78E-03	4.26E-04	1.09E-04	7.15E-03	6.27E-04	1.59E-04	240	2.34	3.49
Yellowcake Precip Area	Plant Operator 2	Thickener	2	0.33	0.33	6.84E-04	3.97E-04	1.80E-04	9.73E-04	5.08E-04	2.28E-04	240	0.37	0.53
		Precip Tank	2	0.33	0.33	1.63E-04	3.18E-05	1.05E-05	2.65E-04	5.17E-05	1.71E-05	240	0.08	0.13
		Cake	2	0.33	0.33	3.69E-05	7.89E-06	2.50E-06	3.69E-05	7.89E-06	2.50E-06	240	0.02	0.02
Water Treatment Area	Plant Operator 3	Thickener	2	0.33	0.33	2.33E-06	1.87E-06	8.74E-07	2.33E-06	1.87E-06	8.74E-07	240	0.001	0.001
Water Treatment Area	Plant Operator 3	Clarifier	6	1	1	1.06E-03	5.03E-04	2.22E-04	1.63E-03	7.51E-04	3.30E-04	240	1.70	2.61
Drying Area	Plant Operator 4	Dryer	3	0.5	0.5	9.12E-06	4.37E-06	1.55E-06	1.51E-05	4.37E-06	1.55E-06	240	0.01	0.01
		Calciner	3	0.5	0.5	1.52E-05	5.10E-06	2.30E-06	1.52E-05	5.10E-06	2.30E-06	240	0.01	0.01
Packaging Loading Area	Plant Operator 5	Drums	6	1	1	4.52E-05	9.05E-06	2.89E-06	4.52E-05	9.05E-06	2.89E-06	240	0.07	0.07
Special Waste Pad	Equipment Operator 1	Waste Pad	0	2	0	1.02E-07	8.54E-08	5.86E-08	1.84E-07	1.55E-07	1.06E-07	240	4.10E-05	0.0001
Fe-Ra Waste Pond	Equipment Operator 1	Waste Pond	0	3	1	2.27E-03	1.07E-03	6.82E-04	2.97E-03	1.34E-03	8.56E-04	240	0.93	1.17
Contaminated Landfill	Equipment Operator 1	No source	0	3	0	-	-	-	-	-	-	240	0	0
Core Shack	Geologist/ Geotech Logger	Cores	2	8	1	6.59E-03	4.39E-04	1.12E-04	1.06E-02	7.09E-04	1.81E-04	120	2.02	3.25

External Dose (mSv/a) = [Σ ET (h/d) x Max Effective Dose (mSv/h)] x ED (d/a)

Dose to Lens (mSv/a) = [Σ ET (h/d) x Max Lens Dose (mSv/h)] x ED (d/a)